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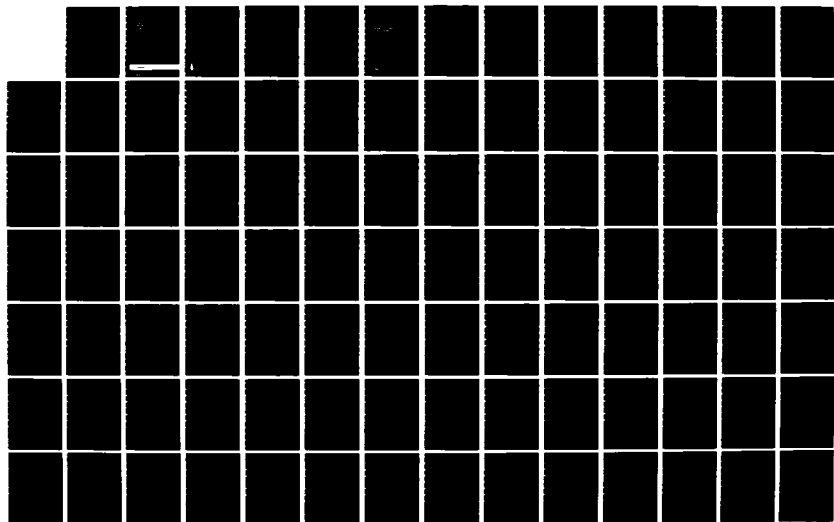
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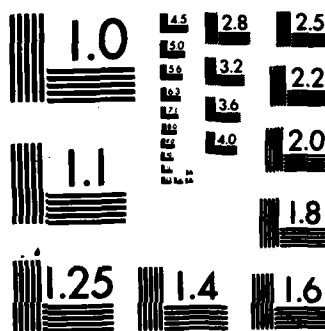
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Techniques for the Analysis of Spectral and Orbital Congestion in Space Systems

A. L. Hiebert, W. Sollfrey

March 1984

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This report is a compendium of the techniques available for analysis of spectral and orbital congestion in space systems. The expansion of signal transmissions and orbiting objects could severely affect the frequency spectrum allocations, orbit assignments, and related earth segments of space systems. The treatment of these problems requires a set of analytical procedures, computer programs to apply these procedures to specific configurations, and a data base to provide inputs to the programs. The proposed Space System Data Base will consist of electromagnetic and operational characteristics of active and projected U.S. and international space systems including related earth and airborne segments. More than 20 analysis and computation codes are described, with the presentation pitched to an engineer's or user's level. The projected capabilities will provide an essential national resource for management decisionmaking and architectural planning on space-related programs.



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Techniques for the Analysis of Spectral and Orbital Congestion in Space Systems

A. L. Hiebert, W. Solfrey

March 1984

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PREFACE

The Rand Corporation has been developing, under the Technology Applications Program of Project AIR FORCE, a capability for analyzing spectral and orbital congestion problems in current and projected U.S. and international space-related systems. This report contains descriptions of the analytical procedures, the computer programs to implement these procedures, and the required space systems data base for investigating such problems. (A previous Rand document on the subject is N-1536-AF, *Transmission and Orbital Constraints in Space-Related Programs: Project Description*, August 1980.) Some of the results presented in this report have appeared in the *Proceedings* of the Conference on Space Systems Data Bases and Analysis Capabilities, held November 17-19, 1981, at the DoD Electromagnetic Compatibility Analysis Center (ECAC) in Annapolis, Maryland.

The Rand project is supported by the Directorate of Space Systems and Command, Control, Communications, Headquarters, United States Air Force (AF/RDS), through Program Management Directive PE63431F of the Advanced Space Communications Program. AF/RDS, which serves as the office of primary responsibility for the Rand effort, assisted in obtaining the support and participation of the Air Force Systems Command, the Air Force Space Division, the Air Force Satellite Control Facility, the North American Air Defense Command, the Aerospace Defense Command, and other DoD organizations, as well as the Federal Communications Commission, the National Aeronautics and Space Administration, the National Telecommunications and Information Administration, and space-related industries. ECAC was tasked by the Office of the Under Secretary of Defense for Research and Engineering with developing the required space systems data base and analysis capability for both military and commercial space systems.

The Air Force Space Division is planning to establish a continuing project to implement applicable recommendations and analysis capabilities documented in this report. The Advanced Space Communications Program Office (SD/YKX) will continue to be the office of primary responsibility at the Space Division for the project. The YKX office

will be supported by the Frequency Management Branch of the Directorate of Communications Electronics (SD/DC) for frequency management issues. The DC office will also act as the point of contact for the ECAC data base described in this report. The Deputy for Mission Integration (SD/YO) will provide support on operational issues (SD Reg. 55-1). The role of the Air Force Space Command in this project and in spacecraft orbital position management is being formulated. The suggested participation of other agencies, of industry, and of universities is discussed in the text.

Copies of this report may be obtained from The Rand Corporation or from the Defense Technical Information Center (DTIC), Building 5, Cameron Station, Alexandria, Virginia 22314, Ph. #202-274-7633 (AUTOVON 284-7633).

SUMMARY

This report is a compendium of the techniques available for analysis of spectral and orbital congestion in space systems. Increased space traffic and debris, spectral demands, requirements for orbital slots and position control, and the very large geographical areas visible to satellites collectively imply potential signal interference, which requires analysis and control. The extensive data base on space and earth electromagnetic environments being established at the Electromagnetic Compatibility Analysis Center (ECAC), Annapolis, MD, and the computer-based analysis programs documented in this report provide the required capability for the analysis process.

The expansion of signal transmissions and orbiting objects could severely affect the frequency spectrum allocations, orbit assignments, and related earth segments of space systems. The available spectrum and useful orbital positions, as defined by today's capabilities, may be inadequate, leading to the condition we refer to as spectral and orbital congestion. A continuing analysis program, described in this report, is needed to provide a resource for evaluating engineering and architectural designs, predicting the impact of intentional and unintentional electromagnetic interference (EMI), and determining probable saturation conditions. The program may also be used to determine systemic effects caused by the repositioning of satellites.

The treatment of these problems requires a set of analytical procedures, computer programs to apply these procedures to specific configurations, and a data base to provide inputs to the programs. Such procedures, programs, and data bases have been developed at many organizations during recent years, and it did not seem appropriate for Rand to develop new ones. Hence, this report principally describes existing and planned techniques to investigate EMI in space systems. The descriptions provide an understanding of the structure and problem-solving capabilities of the analyses and programs, without any study of coding details. Much of the subject matter was initially furnished to Rand by persons from the companies or agencies where the analyses and

codes were developed. The material was then modified by the Rand authors to bring all presentations to approximately the same level of complexity. The revised versions were submitted to the originating authors for approval. Because readers may desire copies of or additional information on particular programs, individuals for contact are indicated at the end of each subsection.

The project has been structured to comply with the technical criteria, rules and regulations, and coordination procedures established by national and international frequency management agencies. The organization and functions of these agencies are reviewed. The procedures for frequency assignment and coordination among potentially interfering channel users are described in detail.

The proposed Space System Data Base will consist of electromagnetic and operational characteristics of active and projected U.S. and international space systems including related earth and airborne segments. A proposed data collection format, described in Appendix A, lists the technical characteristics of the hardware involved and operational characteristics of the system required for the data base. The data base will be maintained at ECAC.

More than 20 analysis and computation codes are described, with the presentation pitched to an engineer's or user's level. The codes are grouped into six categories. The first set, cull and coordination, describes procedures to determine the possibility of interference to ground stations caused by other ground stations or by space systems, and then to coordinate frequency allocations according to the prescriptions of the International Telecommunication Union. The second, cosite analysis, considers interference among various equipments at the same approximate geographic location. The third category of codes, intrasystem EMC analysis, deals with interference induced in equipments via direct or wire couplings, and is devoted primarily to complex circuit analysis. The fourth category, intersystem EMC analysis, involves analyses and codes for determining interference produced by far-field (from earth) and space-based sources. Most of these codes pertain to geosynchronous communications satellites, but some permit the consideration of any orbit. Included in this group is an extensive analysis, original to the Rand authors, of interference problems in

nongeostationary systems. Codes and probability considerations are described, with mathematical details in Appendix B. The fifth category, electromagnetic vulnerability analysis, considers the behavior of complex communication networks under stress caused by intentional and unintentional interference, and the final group, multipurpose, describes programs which partake of several of the previously discussed categories.

The space systems data base and the analysis techniques and computer programs are essential components for predicting and analyzing intentional and unintentional interference on space systems being monitored by the Space Defense Operations Center (SPADOC), and for assisting the Air Force in preparation for the space services World Administrative Radio Conference (WARC). The actions of Rand and ECAC to coordinate this project with SPADOC and WARC objectives are described.

It is recommended that the Space Systems Program Offices of the Air Force Product Divisions, supported by the appropriate contractors and coordinated by the Air Force OPR, provide the necessary access to data bases at ECAC, and be responsible for conducting investigations of orbital and spectral congestion problems, employing the data base and analysis techniques described in this report. In the initial implementation phase of this program, choice among particular analysis models and computer programs described herein should be the responsibility of the analyst who is investigating a specific problem. As this process develops, preferences among models should emerge. Participation could be voluntary during the implementation phase. Air Force documents on spacecraft orbital position management, frequency management, and military standard electromagnetic compatibility requirements should be revised to include references and instructions for use of this project.

The projected capabilities will provide an essential national resource for management decisionmaking and architectural planning on space-related programs.

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The persons providing the material in Section III are cited in each of the descriptions of the analysis codes and computer programs developed by the respective companies and agencies.

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PART 1

EXECUTIVE OVERVIEW

EXECUTIVE OVERVIEW

The U.S. Air Force has a leadership role in the development and operation of space systems for the Department of Defense. There has been a steady advance in the data link traffic and data processing requirements in earth-based and satellite-based communications and relay systems. There also has been a steady increase in the number of objects in orbit, including active and inactive satellites and space debris. The probability of collision of spacecraft and debris will increase as the number of space objects, sizes of spacecraft, and on-orbit lifetimes grow. These expansions of signal transmissions and orbiting objects could severely affect the frequency spectrum allocations, orbit assignments, and related earth segments of space systems. Available spectrum, and the useful orbital positions as defined by today's capabilities, may be inadequate, leading to the condition we refer to as spectral and orbital congestion. Positional changes that may be required to avoid collisions may lead to radio frequency spectrum interference with other satellites. A continuing analysis program, described in this report, is needed to provide a resource for evaluating engineering and architectural designs, predicting and analyzing the impact of intentional and unintentional electromagnetic interference (EMI), and determining probable saturation conditions in spectrum usage and satellite orbital positions for space-related programs.

The intent of this project and the treatment of these problems require a set of analytical procedures, computer programs to implement these procedures, and a data base to provide inputs to the programs. Such procedures, programs, and data bases have been developed at many organizations during recent years, and are compiled in this report. Investigations on nongeostationary orbits originated at Rand are also included. This report is principally devoted to an exposition of existing and planned techniques to investigate electromagnetic interference in space systems. The descriptions are planned to provide a comprehension of the structure and problem-solving capabilities of the analyses and programs. Much of the subject matter was initially

furnished to Rand by persons from the companies or agencies where the analyses and codes were developed. The material was then modified by the Rand authors to bring all presentations to approximately the same level of complexity. The revised versions were submitted to the originating authors for approval. This report may be viewed as a compendium, on an engineering or user's level, of the techniques for evaluating congestion problems in space systems. Since readers may desire copies of or additional information on particular programs, individuals for contact are indicated at the end of each subsection.

Because of the complexities of the spectral and orbital congestion problems, numerous organizations have developed models and programs to treat them. Often these models are of comparable scope and capability, and the prospective user should be aware of the existence of this multiplicity of programs and choose the one (perhaps several) which best suits his particular problem. Hence, we have included descriptions of all of the programs for which we have received data, and have not indicated a selection between competing models. In the initial implementation phase of this program, choice among particular analysis codes and computer programs described herein should be the responsibility of the analyst who is investigating a specific problem. As this process develops, preferences among models should emerge based on utilization.

Orbital congestion problems, involving position allocation, nuclear collateral damage, avoidance of collision with debris or other satellites, and satellite repositioning, must be solved directly if space systems are to avoid catastrophic failures. These debris and collision avoidance issues are being treated by other projects. Extensive references are presented in the Introduction to this report, but the subject is not treated further in the text.

However, satellite repositioning may lead to spectral congestion problems if signals from the repositioned satellites interfere with signals from other satellites. These orbital-inducing-spectral congestion situations should be treated by the procedures described in this report.

The space systems spectral/orbital congestion analysis process has been divided into seven functional categories:

1. Regulations and procedures for radio frequency management
2. Cull and coordination
3. Cosite analysis
4. Intrasytem electromagnetic compatibility (EMC) analysis
5. Intersystem EMC analysis
6. EM vulnerability analysis
7. Multipurpose treatments

These categories separate the general scenario into specific areas which are appropriate for description of particular tasks. In addition, an extensive Space Systems Data Base is being established at the DoD Electromagnetic Compatibility Analysis Center (ECAC) in Annapolis, Maryland, to provide support for the investigation of all of the congestion problems.

Regulations and Procedures for Radio Frequency Management

The project was directed to comply with technical criteria, rules and regulations, and coordination procedures established by the international and national radio frequency management agencies. Section II provides a review of the organization and functions of these agencies.

The principal international organization for coordination of telecommunications is the International Telecommunication Union (ITU), a special agency of the United Nations with 158 member nations at present. It has four permanent organs--the General Secretariat, the International Frequency Registration Board (IFRB), the International Radio Consultative Committee (CCIR), and the International Telephone and Telegraph Consultative Committee (CCITT). The ITU itself is governed by a Plenipotentiary Conference, which meets every five years and determines membership, general policies, financial aspects, and conclusion or revision of agreements, and by an Administrative Council which supervises the administrative functions and coordinates the activities of the permanent organs.

The General Secretariat assembles international telecommunications data, such as lists of radio stations and telegraph offices throughout the world. The IFRB effects the orderly recording of frequency assignments made by the different countries. The two Consultative Committees study technical, operating, and tariff questions relating respectively to radio communication and to telephony and telegraphy. The organs and the general ITU organization hold periodic study group meetings, plenary assemblies, and regional and world administrative conferences.

The ITU compiles and publishes the Radio Regulations, Vol. 1, which includes the International Table of Frequency Allocations. Appendices to the Radio Regulations, Resolutions, and Recommendations are included in Vol. 2.

Frequency management within the United States is under divided jurisdiction. The Federal Communications Commission regulates frequencies assigned to non-federal users, and the National Telecommunications and Information Administration (NTIA) is responsible for the assignment and use of frequencies by U.S. government agencies. Within the government, each agency decides, in the light of policies, rules, and regulations, how much radio communication is needed to carry out its mission. The agency makes the necessary technical studies, selects possible frequencies, coordinates the selection with other agencies involved, and files an application with the Executive Secretary of the Interdepartment Radio Advisory Committee. The procedures of the IRAC and associated councils for evaluation of the frequency assignment applications are described. The systems used by NASA and the Department of Defense for frequency management are considered in considerable detail.

Data Bases

Section III.A of the report describes Electromagnetic Spectrum Data Bases. The proposed Space Systems Data Base (SSDB) will contain electromagnetic and operational characteristics of currently active and projected U.S. and international space systems. Information on both the space segments and related earth segments will be included. The SSDB

will be structured to provide an automated file for quick access, culling, and printouts, and expanded information as available in documents, reports, and measured data. The file will include time-related information on deployed systems, currently active or in standby orbits; approved-for-launch systems with scheduled dates; firm and funded development programs; and future development plans with predicted schedules. The proposed data collection format includes items published by Rand, contributions from other agencies, and recent substantial expansions by ECAC. It provides inputs for preliminary interference analyses and indications of the operational usage of systems. Technical characteristics of the hardware involved and operational characteristics of the system required for the data base are listed in Appendix A. The extensive detail indicated in the proposed format is required to cover the numerous inputs derived from the analyses and included in the computer programs. The data base is being developed and maintained at ECAC. ECAC at present maintains many data bases required for DoD electromagnetic compatibility studies. Section III.A.2 describes these data files.

Analysis Codes and Computer Programs

Section III.B, the longest portion of the report, describes some of the analytical procedures and computer programs that have been developed to treat electromagnetic interference. More than 20 codes are discussed. The subsections follow a common format, as listed below, although there are many differences in detail.

Program Source and Purpose

- Who developed it for whom

- When it was developed or became available

- Program users

Code Description and Capabilities

- Analytical material

- Required inputs

- Detailed code structure

- Typical outputs

Special features and limitations

Orbits

Frequency limitations

Antenna patterns included

Propagation models

Special algorithms

Program Software

Language

Computer type

Size of program

Support software required

Computer storage and memory

Execution time for particular runs

Problem size limitations

Documentation

Individuals to Contact for Additional Information

The descriptions of the analyses and programs, as given in the main text of this report, are the result of a massive reduction process from many volumes of original submissions. In this summary, we shall only present for each program its originator, purpose, and a one-paragraph description. We hope that this will provide enough information for the reader to select which programs will be of principal interest.

Cull and Coordination

Cull models are procedures for excluding clearly non-interfering cases from extensive investigations of interference. Coordination models pertain to the coordination of frequency assignments among potentially interfering systems. Since culling of non-interfering cases is employed in every treatment of interference problems, we shall not consider cull models separately, but shall only describe coordination models in Section III.B.2.

Cull and coordination contains three programs. The first program, described in Section B.2.a, was developed at ECAC/IIT Research Institute; the program gives the procedures used to automate the calculations of coordination contours required by ITU Radio Regulations

Appendix 28. This Appendix applies to coordination of frequency assignments to a satellite system earth station in relation to terrestrial stations, or vice versa. The coordination area to be calculated is that area around a transmitting station within which innocent receivers may be affected, or that area around a receiving station within which transmitters are potential interferers. Propagation between stations may be line of sight or via rain scatter. The automated program calculates the coordination area from a data base that contains terrain and transmitter locations, so the user can operate interactively, with only seven basic data items required to generate coordination contours.

The second coordination program, Section B.2.b, was developed at NTIA; it concerns automated calculation of coordination procedures required for ITU Radio Regulations Appendix 29, which pertains to satellite systems. The Appendix provides procedures for calculation of apparent increase in receiver noise temperature due to interference from other satellite systems. The regulations state that coordination of frequency assignments is necessary if the fractional change in receiver noise temperature exceeds 4 percent. The interactive computer program provides automatic calculation of all the variables in Appendix 29 and all possible interactions of the networks being investigated.

The third coordination program, Section B.2.c, developed at ECAC/IIT Research Institute, automates calculation procedures for coordination contours for ground mobile satellite terminals. The program establishes the electromagnetic environment, then analyzes the potential EM interactions for an earth terminal at a grid of locations within the operating area, using the calculation techniques of Section B.2.a. The outputs are clear areas, within which a mobile earth terminal with specified parameters can operate compatibly with surrounding equipments, and protection areas, within which a mobile transmitter (receiver) produces (experiences) interference.

Cosite Analysis

Cosite analysis, Section III.B.3, contains only the investigations on the subject performed at ECAC. Cosite analysis is primarily concerned with interactions that are associated with system proximity, and includes a variety of nonlinear effects which produce interference between systems located in the same small geographic area. A number of automated models calculate the linear and nonlinear couplings and interference between equipments.

Intrasystem EMC Analysis

Intrasystem EMC analysis, Section III.B.4, covers four programs operated at the Rome Air Development Center and one developed by TRW. These are basically circuit analysis codes, and are concerned with compatibility within a system consisting of electrically interconnected equipments and/or equipments in proximity, such as those within a single aircraft, spacecraft, or ground station. The first program, Intrasystem Electromagnetic Compatibility Analysis Program (IEMCAP), Section B.4.a, is a systems-level computerized analysis program which acts as a link between equipment and subsystem EMC performance and total system EMC functionality. It involves detailed modeling of the system elements and mechanisms of electromagnetic transfer to provide a suitable data base, generate EMC specification limits, survey for incompatibilities, evaluate the impact of waivers and design changes, and provide comparative analysis results upon which to base EMC tradeoff decisions. Emitters and receptors are identified, possible connecting paths determined, and the potential interference levels determined as functions of frequency, leading to threshold margin statements. All calculations are fully automated.

The second intrasystem program, General Electromagnetic Model for the Analysis of Complex Systems (GEMACS), Section B.4.b, is designed to calculate interactions among wire bundles. It employs the Method of Moments technique to calculate currents for an arbitrary geometry of interconnected elements excited by driving voltages or external fields. The self and mutual impedances of the network are found in terms of the geometrical inputs, and the wire coupling parameters, near and far

electric field patterns, and the coupling between pairs of antennas are obtained.

The third intrasystem program, Nonlinear Circuit Analysis Program (NCAP), Section B.4.c, follows IEMCAP. After a more coarse analysis has indicated a potential EMC program at the circuit level, NCAP could be used to calculate the nonlinear transfer functions of the network, which is made up of interconnections of a standard set of circuit elements. The nonlinear network is solved by a power series expansion, and the outputs are found for each harmonic of the input signal frequency. The automated calculations involve the network topology, devices employed, and circuit excitations.

The fourth intrasystem program, Wire Coupling Prediction Models, Section B.4.d, performs detailed calculation of wire-coupled interference. The seven programs included in the modeling predict the coupling between wires and their associated termination networks in closely coupled, high density cable bundles and in flatpack (ribbon) cables in modern electronic systems. The effects of shielding and twisting are included. The models are based on a complete and unified consideration of Multiconductor Transmission Line theory as it applies to the prediction of wire-coupled losses. The programs calculate wire mutual impedances and currents excited by external electromagnetic fields. Each automated program is efficient for the specific problem being investigated.

The remaining intrasystem EMC analysis program, Specification and Electromagnetic Compatibility Analysis Program (SEMCAP), Section B.4.e, was developed by TRW and is very similar to the program IEMCAP described in Section B.4.a. It takes a set of wire or antenna connected generators and receptors, calculates the various mutual couplings, and creates generation and susceptibility specifications for controlling electromagnetic interference, plus analyses to waive the specifications. Outputs display the compatibility conditions within the network and indicate what modifications may be required.

Intersystem EMC Analysis

Intersystem EMC analysis, Section III.B.5, covers several programs relating directly to space systems. Interference problems involving links connecting satellite and ground terminals are treated by these programs. An analytical introduction, Section B.5.a, provides the theoretical material upon which the programs are based. The receiver output from an interfering transmitter is determined analytically in terms of the geometrical configuration, the type of signal being transmitted, and the transmitter and receiver antenna patterns, including polarization effects, atmospheric attenuation, and the responsivity of the receiver as a function of frequency and signal parameters. The interference sources act independently, so the output powers are added to form the interference-to-signal ratio, which then is compared to a threshold sensitivity to determine the system performance. Section B.5.a is the only section in the body of this report which contains any mathematics.

The next three sections, B.5.b, c, and d, describe computer programs which apply the analytical framework of B.5.a to geosynchronous communications satellites. The program of Section B.5.b was originally developed by Rand and has been improved by the FCC and NTIA. It was designed to treat interference among broadcasting satellites, but can be applied to any link involving earth stations and geosynchronous satellites. The code calculates potential interference among signals carrying multichannel telephony, telegraphy, or television for a large number of links (typically 100 to 150). It is fairly simple to use.

Section B.5.c, Adjacent Satellite Interference Model, was developed by the FCC to assess the impact on U.S. domestic satellites of reducing the orbit spacings between satellites. It is based on the analytical framework of Section B.5.a, but deals specifically with the interference and signal margins among the many signal channels on a specified pair of satellites in terms of their orbital spacing.

The program of Section B.5.d, Spectrum Orbit Utilization Program (SOUP), was developed by GE and ORI, Inc. It exists in two versions, SOUP3 and SOUP5, which employ the same analytical framework. They compute the mutual interference between a large number (hundreds) of

communications links, operating at the same or overlapping frequencies, between earth stations at specified locations through satellites in specified orbit positions. SOUP3, designed for both fixed and broadcasting services, computes carrier/interference ratios, total interference power for FDM/FM signals, and error rates for digital signals. SOUP5, developed exclusively for broadcasting service, computes carrier/interference ratios and margins only. Each program provides very extensive output data, available both in summary form and in a detailed systems engineering format.

The next program, Section B.5.e, Co-Channel Interference Analysis for Generalized Satellite Orbits, has been developed by the MITRE Corporation. It calculates downlink interference from many satellites into a single ground station, which may be stationary or mobile. This program has been designed to provide general orbit capability. The satellite orbits implemented are arbitrary ellipses, instead of the geosynchronous configurations of the three preceding programs. This program produces graphical outputs which are very well suited to show interference effects on airborne receivers.

The next section, B.5.f, Interference Problems for Nongeostationary Satellites, original to this Rand project, describes signal interference phenomena associated with satellites other than geosynchronous communications satellites. The signals usually pertain to telemetry and commands. These problems are strongly time-dependent, since nongeostationary satellites will only interfere when they are located in a common antenna beam. The problems may be treated by computer programs, which determine specific occurrences of interference, or by probability considerations, which give the expected total interference, the mean and maximum duration, and how often interference occurs. The computer programs are described in very general terms. The probability theory is outlined and the results applied to several typical cases. Interference among nongeostationary satellites may be expected to worsen as the number of satellites increases. The mathematical details associated with this analysis are presented in Appendix B.

The next two subsections deal with computer programs for geostationary and nongeostationary satellites. Section B.5.g, Air Force Satellite Control Program--Milestone 4, describes the computer program

employed by the Air Force Satellite Control Facility to determine possible radio frequency interference involving satellites under the control of the U.S. Air Force. The program uses an ephemeris generator to determine the positions of the satellites versus time, a time sieve to find whether satellites are simultaneously visible to a ground station, and a frequency sieve to establish whether possible interferers have frequencies in common. Antenna cone angles are then calculated to determine the actual times of interference, if any. Milestone 4 is used for day-by-day scheduling of command and telemetry transmissions of Air Force satellites.

Section B.5.h, Deep Space RFI Prediction Program (DSIP2), describes the program employed by the Jet Propulsion Laboratory to determine possible radio frequency interference with the Deep Space Tracking Net (DSTN). Because of the great distances over which interplanetary signals must be transmitted, the DSTN employs very large antennas and extremely sensitive receivers, and the operations may be subject to impairment when the source of interference is in the sidelobes of the antenna. The program operates with an ephemeris generator and antenna cone angle calculator, and determines the level of interference, ranging from bit errors to receiver droplock, and the occasion and duration of interference, which may be from seconds to hours. With reliable predictions of RFI events available, it is possible to change spacecraft operations plans to avoid the RFI or even to request of those operating the interfering satellite that its transmitter be turned off for certain intervals.

The last subsection under the category of intersystem EMC analysis, Section B.5.j, describes three programs developed by Computer Sciences Corporation. The first, Flexible Satellite Communications System Simulator, simulates multiple satellite communications signals and their RF environments. These simulations are then used for interactive studies of system performance and basic system design. The second program, ECCM Network Evaluation Program (ENEP), provides an interactive model to evaluate ECCM networks under varying degrees of uplink jamming. This program can automatically adapt link EIRP and data rates to meet prescribed operational capabilities. The third program, Satellite Coverage Program, calculates the areas and times of coverage of a

satellite antenna considering motion of the earth and of the satellite, which may be in an arbitrary orbit. Extensive statistical outputs are provided, which may be used for link scheduling.

Electromagnetic Vulnerability Analysis

The next category of programs deals with electromagnetic vulnerability analysis. This subject pertains to the stressing of networks rather than individual equipments. The first program, MILSATCOM Vulnerability Analysis Model (MVAM), Section III.B.6.a, developed by Bell-Textron, is an event-driven traffic model designed to simulate military satellite communication system characteristics. The program is capable of analyzing traffic events such as transmission attempts and processes when completion fails, queueing and preemption of traffic, intentional and unintentional interference, effects of storms and nuclear blasts, and other phenomena which may influence the traffic-handling properties of the network. Outputs involve detailed and statistical presentations of system performance. Also included in this subsection, since the work is being performed under the same auspices, is a brief description of a program now under development which will analyze the vulnerability of laser communications systems.

Section B.6.b, Simstar/Dynamic Multi-Message Simulator, describes a program which was developed by the U.S. Air Force to investigate the behavior of the Minimum Essential Emergency Communications Network (MEECN). The program is designed to analyze the capability and reliability of the network to transmit the required message traffic under a variety of stressing conditions, thereby determining message probabilities and traffic statistics which establish the endurability of present and future command, control, and communications systems. Monte Carlo studies and preservation of link performance calculations permit the investigation of very large scale networks.

Section B.6.c, Propagation Network Analysis Code (PNAC), a program developed by Computer Sciences Corporation, assesses the performance of satellite communications systems in critical strategic C3 and warning networks under threats produced by electronic countermeasures and by disturbances in the radio-frequency propagation medium caused by high-altitude nuclear detonations. The code simulates the propagation of

multiple messages under such scenarios, calculates the link and network error rates, and expresses the results as a probability of acceptable message. Results are both specific and statistical.

Multipurpose Treatments

The final category of programs are multipurpose, combining several of the previous categories. The first of these, Electromagnetic Compatibility Frequency Analysis (EMCFA), Section III.B.7.a, developed by Martin Marietta Aerospace, can determine interference of intra-, cosite-, and inter-system types. The program calculates direct and intermodulation interferences to system receivers from transmitters in the environment, taking nonlinear interactions into account, and determines corrective actions to minimize or eliminate these interferences. The very large number of harmonics associated with the nonlinear mixing terms can lead to literally millions of potential interferences produced by 10 to 20 sources. Outputs are both tabular and graphical, and show which interference sources are significant.

The last subsection of Section III.B, B.7.b, describes the analysis capabilities at ECAC. Since ECAC was established for the purpose of analyzing the EMC aspects of developing communications-electronics systems, it has developed many procedures for investigating interference problems. Analytical tools and computer programs have been devised or secured from other organizations to treat subsystem models (antennas, receivers, and transmitters), propagation models, degradation analysis, environmental synthesis, cosite analysis, and satellite systems. For the situations where no computer models have been developed, an engineering staff is available to apply manual procedures.

Analysis for SPADOC and WARC

The space environment data base and the analysis codes and computer programs were considered essential components for predicting and analyzing intentional and unintentional interference on space systems being monitored by the Space Defense Operations Center (SPADOC), and to assist the Air Force in preparation for Space Services World Administrative Radio Conferences (WARC). Section IV describes the problems involved and the actions of Rand and ECAC to coordinate this project with the SPADOC and WARC objectives.

Conclusions

Increased space traffic and debris, spectral demands, and requirements for orbital slots and position control indicate possible problems of orbital and spectral congestion in space systems at present and in the foreseeable future. The very large geographic areas visible to satellites imply potential electromagnetic signal interference conditions which require analysis and control. We have drawn the following conclusions from the studies of this report:

1. The extensive data base on space and earth electromagnetic environments being established and maintained at ECAC, Annapolis, Maryland, and the computer-based analysis programs documented in this report, provide the required capability for analysis of spectral and orbital congestion problems.
2. The process provides the ability to analyze potential electromagnetic interference produced by orbital repositioning of satellites to avoid collisions with debris or other satellites.
3. The procedures have been structured to comply with the technical criteria, rules and regulations, and coordination requirements established by the national and international frequency management agencies.
4. Project capabilities will provide an essential national resource for management decisionmaking and architectural planning on space-related programs.

Recommendations

In the transition of this project to Air Force management and implementation, we recommend that:

1. An Air Force organization should be established as OPR to manage and maintain a continuing program for analysis of orbital and spectral congestion problems, providing access to and employing the data base and analysis techniques described in this report.

2. The Space Systems Program Offices of the Air Force Product Divisions, supported by the appropriate contractors, should be responsible for the indicated analysis for specific space systems. In the initial implementation phase, choice among particular analysis models and computer programs should be the responsibility of the analyst who is investigating a particular problem. As this process develops, preferences among models should emerge. Participation could be voluntary during the implementation phase.
3. The following Air Force documents should be revised to include references and instructions for the use of this project:
 - Air Force Space Division Regulation (SDR) 55-1, Satellite Position Management, 15 September 1983 (OPR: SD/YO)
 - Air Force Regulation (AFR) 55-XY, Spacecraft Orbital Position Management (Draft) (OPR: AF/XOSO)
 - AFR 100-31, Frequency Management and Electromagnetic Compatibility (OPR: AF/SITI)
 - MIL-STD-1541 (USAF), Military Standard Electromagnetic Compatibility Requirements for Space Systems (OPR: SD/ALTI)
 - AFR 80-23 and SD Supplement, Research and Development, the U.S. Air Force Electromagnetic Compatibility Program (OPR: AF/RDPT)
4. The project capabilities should support identification and analysis of intentional and unintentional electromagnetic interference for the Space Defense Operations Center (SPADOC).
5. The data base and analysis capabilities should be used in preparation of Air Force requirements for the geostationary Space Services World Administrative Radio Conference (WARC), 1985.

Furthermore, we recommend that the analytical capabilities documented in this report be employed for management decisionmaking and architectural planning by all national space-related agencies.

PART 2

DISCUSSION

I. INTRODUCTION

The United States Air Force has a leadership role in the development and operation of space systems for the Department of Defense. Planning for future space-related programs must account for anticipated growth in the number of space systems, which will include ground networks, large multifunction satellites, increased data transmission rates, and effects on future requirements for spectrum allocations and orbital positions. A continuing analysis program, such as that described in this report, is needed to evaluate engineering and architectural designs, and predict and analyze the impact of intentional and unintentional electromagnetic (EM) interference and probable saturation in spectrum usage and satellite/orbital positions for space-related programs.

A. THE SPECTRAL AND ORBITAL CONGESTION PROBLEM

General

Projected advances in the use of space by the military and other organizations for communications, navigation, surveillance, space transportation systems, and other missions, coupled with increased launch rates by U.S. military, intelligence, and commercial interests and by international agencies, will add substantially to the data link traffic and data processing requirements in earth-to-satellite, satellite-to-satellite, and satellite-to-earth communications and relay systems. Data transmission requirements could expand by several orders of magnitude as new and larger spacecraft are developed equipped with spread-spectrum and wide-band spectrum transmission and receiving systems.[1-3]¹ Such expansion could severely affect frequency spectrum allocations, orbit assignments, and related earth segments of space systems. Available spectrum and the useful orbital positions as defined by today's capabilities may be inadequate, affecting the operational

¹References appear at the end of each section, with reference numbers beginning with 1 in each, rather than the usual system of placing all references at the end of the report and numbering consecutively.

advantage of the increased sensing capabilities now being sought in spacecraft. The increased demand in time of crisis could result in disruption of critical data transmission. It is essential to the security of the United States to have telecommunication facilities adequate to satisfy the needs of the nation during and after any national emergency.²

The future growth in both commercial and military space systems could be constrained by technical problems associated with the availability of the frequency spectrum, orbital congestion, and anticipated proliferation of stationary and mobile earth terminals. The seriousness of these constraints is shown in an assessment of the useful areas and coverage of the geostationary circle; commercial communications satellites at the 4-6 GHz bands essentially fill these areas at current assignments and are expected to reach saturation at 12-14 GHz bands in the future. The military frequency bands, used in space systems, are also approaching saturation because large portions of them are shared with terrestrial links.

The Federal Communications Commission (FCC) has acknowledged this problem and additional steps must be taken to meet the continued demand of commercial systems for satellite capacity and to provide for new entry. The FCC has issued a "Notice of Inquiry and Proposed Rulemaking"[4] on the "Licensing of Space Stations in the Domestic Fixed-Satellite Service...." A reduction was proposed in the geostationary orbital space from 4 degrees to 2 degrees between satellites operating in the 4-6 GHz bands, and in spacing from 3 degrees to 2 degrees between satellites operating in the 12-14 GHz bands. A

²The Office of the Manager of the National Communications System (NCS) responded to the White House memorandum of 15 November 1979 (Presidential Directive PD-53) on National Security Telecommunications, listing the capabilities that the nation's telecommunications must provide to support national security policy. To develop recommendations to the President on national security and emergency preparedness and to implement PD-53 and E012382, 13 September 1982, a National Security Telecommunications Advisory Committee (NSTAC) has been organized. The manager of NCS serves as the chairman of NSTAC; members are presidents and chief executive officers of the communication carriers, selected manufacturers, and computer services. Principal areas of study are industry-wide response to national telecommunications needs, joint network planning, commercial telecommunications system survival, automated information processing, and security and survival.

3-dB improvement in earth station antenna sidelobe gain standards and a 10-dB cross-polarization isolation standard for small off-axis angles are also proposed. These changes should provide spacing for 37 additional U.S. satellites in the orbital arc from 55 to 143 degrees west longitude in the combined frequency bands. Station keeping of $\pm .1$ deg for commercial satellites at geostationary orbit assignments is practiced by U.S. systems and is based on requirements of fixed earth station antennas.

The FCC has recently (April 27, 1983) adopted the proposed reduced satellite orbital spacing criteria for 4-6 and 12-14 GHz bands.[5]

Since the launch of Sputnik I in October 1957 with its simple telemetry transmissions, there has been a large growth in deployment of spaceborne elements. These elements include satellites with active and inactive payloads, and burned-out rocket motors and other debris associated with the launch or breakup of payloads or rockets.

At the end of calendar year 1982 13,752 objects in space had been catalogued by NORAD, and 8,973 objects had decayed.[6] NORAD is currently maintaining tracks on 4,779 objects of which approximately 1,228 are satellites with active and inactive payloads (payloads in orbit: USSR 690, U.S. 431, others 107). The population on geostationary orbit includes 160 satellites with payloads plus 60 large objects. Table 1 lists the USSR, U.S. and other international satellite launches and decay for the years 1975 to 1983.

Table 1
LAUNCH (L) AND DECAY (D) RATES FOR SATELLITES WITH PAYLOADS

	1975		1976		1977		1978		1979		1980		1981		1982	
	L	D	L	D	L	D	L	D	L	D	L	D	L	D	L	D
USSR	89	41	105	47	95	48	79	61	88	57	88	75	123	57	101	47
U.S.	30	6	27	6	23	3	30	4	17	5	13	4	17	18	18	5
Other nations	18	4	13	3	8	1	6	2	6	4	4	7	17	5	2	1

Satellites with active and inactive payloads, and proliferation of earth-orbiting manmade debris[7-11] resulting from burned-out or exploded rocket motors and breakup of rocket bodies and payloads, make up the orbital congestion problem. This orbital congestion suggests there is a potential for signal interference and an injurious environment for future spacecraft. As the number of satellites in orbit increases, the probability of collisions between satellites increases. Many of these satellites are in orbits that cross one another, producing a finite probability of collisions, which in turn would produce orbiting fragments which would again increase the probability of further collision.[7] This proliferation may become sufficiently dense that the international and national space community may need to develop capabilities to analyze, predict, and control probable collisions in future space operations.

The objectives of this project are to design and develop capabilities to predict and analyze potential signal interference and saturation conditions in spectrum usage and orbital positions for satellites with active, standby, and future payloads. Changes in satellite orbital positions to avoid potential collisions can affect the signal transmission and reception (up and down links/relays), coordination of interference protection, and control of adjacent satellites. Potential interference effects should be analyzed before changes are made in international and national coordinated satellite orbital positions (see Sec. II).

A program for assessment of space debris and probable collision hazards is being sponsored in a 10-year program plan by the Space Environment Office, Program Planning Office, NASA/Johnson Space Center.

Spacecraft Orbital Position Management Regulation

The U.S. Air Force is preparing a regulation that describes procedures for management of spacecraft orbital positions.[12] It contains procedures for resolving conflicts among Air Force/DoD organizations responsible for developing, launching, and providing on-orbit support for spacecraft. The Aerospace Defense Center will be the single point of contact for DoD orbital data products.

Maintaining acceptable distance between satellites is necessary to reduce the probability of mutual radio frequency (RF) interference, collateral damage in the event of a nuclear attack on another satellite, and physical damage resulting from collision with another satellite (active or inactive debris). The Air Force regulation on spacecraft position management discusses each of these. Concentration of satellites in a particular orbital region is an immediate concern at geostationary altitudes where many space systems favor the same regions of space for maximizing mission performance and earth segment access. Conflicts among satellites at lower orbit, either in final or transfer orbit, are more complex. These conflicts must be considered when planning final orbit locations or satellite maneuvers.

Radio Frequency Interference. The International Telecommunication Union (ITU) approves international registration of projected on-orbit frequency assignments in accordance with established procedures. These procedures provide international protection for registered frequency channels. National and DoD regulations and procedures for space system radio frequency management are discussed in Sec. II. The radio frequency interference analysis capabilities which can be applied to this regulation are discussed in Sec. III.

Nuclear Collateral Damage. Dependence of the United States on space systems introduces the potential of enemy attack on space assets. Space systems planning, deployment, and operations must consider potential satellite attack. The Space Defense Operations Center (SPADOC) at North American Air Defense Command/ADCOM/SPACECOM, Cheyenne Mountain Complex, is responsible for warning of attacks and coordinating spacecraft defenses. Nuclear collateral damage to spacecraft may result from an attack on another spacecraft. The Joint Chiefs of Staff (JCS) validate nuclear hardening requirements for systems used by the unified and specified commands and publish guidelines for hardening military satellites against the effects of nuclear weapons.

Physical Damage from Collision. The potential for collision increases as more objects are placed in orbit. Some orbits, such as geostationary, sun-synchronous, polar, and equatorial, offer particular operational advantages, and lead to concentration of satellites in these

orbital planes. At geostationary altitude active satellites maintain fixed longitudinal positions; inactive satellites and debris generally drift from or oscillate about stable positions. The advent of frequent launches of the Space Transportation System (Shuttle) means that hazards will increase at lower altitudes. The probability of collision of spacecraft and debris will increase as the number of space objects, sizes of spacecraft, and on-orbit lifetimes grow. Future planning must ensure that the probability of collision is addressed and controlled. If changes are required for satellites operating in orbit to avoid collision, prediction and analysis of RF spectrum interference with other satellites with active payloads should become an essential process and be stipulated in the Air Force Spacecraft Orbital Position Management Regulation.

Orbital congestion problems, involving position allocation, nuclear collateral damage, avoidance of collision with debris or other satellites, and satellite repositioning, must be solved directly if space systems are to avoid catastrophic failures. These debris and collision avoidance issues are being treated by other projects, and there is an extensive literature.[6-11] These matters are not treated further in the text.

However, satellite repositioning may lead to spectral congestion problems if signals from the repositioned satellites can interfere with signals from other satellites. These orbital-congestion-inducing spectral-congestion situations should be treated by the procedures described in this report.

B. PROJECT OBJECTIVES

The objective of this project is to design and develop a continuing analysis program for space-related systems.[2] Specific objectives include:

1. Predicting and analyzing spectrum/orbital position requirements and current and projected U.S. and international space-related programs.

2. Evaluating engineering and architectural designs.
3. Identifying and analyzing intentional/unintentional electromagnetic interference.
4. Predicting and analyzing saturation in spectrum/orbital positions.
5. Supporting preparations for Air Force/U.S. requirements for space services for the World Administrative Radio Conferences (WARC) scheduled for 1985 and 1988.

C. USER'S GUIDE TO REPORT

The analysis process required to meet the project objectives has been developed and divided into seven functional categories:

1. Regulations and procedures for radio frequency management
2. Cull and coordination
3. Cosite analysis
4. Intrasytem electromagnetic compatibility (EMC) analysis
5. Intersystem EMC analysis
6. EM vulnerability analysis
7. Multipurpose treatments

These categories separate the general scenario into specific areas which are appropriate for investigation of particular problems. The analysis of a complete system may be quite complex and several of the above categories may be involved. Some of the calculations may be conducted in parallel, and system or equipment design changes may force repetition of parts of the signal interference study. We shall briefly describe the types of problems that would be included in each of the categories, and indicate which are the appropriate sections of the report.

One of the first problems confronted by a systems designer is the choice of an operating frequency. This is governed by a set of frequency management requirements. Section II reviews the technical criteria, rules and regulations, and coordination procedures established by the national and international radio frequency management agencies for space systems. The structures, functions, and interrelations of the

several agencies are described. International regulations which determine the coordination of frequency allocations among neighboring countries are referenced in Section II. The jurisdictions and operations of the U.S. government agencies are discussed.

The computer programs that are used to treat the various problems require an extensive data base. Section III.A describes the electromagnetic spectrum data bases that will be used to store data on present or future equipment that may be involved in electromagnetic compatibility or interference studies. The proposed Space Systems Data Base will be developed and maintained at the Electromagnetic Compatibility Analysis Center (ECAC) in Annapolis. Appendix A presents the proposed form (somewhat simplified) which will be used to collect these data.

Section III.B describes more than 20 computer programs and associated analytical procedures which have been developed to investigate the listed categories of problems. The presentation is on an engineer's or user's level. The structure and problem-solving capabilities of the programs are described.

Cull and coordination programs deal with coordination of frequency assignments where signal paths may overlap international boundaries. The ITU regulations require calculation of the areas within which interference is possible, and the programs have been developed to automate these calculations. The coordination may be between earth stations associated with satellite systems and stations involving terrestrial services (Sec. III.B.2.a), or between earth stations associated with different satellite systems (Sec. B.2.b), and there is a special set of coordination calculations involving ground mobile satellite terminals (Sec. B.2.c).

Cosite analysis (Sec. B.3) is concerned with interference between independent systems located in the same small geographic area. A number of automated models calculate the linear and nonlinear couplings.

Intrasystem electromagnetic compatibility analysis treats compatibility within a system consisting of electrically interconnected equipments and/or equipments in proximity, such as those within a single aircraft, spacecraft, or ground station. General programs calculating interference in wire-coupled or antenna-coupled systems are presented in

B.4.a and B.4.e. Supporting programs determine interactions among wire bundles (B.4.b), nonlinear circuit transfer functions (B.4.c), and multiconductor transmission line interference (B.4.d).

Intersystem EMC analysis involves compatibility between systems that operate remotely and are coupled by antennas. The links to be treated are between satellites and ground terminals. The interference may be uplink, when the transmission from a ground station is received at a satellite other than that associated with that ground station, or downlink, when a satellite transmits to stations other than the designated receiver. The satellites may be divided into two classes, geosynchronous and nongeosynchronous. The theoretical material for analysis involving geosynchronous satellites is presented in Sec. B.5.a, and computer programs implementing this theory are described in Secs. B.5.b-e. Interference among nongeostationary satellites is analyzed in Sec. B.5.f, a treatment original to the Rand authors, and computer programs to evaluate such interference are in B.5.g and h. A computer program which covers both orbit classes appears in B.5.j.

Electromagnetic vulnerability analysis pertains to the stressing of networks rather than individual equipments. The stress may be jamming, physical attack, or failure due to natural causes. Computer programs calculate message statistics such as failure of completion, queueing and preemption, and link and network error rates. Particular applications include military satellite communications networks (B.6.a and B.6.b), and command, control, and warning networks (B.6.c).

The final set of programs (Sec. B.7.a and b) are *multipurpose*, and can calculate interference of intra-, cosite-, and inter-system types.

The separation into functional categories is basically geographic. Interference may be between parts of the same equipment complex (intrasystem), equipments at the same location (cosite), equipments at different sites (cull and coordination), via satellite links (intersystem), on complete networks (vulnerability), or several of these (multipurpose). This brief description should indicate to the user where he should look in the main text for more extensive detail on his particular problem.

The subject matter of Sec. III was initially provided by persons from the companies or agencies where the analyses and codes were developed. The material was then modified by the Rand authors to bring all the material to approximately the same level of complexity. The originating authors approved the revised versions. For additional information on particular programs, individuals to be contacted are indicated at the end of each subsection.

We have not indicated a selection between competing models. In the initial implementation phase of this program, choice among particular analysis models and computer programs should be the responsibility of the analyst who is investigating a specific problem. As this process develops, preferences among models should emerge as indicated by utilization.

Section IV describes related analyses for SPADOC and WARC, and Sec. V contains conclusions and recommendations.

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12. Air Force Regulation 55/XY, "Operations, Spacecraft Orbital Position Management," Headquarters USAF, in preparation.

II. REGULATIONS AND PROCEDURES FOR RADIO FREQUENCY MANAGEMENT RELATED TO SPACE SYSTEMS

The objective of the overall project is to design and develop a continuing program for analyzing the current and future requirements for the radio frequency spectrum, orbital positions, and earth stations, for evaluating engineering and architectural designs, and for predicting and analyzing the impact of intentional and unintentional electromagnetic interference of space systems. The project was directed to comply with technical criteria, rules and regulations, and coordination procedures established by international and national radio frequency management agencies. A brief review of these agencies and their functions should provide useful information to the aerospace industries which develop space systems and provide much of the technical data involved in the RF spectrum management process.¹

Technical and administrative coordination is essential in space communications.[1-4] Transmissions from spacecraft can cover wide geographical areas depending on altitude and orbital periods. A satellite in low earth orbit passes regularly over many international boundaries. A satellite placed in geostationary orbit (approximate altitude of 35,000 km) can transmit signals to 40 percent of the earth's surface 24 hours a day. In these areas or coverage zones the frequencies used by the space services must be allocated through technical analysis and coordination to avoid interference with other space and terrestrial services. The agencies that were established to provide this service and to manage the terrestrial use of the RF spectrum now include space systems. The regulations and procedures for space-related systems are discussed below.

¹The technical data requirements are documented in DD Form 1494, "Application for Frequency Allocation," and the USAF Standard Action Frequency Format (SAFF), "Application for Frequency Assignment" (copies of these forms can be obtained from the Frequency Management Offices of the USAF Product Divisions), and FCC Form 130 series B, C, D, E, the revised space radio communication, earth and space stations, notification forms (copies of the FCC forms are available from the Federal Communications Commission, Office of Science and Technology, Spectrum Management Division, Treaty Branch, Washington, D.C. 20554).

A. INTERNATIONAL FREQUENCY MANAGEMENT: INTERNATIONAL TELECOMMUNICATION UNION (ITU)

A.1 ORGANIZATION AND FUNCTIONS

The International Telecommunication Union is a specialized agency of the United Nations, with its own voluntary budget, specializing in coordination of telecommunications. The ITU is an organization, a union, of member countries. At present there are 158 member nations. Each nation, irrespective of size, population, or economic posture, carries a single vote in coordination or conference proceedings. The ITU headquarters is located at Place des Nations, CH-1211, Geneva 20, Switzerland.

Purpose

The purpose of the ITU is to facilitate improved efficiency and understanding in the worldwide use of telecommunications. It exists to: (a) maintain and extend international cooperation for the improvement and rational use of telecommunications of all kinds; (b) promote the development of technical facilities and their most efficient operation with a view to improving the efficiency of telecommunication services, increasing their usefulness and making them, so far as possible, generally available to the public; (c) harmonize the actions of nations in the attainment of those common ends.

In particular, the Union: allocates the radio frequency spectrum and registers radio frequency assignments in order to avoid harmful interference between radio stations of different countries; coordinates efforts to eliminate harmful interference between radio stations of different countries and to improve the use made of the radio spectrum; fosters collaboration among its members to establish rates at levels as low as possible consistent with efficient service and taking into account the necessity for maintaining independent financial administration of telecommunication on a sound basis; fosters the creation, development, and improvement of telecommunication equipment and networks in new or developing countries by every means at its disposal, especially in participation in appropriate programs of the United Nations; promotes the adoption of measures for ensuring the

safety of life through the cooperation of telecommunication services; and undertakes studies, makes regulations, adopts resolutions, formulates recommendations and opinions, and collects and publishes information concerning telecommunication matters for the benefit of all members.

The ITU compiles and publishes *Radio Regulations*, Vol. I, which includes the international Table of Frequency Allocations, and Vol. II, *Appendices to the Radio Regulations, Resolutions, and Recommendations*. [5]

Structure of the Union

The structure and organization of the ITU consists of:

- a. The Plenipotentiary Conference--the supreme organ of the Union;
- b. Administrative Conferences;
- c. The Administrative Council;
- d. Permanent organs of the Union:
 - the General Secretariat;
 - the International Frequency Registration Board (IFRB);
 - the International Radio Consultative Committee (CCIR);
 - the International Telegraph and Telephone Consultative Committee (CCITT).

a. Plenipotentiary Conference. The Plenipotentiary Conference, which nominally meets every five years, is composed of delegations representing members. Such conferences determine the general policies of the Union, review reports of the Administrative Council, establish the basis for the budget of the Union, supervise the financial aspects of the Union, elect the members of the Union which are to serve on the Administrative Council, as well as all the elected officials, the members of the IFRB and Directors of the CCIs, and revise the ITU Convention as considered necessary. Additionally, the Plenipotentiary Conference concludes or revises, as necessary, agreements between the Union and other international organizations.

b. Administrative Conferences. There are two kinds of administrative conferences held by the members of the Union: world administrative conferences and regional administrative conferences.² The agenda of a world administrative conference may include the partial revision of the Administrative Regulations (Telegraph Regulations, Telephone Regulations, Radio Regulations), the documents which govern the international operation of the three modes of communication, exceptionally, the complete revision of one or more of these regulations, and any other question of a worldwide character within the competence of the conference.

The agenda of a regional administrative conference may provide only for specific telecommunication questions of a regional nature, including instructions to the International Frequency Registration Board on its activities in the region concerned, provided such instructions do not conflict with the interests of other regions. Furthermore, the decisions of such a conference must conform with the provisions of the Administrative Regulations.

c. Administrative Council. The Administrative Council is composed of 41 members of the Union elected by the Plenipotentiary Conference. It normally meets for about a month once a year at Union headquarters in Geneva and at these formal sessions acts for the Plenipotentiary Conference between the latter's meetings. It supervises the administrative functions and coordinates the activities of the four permanent organs at ITU headquarters and examines and approves the annual budget.

d. Permanent Organs of the Union: The General Secretariat. The Secretary-General directs the General Secretariat and is responsible to the Administrative Council for the administrative and financial aspects

²An ITU Space Extraordinary Administrative Radio Conference was held in 1963, recognizing the need for accommodating space services. The continued growth in space services led to convening of a World Administrative Radio Conference on Space Telecommunications (WARC) in 1971. An ITU Plenipotentiary Conference held in 1973 established the requirements of the General WARC of 1979, which included additional space-related issues. The 1979 WARC established Resolution Number 3, "Relating to the Use of the Geostationary Satellite Orbit and to the Planning of Space Services Utilizing It." Future schedules have been adopted for 1985 and 1987 for space services WARC.

of the Union's activity. He coordinates the activities of the permanent organs of the Union, organizes the work of the General Secretariat, undertakes the secretarial work preparatory to, during, and following conferences of the Union, and prepares an annual report on the activities of the Union which, after approval by the Administrative Council, is transmitted to all members. The General Secretariat assembles international telecommunication data that are published for the benefit of telecommunication engineers and operating authorities. There are lists of radio stations and telegraph offices throughout the world, statistics, maps, charts, tables, and a monthly *Telecommunication Journal*.

The International Frequency Registration Board (IFRB). The International Frequency Registration Board effects the orderly recording of frequency assignments made by the different countries to establish, in accordance with the procedure provided for in the Radio Regulations, the date, purpose and technical characteristics of each of these assignments, to ensure formal international recognition thereof. It also furnishes advice to members on the operation of the maximum practicable number of radio channels in those parts of the spectrum where harmful interference may occur, and performs additional duties on the assignment and use of the frequencies as may be prescribed by a conference of the Union or by the Administrative Council with the consent of the majority of the members. Essential records are maintained. The information is recorded in the Master International Frequency Register for international recognition and protection. An average of more than 1200 frequency assignment notices, covering new assignments or changes to existing assignments are processed each week.

Among the other major tasks of the IFRB are participation at government request in the obligatory intergovernmental coordination of the use of frequencies involving space techniques prior to their notification for recording in the Master Register, the orderly recording of the positions assigned by countries to geostationary satellites to ensure formal international recognition thereof, and the technical preparation of radio conferences.

The data recorded in the IFRB's Master International Frequency Register are published periodically in International Frequency Lists. The IFRB also prepares for publication a monthly Summary of Monitoring Information showing the precision with which radio stations keep to their assigned frequency, their strength of reception, and observed times of operation.

International Radio Consultative Committee (CCIR). The CCIR studies technical and operating questions relating specifically to radio communication and issues recommendations. To carry on the work of the CCIR and prepare for Study Group Meetings and CCIR Plenary Assemblies, U.S. Working Groups are formed to parallel the International Study Groups. These groups, together with an Executive Committee chaired by the Department of State, constitute the U.S. Preparatory Committee for the CCIR. These groups develop study programs, recommendations, and reports which, upon approval by the Executive Committee and the Department, are sent to the CCIR Director and International Chairman of the relevant Study Group.

The United States participates heavily in the CCIR and in recent meetings has contributed more papers than any other Administration. Numerous individuals in the United States are involved in the preparatory work for Plenary Assemblies and other associated meetings.

International Telegraph and Telephone Consultative Committee (CCITT). The CCITT studies technical, operating, and tariff questions relating to telegraphy and telephony and issues recommendations. The preparatory work for Administrative Telegraph and Telephone Conferences is essentially the same as for Administrative Radio Conferences, except that fewer representatives from the government and industry are involved.

The two CCIs are separate bodies dealing respectively with technical radio problems and technical telegraph and telephone problems. All member countries of the Union can participate in their work, as well as certain private companies operating telecommunication services and certain scientific and industrial organizations having related interests.

Each CCI holds a Plenary Assembly every four years. The Plenary Assembly draws up a list of technical telecommunication subjects or "questions," the study of which would lead to improvements in international radio communication or international telegraphy and telephony. These questions are then entrusted to a number of Study Groups, composed of experts from different countries. The Study Groups draw up recommendations which are submitted to the next Plenary Assembly. If the Assembly adopts the recommendations, they are published. CCIR and CCITT recommendations have an important influence on telecommunication scientists and technicians, operating administrations and companies, and manufacturers and designers of equipment throughout the world.

Related International Bodies

In addition to the ITU, other international bodies and organizations such as the Intergovernmental Oceanographic Commission (IOC) of UNESCO, the World Meteorological Organization (WMO), the International Civil Aviation Organization (ICAO), and the International Maritime Organization (IMO) treat items bearing on the use of the radio spectrum. At the international level, coordination with these bodies is effected by the ITU and its organs. Coordination with NATO/SEATO is effected through Department of State and/or military channels. Multilateral and bilateral agreements are undertaken through the Department of State and implemented by the affected interests--Defense, NASA, or other.

Effect of International Growth

Since the close of World War II, advances in radio technology have exceeded expectations. The trend in the use of communications-electronics is illustrated by the growth in the ITU from 78 members in 1947 to 158 members in 1983. The resultant increased need for information exchange among peoples of all nations has been met by expansion of communication facilities and improvements in intelligence-handling capabilities--higher capacity in both video and data, and satellite technology. New concepts such as radar, airborne navigational

aids, and ocean data sensors have come into increased use throughout the world. The resultant proliferation in the use of communication-electronic devices has increased the importance of the role of the ITU in ensuring maximum practicable use of the radio spectrum.

A.2 ITU RADIO REGULATIONS RELATED TO SPACE SYSTEMS

The current edition of the Radio Regulations is published under the authority of the Secretary-General of the International Telecommunication Union.[5] The consolidated document incorporates, in Vol. I, the provisions of the Radio Regulations (Geneva, 1979) and Table of Frequency Allocations and, in Vol. II, the Appendices thereto, as well as the Resolutions and Recommendations adopted by the World Administrative Radio Conference, Geneva, 1979.

It should be noted that not all allocations listed in the Table of Frequency Allocations have universal geographic application. The ITU geographical areas have been divided into three regions, as shown in Fig. 1. Frequencies may be allocated for different applications in each region.

The principal Appendices to the ITU Radio Regulations, Resolutions and Recommendations (1982 Edition, Ref. 5) related to space systems include:

Appendix 3: Notices Relating to Space Radio Communications and
Radio Astronomy Stations

Appendix 4: Advance Publication Information to be Furnished
for a Satellite Network

Appendix 28: Method for the Determination of the Coordination
Area Around an Earth Station in Frequency Bands Between 1 GHz
and 40 GHz Shared Between Space and Terrestrial
Radiocommunication Services

Appendix 29: Method of Calculation for Determining if
Coordination is Required Between Geostationary-Satellite
Networks Sharing the Same Frequency Bands

(Excerpts of the provisions related to space systems have been reprinted
in Ref. 6.)

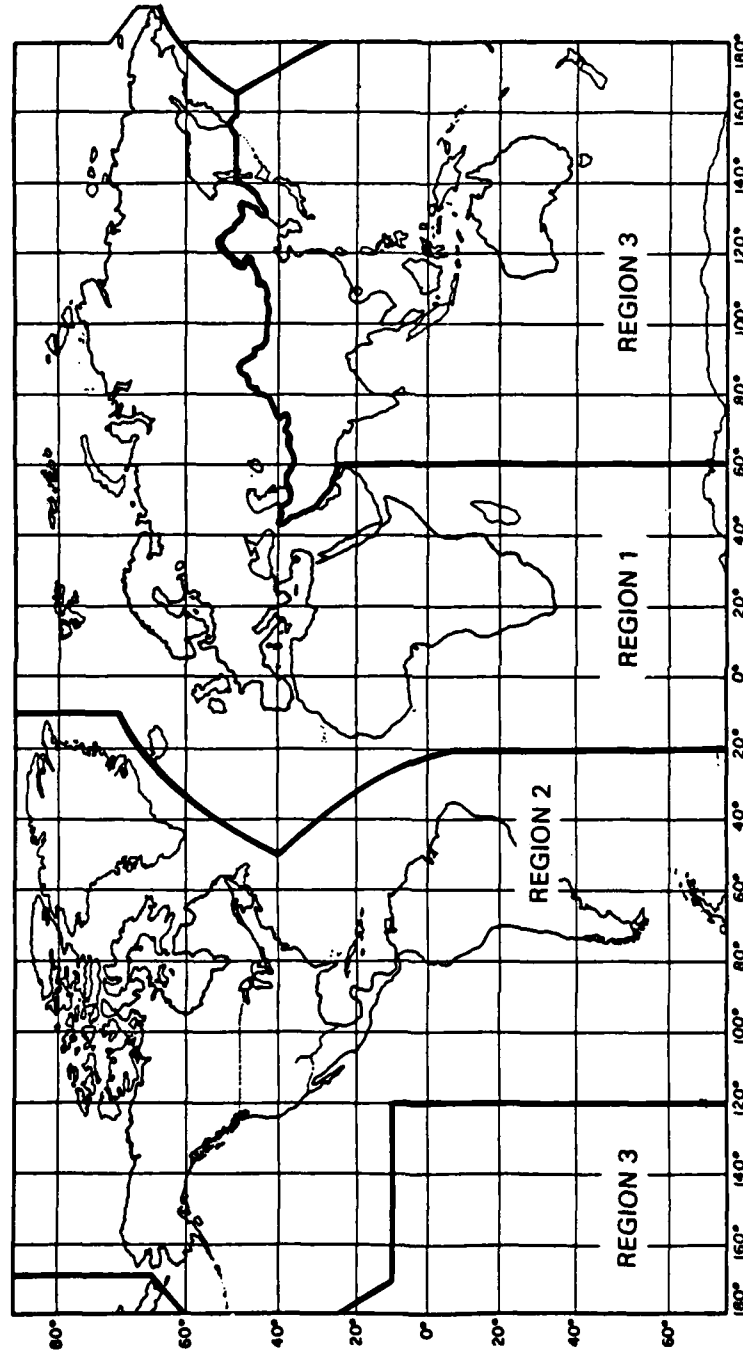


Fig. 1 — Geographical regions of the International Telecommunication Union

B. NATIONAL FREQUENCY MANAGEMENT

There are two government agencies responsible for assignment and control of frequencies in the United States: the Federal Communications Commission (FCC) and the National Telecommunications and Information Administration (NTIA).

B.1 FEDERAL COMMUNICATIONS COMMISSION (FCC)

The FCC under direction of the Legislative (Congressional) Branch regulates frequencies assigned to nonfederal users. The Communications Act of 1934, as amended, vests in the Federal Communications Commission responsibility for the regulation of nongovernment interstate and foreign telecommunication, including the assignment of space in the radio frequency spectrum among private users, regulation of the use of that space, and authorization of alien amateur operators, licensed by their governments, to operate in the United States under reciprocal arrangements. FCC-regulated frequencies may be available to U.S. Government users with sufficient justification and on an individual request, secondary, non-interference basis.

Volume II of the Rules and Regulations of the Federal Communications Commission contains general rules concerning use of the radio spectrum, including frequency allocations, treaties and other international agreements, emission designations, and radio equipment authorization procedures. In particular, the Table of Frequency Allocations specifies the frequency bands that can be used by each of the nongovernment radio services regulated by the Commission. Detailed operating rules, technical standards, and licensing procedures for individual radio stations in each radio service are published in other parts of the rules.

Volume VII of the Federal Communications Commissions Rules and Regulations[7] contains all the rules concerning domestic public radio services (other than maritime mobile), international fixed public radio communication services, and satellite communications. Part 25 of the Rules and Regulations covers satellite communications.

With respect to the use of the radio spectrum for satellite communications, Part 25 contains definitions, available frequencies, sharing criteria, frequency coordination procedures between earth stations and terrestrial stations, and an antenna performance standard.³ The technical bases for these rules are derived from the international Radio Regulations, but their application is tailored to the domestic U.S. regulatory and industry environment. For example, the coordination distance contours used in the earth station/terrestrial frequency coordination process are based on Appendix 28 of the international Radio Regulations. However, certain parameters, such as the number of assumed interference entries or the maximum permissible interference level, are adjusted to reflect domestic applications. Similarly, the earth station antenna performance standard is based on CCIR Recommendation 365, but is somewhat more stringent because of the more intensive spectrum use in this country.

In frequency bands shared co-equally by space and terrestrial services, a frequency coordination procedure is specified in Parts 21 and 25 of the rules. This frequency coordination procedure was first developed to resolve frequency conflicts between terrestrial operators in 1970, and was extended to include earth station operators in 1973. Each applicant for either a terrestrial or earth station license must complete this process before filing an application with the Commission.⁴ After coordination has begun for a particular station, each new applicant, whether terrestrial or earth station, must protect previously coordinated stations. This procedure is mandatory for all transmitting facilities since they must be licensed by the Commission. Licensing of receive-only earth stations is optional. However, protection from interference is afforded only to those receiving earth stations which

³Part 25 also contains regulations which do not deal with radio frequency management.

⁴In practice, a number of private consulting companies do the actual frequency coordination as agents for the applicants. This includes generation of the coordination contour, search of the data base, notification to affected operators, exchange of interference analyses with other spectrum users, final reports, and ongoing responses to coordination requests of other users.

are licensed after frequency coordination has been successfully completed.

The authorization of space stations generally consists of three elements:

1. The construction permit which authorizes the building of the satellite and specifies the technical parameters of the satellite (basic regulatory issues, such as the qualifications of the licensee, are also resolved at this stage).
2. The launch authorization which authorizes the launch of the satellite and assigns the orbital location at which it is to be operated.
3. The radio station license.

In 1980, the three elements were combined into a single authorization step for most satellite authorizations.

After the Commission issues construction authority, it assigns orbital locations to particular satellites. Although specific orbital locations are requested by the applicants, the Commission assigns orbital locations to best serve the public interest after evaluating the arguments of the applicant and the opposition, if any, to the applicant's request. In determining the orbital location assigned to any particular satellite, the Commission takes into account the other orbital locations assigned to the applicant, the nature of the services to be offered, traffic volume and coverage requirements, other pending requests, and the location and status of satellites already in service. The announced plans of other countries and INTELSAT satellites must also be taken into account through the frequency coordination procedures required by the ITU Radio Regulations. This approach has been followed to avoid the need for comparative hearings between applicants who might request the same orbital location.

Because of the increasing complexity of this task for domestic satellites, the Commission has recently evaluated applications on a group rather than on an individual basis. Thus, for example, the Commission adopted an orbit deployment plan in 1980 for over 20 domestic satellites then in orbit or scheduled for launch by 1985. The

Commission is also engaged in a rulemaking proceeding to reduce orbital spacings between domestic satellites from 4 deg to 2 deg at 4-6 GHz and from 3 deg to 2 deg at 12-14 GHz.[4, Sec. I] The earlier and larger orbital separations were based on orbital compatibility studies in the early to mid 1970s, which had somewhat conservative assumptions. The current orbital spacing studies under review at the Commission span a wide range of services and facilities and are employing more sophisticated analytical techniques to evaluate the feasibility of reduced spacings and calculate interference levels. More stringent control of earth station sidelobe levels and greater reliance on polarization isolation is also being proposed. Thus, if these reductions in orbital spacings are ultimately adopted by the Commission, orbital and frequency management of domestic satellites will become significantly more complicated. New or more detailed standards and coordination procedures might be required.

The Satellite Radio Branch, Federal Communications Commission, Washington, D.C. 20554 can provide additional documentation and information on FCC regulations and procedures for radio frequency management related to space systems.

B.2 NATIONAL TELECOMMUNICATIONS AND INFORMATION ADMINISTRATION (NTIA)

The National Telecommunications and Information Administration (NTIA), an agency of the U.S. Department of Commerce, is responsible for the assignment and use of frequencies by U.S. government agencies. NTIA is under the direction of the Executive Branch through the Assistant Secretary of Commerce for Communications and Information, and publishes the *Manual of Regulations and Procedures for Federal Radio Frequency Management*. [8] Within the Government, the Interdepartment Radio Advisory Committee (IRAC) assists the NTIA administrator in developing and executing policies, programs, procedures, and criteria concerning allocation management and use of the spectrum. The NTIA manual also includes the ITU International and National Table of Frequency Allocations. The manual is issued by the Assistant Secretary of Commerce for Communications and Information and is specifically designed to cover his frequency management responsibilities. Its contents are based on the advice of the Interdepartment Radio Advisory Committee.

Within the jurisdiction of the U.S. government, use of the radio frequency spectrum for radio transmissions shall be made by government stations only as authorized by the Assistant Secretary. Such use must comply with the provisions of the manual.

The Communications Act of 1934, as amended, provides that radio stations "belonging to and operated by the United States" shall use frequencies as assigned by the President. The Act empowers the President to authorize foreign governments to construct and operate radio stations in the fixed service (between fixed points) at the United States seat of government, and to assign them frequencies.

The President in 1977 and 1978 delegated to the Secretary of Commerce authority to act for him in the discharge of certain of his telecommunication functions under the Communications Act of 1934 and the Communications Satellite Act of 1962. The Secretary of Commerce in turn delegated this Presidential authority to the Assistant Secretary of Commerce for Communications and Information (Administrator of the National Telecommunications and Information Administration). The Assistant Secretary discharges his radio communication and frequency management functions as the Administrator of NTIA with the aid of the Interdepartment Radio Advisory Committee and the Frequency Management Advisory Council (FMAC).

The IRAC, under the NTIA Chairman and Executive Secretary, provides the major forum for the review processes necessary for each frequency allocation and assignment. The IRAC is now composed of representatives of the Department of Agriculture; Army; Air Force; Commerce; Energy; Health and Human Services; Interior; Justice; Navy; State, Treasury; the Coast Guard; the Federal Aviation Administration; Federal Emergency Management Agency; the General Services Administration; the National Aeronautics and Space Administration; the National Science Foundation; United States Information Agency, U.S. Postal Service, and the Veterans Administration. The FCC is not a member of the IRAC; however, the Commission has designated an FCC liaison representative to the IRAC to work with the IRAC and its subcommittees. The officers of the IRAC and the chairman of its subcommittees are appointed by the Assistant Secretary.

The IRAC substructure consists of the Frequency Assignment Subcommittee (FAS), the Spectrum Planning Subcommittee (SPS), the Space Systems Group (SSG)⁵ subgroup of the SPS, the Technical Subcommittee (TSC), the International Notification Group (ING), and the secretariat.

The FAS membership consists of a representative appointed by each of the IRAC member departments and agencies. It assigns and coordinates radio frequencies and develops and executes relevant procedures.

The SPS is responsible to the IRAC for planning for the use of the electromagnetic spectrum, including the apportionment of spectrum space for established or anticipated radio services, and apportionment among government and nongovernment activities. It maintains continuing appraisal of current and future needs of various radio services and recommends changes in the Table of Frequency Allocation.

The Space Systems Group (SSG) of the IRAC's Spectrum Planning Subcommittee is the focal point for the federal agencies to submit data on their space networks to the International Frequency Registration Board (IFRB) of the ITU and to comment on the networks of other administrations. The SSG initiates the advance publication, international coordination, and notification of government space systems under the provisions of the ITU Radio Regulations and reviews and responds to the data furnished by other administrations and the IFRB regarding proposed space systems. In essence, the data submitted to the IFRB on U.S. space systems provide a basis for the protection of U.S. satellite frequency assets. Similarly, data obtained via the IFRB from other countries on their proposed satellite systems provide the United States the basis for determining possible interference with U.S. space systems.

The information in Appendices 3 and 4 of the ITU Radio Regulations discussed earlier is furnished to the SPS in accordance with the instructions appearing in Part 8.3 of the NTIA Manual.[8]

The information in Appendix 4 is furnished to the SSG in accordance with the instructions in the current Manual of Instructions for

⁵The terms of reference for the SSG and amendments to the NTIA Manual are included in Ref. 8. For further information, contact Mr. W. D. Gamble at NTIA, Washington, D.C. 20230.

notifying U.S. Radio Frequency Assignment Data to The International Frequency Registration Board. The Appendix 4 data are provided to the SSG at the same time as the request for System Acquisition Stage 2 (Experimental Research or Exploratory Development) Systems review approval and is not normally transmitted to the IFRB for advance publication until Stage 2 approval has been granted or earlier if sufficient information is available.

The information in Appendix 3 is furnished to the SSG in accordance with the instructions in the current Manual of Instructions for Notifying U.S. Radio Frequency Assignments Data to The International Frequency Registration Board. The Appendix 3 data are provided at the same time as the Systems Acquisition Stage 3 (Advanced or Engineering Development) Systems Review approval request. After Stage 3 approval, the required coordination is initiated. Notification of frequency assignments to the IFRB is made after Stage 4 approval has been granted and any required coordination has been accomplished. Operational frequency assignments will not normally be granted until notification has been initiated.

Before Stage 2, 3, or 4 (Operational) support is granted by the SPS, the SSG must indicate that the appropriate Appendix 3 or 4 data have been submitted and reviewed.

The SSG of the SPS will review the information and:

- a. Notify the SPS that the required data are on file.
- b. Request the Chairman of ING to submit the appropriate data to the IFRB or to other administrations under the provisions of Articles 8, 11, 13 and 14 of the ITU Radio Regulations.

The Technical Subcommittee is concerned with technical aspects of the electromagnetic spectrum, including standards, propagation techniques, side effects, and EMC capabilities. The International Notification Group prepares responses to the ITU concerning questionnaires and other correspondence related to notification of U.S. frequency assignments. National frequency coordination and assignments are effected as follows:

Each government agency decides, in the light of policies, rules, regulations, frequency allocations, and availability of frequencies, the radio communication that is needed to carry out its mission. The agency makes the necessary technical studies, selects possible frequencies, coordinates the selection with other agencies involved, and prepares and files an application with the Executive Secretary of the IRAC.

The FCC liaison representative to the IRAC submits memoranda requests on nongovernment use of frequencies in shared bands, and in other bands where he considers there might be an impact on or from government operations.

The IRAC Secretariat, using a combination of computer and manual procedures, screens the application for accuracy, completeness, and compliance with procedures. Applications that have been screened and accepted are processed for the agenda of the Frequency Assignment Subcommittee. A computer program arranges the agenda in frequency sequence and assigns a docket number to each application for identification and reference. The application particulars are included in a weekly agenda section which is distributed to each agency and the FCC for study. The National Telecommunications and Information Administration reviews the government applications to ensure adequate justification, compliance with policy and regulations, technical appropriateness, probability of major problems, and whether there is a conflict with radio authorizations of nonmembers of the IRAC.

Each month the FAS and FCC consider pending items and take agreed action within policy guidance. When policy guidance is needed and agreement cannot be reached, the IRAC directs, or an agency requests, that applications be referred to the Director for Spectrum Plans and Policies, NTIA, who resolves them or refers them to the Assistant Secretary for decision. Decisions of the Assistant Secretary relating to frequency assignments may be appealed to the Office of Management and Budget.

Matters of considerable importance, such as changes in the Table of Frequency Allocations, significant government use of nongovernment frequency bands, and advice to the Department of State, are recommended by the IRAC to the NTIA for consultation with the FCC or other

appropriate agencies. Changes in either the Table of Allocations or frequency assignments which could adversely affect the public sector must be published by the FCC in the Federal Register for comments by the public. Although some government applications are not reviewed or examined in public for security reasons, the public is represented by the FCC liaison representative.

As soon as possible after each FAS meeting the IRAC Secretariat prepares the FAS minutes and submits them to the NTIA for approval. After approval, the IRAC Secretariat updates the Government Master File, from which it prints the list of Frequency Assignments to Government Radio Stations. The list is distributed to the agencies each month on microfiche.

International frequency coordination is carried out through the International Telecommunication Union. Usually bilateral coordination is performed under the Rules and Regulations with FCC acting as interface between government agencies and foreign administrations.

Preparation of U.S. government positions to international radio conferences, formulation of government telecommunication policy advice to the Department of State, advice and assistance in coordination with other countries, where not a function of the FCC; and guidance for implementing U.S. telecommunication treaty obligations with respect to government operations usually originate in, or are carried out in, the IRAC. Recommendations of the IRAC are reviewed by the NTIA and, if satisfactory, are coordinated with the FCC. The FCC conducts parallel rule-making procedures that may be required. The FCC and the NTIA then make their recommendations to the Department of State for international projection.

Officials from the NTIA, the FCC, and other government agencies having responsibilities on the subject under consideration serve as members of U.S. delegations to international telecommunication conferences. In addition, private individuals may serve as advisers to U.S. delegations.

To ensure compliance with the provisions of the ITU Radio Regulations, any government agency intending to establish a satellite system must provide to the IRAC's Spectrum Planning Subcommittee the details contained in Appendix 4 of the 1982 edition of ITU Radio

Regulations, for each satellite network within the planned satellite system, including changes in the technical characteristics and the employment and deployment of satellite stations.

Instructions for providing the information required by the ITU, Appendix 4, are contained in the Manual of Instructions for Notifying U.S. Radio Frequency Assignment Data to the International Frequency Registration Board IFRB.

The Notification Manual is currently being reviewed and appropriately revised by the International Notification Group (ING) of IRAC in coordination with the Spectrum Planning Subcommittee (SPS) of IRAC to align it with the decisions of the World Administrative Radio Conference, Geneva, 1979. The IFRB was charged by WARC-79 with developing the various forms of notice to meet fully the statutory provisions of Appendices 1 and 3 of the Radio Regulations. The development of the forms has been performed in conjunction with the study and design of an integrated system for the extended use of the computer by the IFRB. Consequently, the IFRB was greatly delayed in providing revised forms to ITU administrations. This, of course, has delayed the U.S. review and revision effort.

The revised space radiocommunication station notification forms;

Transmitting Earth Station - FCC Form 130-B
(formerly 130-E)

Receiving Earth Station - FCC Form 130-C
(formerly 130-A)

Transmitting Space Station - FCC Form 130-D
(formerly 130-S)

Receiving Space Station - FCC Form 130-E
(formerly 130-B)

are presently in the forms management review process leading to their printing. When the Notification Manual is finalized, including examples of the various forms, it will be submitted to IRAC for formal adoption. Subsequent to IRAC approval, NTIA will arrange to have the Notification Manual published. Copies are distributed to all member agencies of

IRAC in the quantity they request in order to meet their internal needs and those of companies providing contract services. The companies providing such services should bring to the attention of the contracting agency the number of copies needed in order that a sufficient number will be initially printed. Additional copies will be furnished on a case-by-case basis by NTIA or the FCC. Copies of the notification forms will be available from the FCC.⁶

B.3 NATIONAL AERONAUTICS AND SPACE ADMINISTRATION (NASA)

The National Aeronautics and Space Administration Associate Administrator for Space Tracking and Data Systems is, among other things, responsible for all frequency management activities inside NASA.⁷ Frequency management is delegated to the Director of Communications and Data Systems, HQ NASA, Code TS, Washington D.C. 20456.

The Director of Communications and Data Systems is directly responsible for all NASA activities associated with the preparation of material for U.S. inputs to the ITU/WARC/CCIR, with two of his senior staff responsible for NASA frequency allocation and NASA frequency assignment, respectively. These personnel are located at NASA Headquarters in Washington, D.C., and their responsibilities encompass:

- a. Representing NASA at the IRAC, SPS, FAS, and other committees.
- b. Liaison with the Department of Defense, FCC, and foreign space agencies.
- c. Consultation and assistance with all NASA project and program offices.
- d. Preparation for and participation in ITU/WARC/CCIR activities.

⁶For further information, contact the Chairman, International Notification Group, Mr. Paul E. Carroll, Federal Communications Commission, Office of Science and Technology, Spectrum Management Division, Treaty Branch, Washington, D.C. 20554.

⁷NASA Management Instruction: "Control of Radio Frequency Transmission from Space Vehicles and Spacecraft," NMI2570.B, December 9, 1977.

- e. NASA notifications to the IFRB.
- f. Interagency consultation.
- g. Frequency management requirements for long-range planning.

The NASA Headquarters frequency management staff work closely with, and oversee the activities of, the NASA frequency managers located at the various centers.

NASA Frequency Management Definitions

Frequency Allocation is the process whereby a portion of the RF spectrum is reserved for a particular use or service. (Allocation of a band does not constitute authority to develop and build a system. This is obtained after the NTIA system review procedures.)

Frequency Assignment is the authorization for the use of a particular frequency. (When a frequency is assigned, the authorization is the license to operate.)

Summary of NASA RF Management Policy

Frequencies should be selected to avoid or minimize radio frequency interference (RFI). The aim should be for the maximum compatibility consistent with national and international policy. Funds for any radio frequency system must not be obligated until spectrum allocation support is assured by the NASA Office of Space Tracking and Data Systems.

NASA Allocation and Assignment Process

Allocation. The center project manager consults the center frequency manager to determine the availability of allocated spectrum for use by his project. This request is passed to the NASA Headquarters Frequency Manager, who ascertains availability. If confirmed, the center frequency manager generates documentation to enable Headquarters frequency management to submit to the SPS/IRAC a mission spectrum review and support request. On receipt of an SPS reply indicating spectrum support, Headquarters forwards qualified guidelines for assignment request to the center frequency manager.

Assignment. The center frequency manager then obtains the detailed frequency-associated parameters (e.g., radiated power, antenna gain, beamwidths, modulation characteristics, etc.) along with trajectory/position parameters and with the help of the program manager completes the necessary paperwork for submission to NASA Headquarters requesting assignment of specific frequency(s) for the project.

This package is then reviewed by the FAS/IRAC, which from the point of view of operational compatibility represents all national users of the spectrum. When approved by the FAS/IRAC, the assignment is forwarded to the NTIA for official issuance, which constitutes a license to operate.

NASA Space Research Satellite Frequency Selection

NASA is responsible for the frequency assignments for numerous types of NASA systems such as aircraft radio communications, location, and navigation as well as balloon, ship, and terrestrial fixed and mobile services. These are handled the same as all other government frequency assignments. A more detailed description of the practical aspects of frequency assignment processes in obtaining an assignment for a space research satellite follows.

Space research satellite missions fall into two main categories: deep space missions and earth orbiting missions. Deep space missions are few in number and usually operate compatibly or noncompatibly for long periods of time. The periods are reasonably easy to predict during a mission planning stage. Earth orbiting missions are large in number and operate compatibly or noncompatibly for short periods of time. The periods are predictable for a short time span for any particular date.

Frequency selection for the two cases are very different. Deep space frequency selection is made only after exhaustive and detailed analysis. Earth orbiting frequency selection is more by human judgment and coordination.

*Deep Space Missions.*⁸ The process used to select frequencies for deep space missions uses frequency, ephemeris, and other parameters

⁸ITU Regulation No. 169 defines deep space as space at distances from earth approximately equal to or greater than the distance between the earth and the moon. This definition can create problems for the deep space network for lunar missions and spacecraft operating at or

(radiated power, modulation) for all active and planned space stations.[9] For example, for any one frequency earth station tracking angles for all space stations on that frequency are determined for several years and compared. When the angles are sufficiently small between any two space stations they may be noncompatible. Frequencies are chosen so the noncompatible periods are minimized and will not occur at critical time periods (planet encounter) for any space station.

The processes described in Ref. 9 apply to all U.S. deep space missions and also determine the optimum set of frequencies for Japanese, European Space Agency (ESA) and U.S. plans for multiple spacecraft on similar missions, resulting in several spacecraft with similar view periods.

Reference 9 also depicts a frequency channelization proposal and describes a set of parameters for interference analysis, and subsequent channel selection, for a planned deep space mission. This rather extensive coordination and analysis is necessary to ensure optimum protection for the extremely weak deep space signals coupled with the extremely sensitive earth stations, and is carried out prior to the submission of an assignment request to NASA Headquarters, which ensures concurrence, both nationally and internationally, on the selected frequency.

In spite of coordination and analysis, signal strength on earth from deep space can typically be six or seven orders of magnitude weaker than signals from satellites in earth orbit. This means that an earth orbiting satellite operating in a band adjacent to a band allocated to deep space can interfere with reception of deep space signals. This interference is caused by modulation products which, although quite weak, can extend out of band and still be greater in amplitude than a signal from deep space. Such interference can be predicted by the Deep Space RFI Prediction Program (DSIP2) operated by JPL (see Sec. III.B.5.h). When the DSIP2 Program predicts interference, coordination

near the libration (Lagrangian) point. Efforts have been initiated within the CCIR and NASA (the Jet Propulsion Laboratory) to extend the deep space definition to beyond lunar distance.

is effected; either the deep space mission tolerates the interference or source-interferer changes operations by mode change or turn off.

Earth Orbiting Missions. Earth orbiting mission frequency selection is more a process of elimination and judgment based on experience and knowledge of other users than it is analytical. The following paragraphs list the major steps in the process.

- a. Determine if the using project has any preferences or restrictions. For example, a follow-on project may prefer to use a frequency it is currently using. This is usually possible. Multiple spacecraft projects may or may not want their spacecraft on the same frequencies. Restrictions may also be imposed due to on-board RFI or other considerations.
- b. Examine the remaining spectrum and compare it with other existing or planned space assignments to find likely looking spot frequencies.
- c. Examine the apparently available spectrum with regard to suitability for usage from other points of view, e.g., local earth station area restrictions or equipment considerations. (In general, area restrictions should be thought of as fixable instead of limiting frequency band usage. Restrictions in different areas at different frequencies would soon use up the band.)
- d. Begin a dialogue with other users of the spectrum to select from the above the best frequency to apply for (this particularly pertains to the U.S. Department of Defense and the European Space Agency.)
- e. Apply for the frequency(s) selected through NASA Headquarters and the national and international agencies.
- f. About six months prior to launch, tabulate known users of frequencies in proximity to those for the forthcoming mission. Conduct an analysis to determine the potential for interference to the mission, especially during launch and early orbit. This analysis serves as a final check on the suitability of the chosen frequency and alerts the project to any known potential interference they might experience.

Fig. 2 – Department of Defense frequency management channels

- The JCS Military Communications-Electronics Board (MCEB) formulates policy and provides direction to the unified and specified commands in military communications-electronics (C-E) matters including frequency management within DoD (Directive 4650.1). The Air Force member of the MCEB is the Assistant Chief of Staff for Information Systems. The Joint Frequency Panel (JFP) under the MCEB formulates DoD positions on spectrum management, implements national and international policies for DoD spectrum use, and guides joint use of the spectrum. The JFP includes voting members from the Army, Navy, Air Force, Marine Corps, Defense Communications Agency (DCA), and the National Security Agency, and nonvoting members from the Coast Guard, JCS, and the Electromagnetic Compatibility Analysis Center (ECAC). Permanent and ad hoc working groups assist in the work; one of them deals with space frequency matters.
- The DoD Area Frequency Coordinator (AFC) is part of an interservice frequency coordination system set up by the MCEB to minimize electromagnetic interference (EMI) and avoid conflicts at military test ranges and other designated areas. Frequencies for use in these areas must be coordinated with the applicable DoD AFC before assignment. DoD AFC frequency records are available to military activities for frequency planning.
- The Defense Communications Agency maintains frequency records, analyzes frequency use, and requests the assignment of frequencies needed by the Defense Communications System (DCS).
- The military departments each have a senior officer position responsible for frequency management. In the Army, it is the Assistant Chief of Staff for Automation and Communications; in the Navy, it is the Director, Naval Communications Division; and in the Air Force, it is the Assistant Chief of Staff for Information Systems (AF/SI).

DoD Electromagnetic Compatibility Services

The DoD Electromagnetic Compatibility Program (EMCP) ensures EMC of all military C-E equipment, subsystems, and systems. The program is an integrated DoD effort that assigns specific and joint responsibilities to DoD components in each of the program areas of standards and specifications, measurement techniques and instrumentation, education for EMC, data base and analysis capability, design concepts and doctrines, operational problems, and test and validation capability. AFR 80-23 implements the Air Force program and assigns responsibilities for accomplishing the program objectives.

The Electromagnetic Compatibility Analysis Center. ECAC is a joint activity chartered by DoD Directive 5160.57 and administratively managed and operated by the Air Force. ECAC maintains the data bases and mathematical and computer analysis techniques for investigating DoD and interservice EMC problems. It provides DoD components convenient and rapid access to the data bases and analysis techniques and assists in problems within and between the services. As the DoD focal point of joint analysis for the EMCP, the ECAC analyzes C-E equipment in being, under development, or proposed for development to determine its EMC with other types of equipment. ECAC can provide spectrum supportability analysis on the ability of new systems and equipment to operate in their intended environment without suffering or causing unacceptable degradation due to EMI. ECAC provides analysis support to the MCEB Frequency Panel J-12 working group on the DD Form 1494 Application for Frequency Allocation process.

ECAC Data Files. The ECAC collects, catalogs, and stores large amounts of detailed information to form an EMC data base. This data base includes information about selected technical characteristics of equipment, frequency assignments, selected terrain elevation information, and rules governing the use of the frequency spectrum worldwide.

ECAC Analytical Services. The availability of a large data base at ECAC and the development of specialized analysis techniques enable ECAC to provide a unique service in studying and investigating EMC problems.

ECAC primarily assists in the system-to-environment and the environment-to-system compatibility areas, with some capability for intersystem analysis. Instructions for requesting for ECAC Data Base information and analysis support are provided in Sec. III.A.2.

Regulations of the Military Departments

1. Department of the Army, Army Regulation No. 5-12, Army Management of the Electromagnetic Spectrum (Effective 1 March 1978). Headquarters, Department of the Army, Washington, D.C., 23 January 1978. This regulation prescribes policies, responsibilities, and procedures for Army management of the electromagnetic spectrum (radio frequencies from 3.0 KHz to 3000 GHz), and implements the Radio Regulations of the International Telecommunication Union and the Manual of Regulations and Procedures for Radio Frequency Management (Office of Telecommunications Policy [OTP] Executive Office of the President, now NTIA) and the provisions of the DoD Directives 3222.3, 4650.1 and 5160.75.

2. Department of the Navy, Naval Telecommunications Procedures Spectrum Management Manual NTP6(A), October 1982. Commander, Naval Telecommunications Command, 4401 Massachusetts Avenue, NW, Washington, D.C. The Spectrum Management Manual is the single manual of procedures for the effective execution of spectrum management within the Department of the Navy, Marine Corps, and Coast Guard. This manual provides an overview of organizational responsibilities and roles in the regulation of spectrum use and covers international, national, DoD, and Department of the Navy regulation of the use of the spectrum.

3. Department of the Air Force, AF Regulation 100-31, 23 July 1980, AFSC Supplement 1, 22 June 1981. Communications-Electronics. Frequency Management and Electromagnetic Compatibility, Headquarters, United States Air Force, Washington, D.C. This regulation details responsibilities and provides policy guidance, procedures, and information concerning Air Force management of the electromagnetic spectrum. It assists in system planning, prescribes the procedures for obtaining frequency support for new systems, and lists detailed procedures for frequency allocations and assignments. It applies to all Air Force activities using the electromagnetic spectrum. It implements DoD Directive 4650.1, Management and Use of the Radio Frequency Spectrum (DTACCS), 13 December 1974.

Air Force Frequency Management

The Assistant Chief of Staff for Information Systems (Hq. USAF/SI) provides overall policy and planning guidance for Air Force frequency management. The Air Force Frequency Management Center (formerly USAF/FMO) is under the operational direction of the Air Force Communications Command (AFCC) and provides technical services relating to frequency management and implements Air Force frequency management policy.

Application for Frequency Allocations

All applications for frequency allocation (DD Form 1494) are submitted to USAF/FMC through appropriate major command channels. DD Form 1494 is processed as follows:

- The FMC reviews the DD Form 1494 for completeness, accuracy, and availability of spectrum support. The FMC then assigns a unique J/F 12/XXXX number and submits the DD Form 1494 as a J/F 12 series paper (Application for Frequency Allocation) to the MCEB Secretariat for distribution to all J-12 holders. A copy is also submitted to the IRAC Spectrum Planning Subcommittee for review. When appropriate, the FMC requests interested Hq USAF directorates and other activities and unified commands to coordinate on these applications. Overseas military organizations, including possible host nations, may comment on the feasibility and probability of adding space systems to the frequency band before international registration is sought. All J-12 holders may submit comments on receipt of the applications.
- The DoD Electromagnetic Compatibility Analysis Center provides EMC comments to the MCEB frequency panel's J-12 working group. The USAF FMC drafts a memorandum for consideration by the MCEB J-12 working group. The J-12 working group reviews the application for frequency allocation to see if the equipment or system can receive the necessary frequency support in the geographical areas outlined. They review the memorandum to make sure that it provides appropriate guidance.

- The MCEB coordinates the allocation applications with the United Kingdom, Australia, New Zealand, and Canada, when appropriate. In these cases, the J/F 12 series papers also become the Combined Communications-Electronics Board (CCEB) C/F 299 series papers.
- After review and approval by the MCEB frequency panel, the MCEB issues a memorandum bearing an adjusted J/F 12 number such as J/F 12/XXXX/1 for identification purposes. This memorandum contains guidance on the application and the ECAC EMC comments. The same basic number and a serially assigned last digit will identify any subsequent memorandums or papers dealing with the same application. The MCEB distributes these papers to all holders of J/F 12 series papers.
- The MCEB frequency panel guidance contained in the J/F 12 memoranda outlines general considerations and restrictions that apply to a particular equipment; they provide directions for the submitting MAJCOM. The MAJCOM that submitted the application ensures adherence to the guidance, provisions, and restrictions shown in J/F 12 memoranda. If questions exist concerning compliance, the MAJCOM explains the problem to the FMC through command channels within 60 days of receipt of the memoranda. The FMC coordinates any response with the appropriate Hq USAF office.
- The field commands direct inquiries regarding the J/F 12 series memoranda to the FMC through channels.

There are special instructions for frequency allocations for space systems. They are found in the ITU Radio Regulations and, under instructions for notifying U.S. radio frequency assignment data to the International Frequency Registration Board, in the FCC Manual. FCC space radio communication notification forms⁹ are filled out for

⁹These forms are also used to comply with international and national limits of power flux density and effective radiated power. Limits and control of emission from space stations and earth stations are addressed in Chapter 8 in the *NTIA Manual of Regulation and Procedures for Federal Radio Frequency Management*. [8] See Sec. II, p. 50, for changes in the FCC Manual.

transmitting earth station, receiving earth station, transmitting space station, or receiving space station, as appropriate. There are four stages of systems acquisition: conceptual, experimental research or exploratory development, advanced or engineering development, and operation.

Applications for Frequency Assignments

All applications for frequency assignments are also submitted to FMC in the Standard Action Frequency Format (SAFF) through Air Force command channels. A request for new frequency assignment must contain the information required by the SMF and any additional information necessary to provide a clear and accurate description of the requirement. Attachment 5 of AFR 100-31 contains details for completing the SMF.

Frequency Requests for Space Systems

The following special policies apply for space system frequency requests.

- On-Off Capability for Spacecraft Systems. Each request for a frequency to support systems radiating electromagnetic energy from spacecraft will contain either a detailed description of the methods used to provide on-off telecommand or a justified request for an exception.
- Frequency Request Action. Requests for new, renewal, or modified frequency assignments for earth or space stations will require additional information on the SMF. When the information on the frequency request requires special access clearance (see AFR 205-32), item 501 of the SMF will show the special access required.
- Space Ground Link Subsystem (SGLS) Frequency Assignments. The SGLS is used on all DoD space programs for telemetry, tracking, and command of satellites from Air Force satellite earth stations. Eighteen channels in the downlink band (2200-2290 MHz) and 20 channels in the uplink band (1761-1842 MHz) have

been assigned to the Space Division (SD) of the Air Force Systems Command, the Eastern Test Range (ETR), and the Ballistic Missile Office (BMO). The SD, ETR, and BMO frequency managers manage and issue local discrete frequency assignments on a program-by-program basis.

REFERENCES FOR SEC. II

1. *IEEE Transactions on Electromagnetic Compatibility*, Vol. EMC-19, No. 3, Part II, Special Issue on Spectrum Management, August 1977.
2. *IEEE Transactions on Communications*, Vol. COM-27, No. 10, Part I, Special Issue on Satellite Communications, October 1979.
3. *Proceedings of the Conference on Space Systems Data Bases and Analysis Capabilities*, Department of Defense, Electromagnetic Compatibility Analysis Center, Annapolis, November 17-19, 1981.
4. Jansky, D. M., and M. C. Jeruchim, *Communications Satellites in the Geostationary Orbit*, Artech House, Inc., Dedham, MA, 1983, Part 1.
5. *ITU Radio Regulations*, Vol. I, *Appendices to the Radio Regulations, Resolutions, and Recommendations*, Vol. II, Place des Nations, CH-1211, Geneva, 1982.
6. *Space Handbook, a Compendium of Provisions Affecting Space Services*, Vols. 1 and 2, prepared for U.S. Air Force Frequency Management Office, Washington, D.C., June 1983.
7. Federal Communications Commission, *Rules and Regulations*, Vol. VII; available from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C.
8. *Manual of Regulations and Procedures for Federal Radio Frequency Management*, U.S. Department of Commerce, National Telecommunications and Information Administration, Interdepartmental Radio Advisory Committee, May 1983; available from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C.
9. deGroot, Norman F., and M.K.W. Sue, "Selection of Frequencies for Deep Space Telecommunications," *The Telecommunications and Data Acquisition (TDA) Progress Report 42-69*, National Aeronautics and Space Administration, Jet Propulsion Laboratory, California Institute of Technology, March and April 1982, pp. 49-61.

III. TECHNICAL REQUIREMENTS AND ANALYSIS CAPABILITIES

To meet the project objectives (Sec. I) and provide the information required by the radio frequency management process (Sec. II), it will be necessary to develop and maintain a comprehensive space environment data base on RF spectrum utilization of space systems, contact other spectrum users that may affect space operations, and develop analysis and computation capabilities to apply the data in the base to existing and planned space systems. The data base and other comparable data bases are described in Sec. III.A. Section III.B documents existing analytical investigations and computer programs.

Some of the subsections of Section III.B represent original Rand investigations. Others are based on descriptive materials provided by various agencies and contractors. Materials from external sources were modified by the Rand authors, partly for simplification and clarification and partly to avoid excessive length. All externally based subsections identify the originating source and have been approved by the original author.

A significant portion of Rand's effort on the project has been to establish cooperation and coordination between persons who develop analytical and computational models for RF spectrum utilization and persons in the frequency management community who are tasked to prevent signal interference. The descriptions of models and codes in this report should prove valuable for this purpose.

A. ELECTROMAGNETIC SPECTRUM DATA BASES

A.1 SPACE SYSTEMS DATA BASE

The Space Systems Data Base (SSDB) will contain electromagnetic and operational characteristics of active and projected U.S. and international space systems including both space segments and related earth segments. The SSDB will be structured to provide several levels of information: an automated file for quick access, a culling process, printouts, and expanded information as available in documents, reports, and measured data. The level of data will vary and is dependent on frequency coordination and type of analysis problems.

The SSDB will include time-related information in the following categories:

- Actively deployed systems
- Deployed systems in standby orbits
- Approved-for-launch systems and scheduled dates
- Firm and funded development space programs
- Future development plans and predicted schedules

The data collection format includes items published by Rand [Sec. I, Ref. 2], contributions from other agencies, and recent expansions by ECAC. The format will be used in developing the automated data base on space systems. The data will support preliminary interference analyses and will provide indications of the operational usage of systems. The format applies to satellites, their related earth segments, launch vehicles, and Tracking, Telemetry and Command (TT&C) operations. Technical characteristics of the hardware and operational environmental characteristics of the system required for the data base are listed in Appendix A. The extensive detail indicated in the proposed format is required to cover the numerous inputs derived from the analyses and included in the computer programs. A comprehensive space systems format and compilation guidelines are documented in Ref. 1. Other types of satellites, such as solar power satellites, may require additional data to describe the system adequately.

Design and modification of the SSDB should be conducted as a joint effort by the DoD Electromagnetic Compatibility Analysis Center, the DoD Frequency Management Agencies, NTIA, FCC, and other participating agencies. Responsibility for constructing and maintaining the data base and developing an analysis capability for space systems planning has been assigned to the ECAC at Annapolis.[2] ECAC already has the necessary computer and data-processing equipment, the trained personnel, and a substantial portion of the required space-environment data and associated analysis codes and programs. Additional facilities may be needed to process highly classified and proprietary data.

Preliminary discussions have been initiated with NORAD, ADCOM (SPADOC), and other agencies about the acquisition and processing of needed data on the operational condition and status of space systems. Since these data will be at various levels of security and in some cases will include proprietary information, appropriate means for processing proprietary and classified information will need to be developed and approved by the cognizant agencies.

The data base should be made available--as needed, and under appropriate security procedures--to Rand space studies, to DoD, and to government agencies and sponsored contractors conducting analyses in the subject areas. The data base should be updated for satellite launches/decays and changes in space systems development plans to provide a continuing source of information for analyzing current and future space systems.

Prediction and analysis of the probability of spacecraft collision and/or physical impact with space objects will not be addressed in this project. However, the data base should provide useful information on the ephemerides of current and future satellites, which is essential to such investigations. It will also be useful in EMC analysis when changes in satellite positions are made to avoid collision.

References for Sec. III.A.1

1. Apirian, L., *Space Systems Data and Compilation Guidelines*, ECAC-CR-83-084, September 1983, Consulting Report, ECAC/IIT Research Institute, Annapolis, MD 21402.
2. "Memorandum: Electromagnetic Compatibility Analysis Center Support for Space Systems Planning," Office of the Under Secretary of Defense, Research and Engineering, Assistant Deputy Under Secretary (Technical Policy and Operations), 25 June 1981.

A.2 EMC DATA BASES AT ECAC

A primary function of the Electromagnetic Compatibility Analysis Center is to establish and maintain the data base necessary for EMC analysis to support DoD components and, as approved by the managers of the DoD EMC Program, for other government agencies. ECAC has compiled and continually updates the most complete EMC-related data base

available, consisting of numerous data files on equipment characteristics, equipment complements, frequency spectrum usage, background environment, topographic data, space systems, and a hard-copy library.

The ECAC Equipment Characteristics File contains basic technical characteristics of military and commercial transmitters, receivers, and antennas, extracted from all available data sources.

Equipment complement information is composed of data files that describe the communications-electronics equipments resident on ships and aircraft, and assigned to mobile ground tactical units, and location data for the various DoD platforms and military units.

The Frequency Resource Record System (FRRS) data base contains worldwide DoD frequency-assignment records. Each record has administrative and technical data concerning the type of assignment, organizational information, and transmitter and receiver location, and is provided daily (ten days for posting to the master files) by all DoD components.

Background environmental data consist of numerous files, both automated and nonautomated, that contain electromagnetic environmental information describing military and civilian communications-electronics operations worldwide. The data, both classified and unclassified, are obtained from U.S. and international government agencies.

The automated topographic data file consists of digitized ground elevation information, with the spacing between elevations given in angular measure, that is used to characterize a geographical region.

Satellite system data include general system information, detailed technical characteristics, and orbital characteristics. General systems information is derived from International Frequency Registration Board notifications, technical articles, and bibliographies. The detailed technical characteristics are obtained from technical manuals and reports, system description documents, and frequency allocation applications. Orbital characteristics are received from the North American Aerospace Defense Command.

Data for the various files are obtained in hard-copy, punch card, and magnetic tape form. Some of the nonautomated material is extracted and entered into automated files. That which is too voluminous or would

not be cost effective to automate is retained in a hard-copy library. When possible, multiple sources are consulted to ensure that the best data are extracted for inclusion in the automated files. The quality of the material is chiefly determined by the validity and currency of the source documents.

ECAC services range from providing data from the data base (tapes, card decks, printed copies, microfiche, and microfilm), through engineering consultation, to detailed and continuing analyses.[1] The cost of the data base outputs and analysis efforts is reimbursed by the requestor.

Each of the military departments is represented by a deputy director at ECAC. DoD activities are encouraged to contact the appropriate deputy director directly before submitting requests for ECAC data base and analytic services to determine the scope of required services. Once these needs have been determined, a written request for services should be initiated. Requests by industry and universities on contract with DoD should be processed through the appropriate DoD contracting agencies. Telephone numbers at ECAC are:

Commercial: 301 - 267 + extension
Autovon: 281 + extension
FTS: 930 + extension
Secure: 2339 wideband.

DoD activities may contact appropriate ECAC offices at the following addresses:

U.S. Army

Army Deputy Director (ECAC/CA)
ECAC, North Severn
Annapolis, MD 21402
Extension: 2103

U.S. Air Force

Air Force Deputy Director (ECAC/CF)
ECAC, North Severn
Annapolis, MD 21402
Extension: 2681

U.S. Navy

Navy Deputy Director (ECAC/CN)
ECAC, North Severn
Annapolis, MD 21402
Extension: 2556

U.S. Marine Corps

Marine Corps Deputy Director (ECAC/CM)
ECAC, North Severn
Annapolis, MD 21402
Extension: 2555

Other DoD

Chief, Plans and Technical Resources (ECAC/XM)
ECAC, North Severn
Annapolis, MD 21402
Extension: 2353

Reference for Sec. III.A.2

1. "A Guide to Capabilities and Services," Department of Defense Electromagnetic Compatibility Analysis Center (ECAC), August 1982.

B. ANALYSIS CODES AND COMPUTER PROGRAMS

B.1 INTRODUCTION

Analytic codes and computer programs were assembled to analyze predicted types of problems encountered in spectral and orbital congestion. Modifications and improvements to analysis models, and corresponding additions to the data base described in Sec. III.A.1, will take place as part of the continuing project, and will accommodate the growth and changes in space systems development and operations.

At the request of the Air Force, this project was designed to provide a continuing analysis capability in this problem area and is to be used by aerospace contractors during the acquisition process. Analyses are to be conducted during the early concept architectural planning phase and continued during the development cycle as changes are made to original designs. The analysis codes and computer programs designed by Rand and those compiled in this report are available from the sources listed. Access to the data base at ECAC is provided through the procedures discussed in Sec. III.A.2.

The space systems EMC and EM vulnerability analysis process is illustrated in Fig. 3.

1. Regulations and Procedures for Radio Frequency Management (Section II)
2. Cull and coordination
3. Cosite analysis
4. Intrasytem EMC analysis
5. Intersystem EMC analysis
6. EM vulnerability analysis
7. Multipurpose treatments

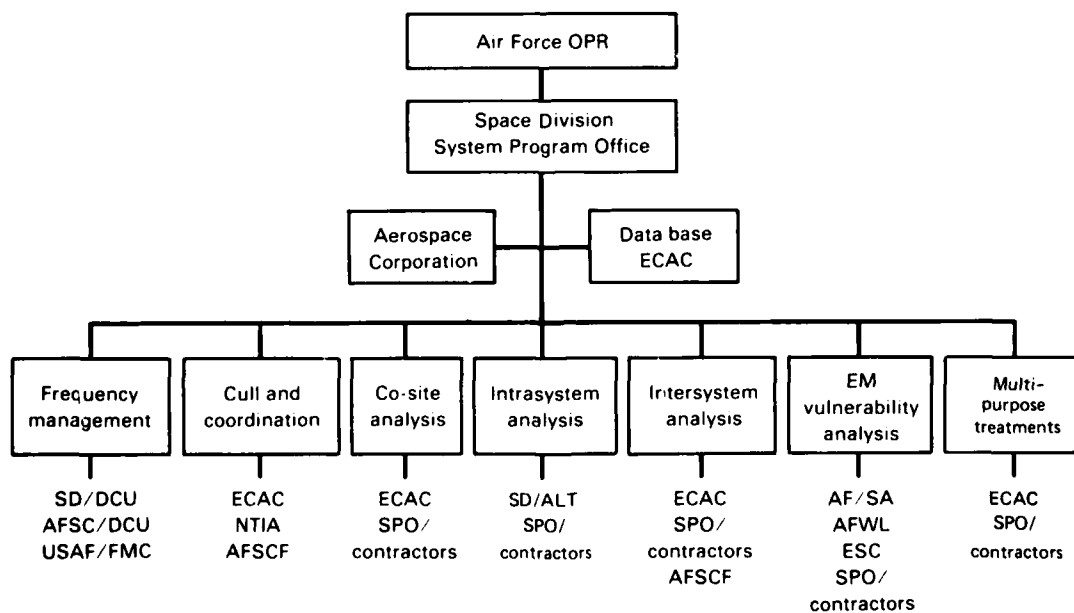


Fig. 3 — Space systems spectral/orbital congestion analysis process

The tree diagram depicts the process to be used to investigate spectral or orbital problems that may arise when a new space system is developed or deployed by the Air Force Space Division. Similar procedures will be employed by other space-related organizations. The Air Force OPR would provide for management of the project and maintenance of a continuing analysis capability for use by the space-related System Program Offices (SPO) and SPO contractors of the Air Force Product Divisions. The SPO would provide access to the data base at ECAC, the analysis codes and computer programs, and analytic support by the respective SPO contractors. The Aerospace Corporation would assist the SPOs of the Air Force Space Division in monitoring contractor performance. The project contractor, in collaboration with the System Program Office, would determine which category or group of categories of analysis and programs are appropriate to investigate the potential spectral and orbital problems. When the category is selected, the project personnel arrange required support with the agencies or contractors indicated at the bottom of Fig. 3.

The analysis codes and computer programs are described under each respective category. A standard format was used to describe the purpose, source, code operations and capabilities, software, and computer type for each of the programs.

This process will require preparation by the Air Force of plans and procedures to address the following topics:

1. Designation of an Air Force organization as OPR for management of the project and establishment of SPO functions as stated above.
2. Revising Air Force contract regulations and standards to include references to the Space Systems Data Base, analysis codes, and computer programs and procedures for their use.

Revisions are required on:

SDR 55-1, Satellite Position Management, 15 September 1983
(OPR: SD/YO)

AFR 55-XY, Operations Spacecraft Orbital Position Management,
Draft 10 March 1982 (OPR: AF/XOSO)

AFR 100-31, Communications-Electronics, Frequency Management
and Electromagnetic Compatibility, 23 July 1980, AFSC
Supplement, 22 June 1981 (OPR: AF/SITI)

MIL-STD-1541 (USAF) Military Standard, Electromagnetic
Compatibility Requirements for Space System, 15 October 1973,
Proposed MIL-STD-1541A (USAF), Draft 15 August 1982 (OPR:
SD/ALTI)

AFR 80-23, Research and Development, The Air Force
Electromagnetic Compatibility Program, 29 March 1982 (OPR:
AF/RDPT), Space Division (AFSC) Supplement AFR 80-23, Draft
19 April 1983 (OPR: AF/ALTI)

More than 20 analysis and computation codes are discussed in the subsections that follow; the codes have been grouped according to the structure in Fig. 3. The first set, cull and coordination, describes procedures to determine the possibility of interference to ground stations caused by other ground stations or by space systems, and thence to coordinate frequency allocations according to the prescriptions of the ITU. The second, cosite analysis, considers interference among various equipments at the same approximate geographic location. The third category of codes, intrasystem EMC analysis, deals with interference induced in equipments from direct or wire couplings, and is devoted primarily to complex circuit analysis. The fourth category, intersystem EMC analysis, involves analyses and codes for determining interference produced by distant (far-field) sources, space or earth based. Most of these codes pertain to geosynchronous communications satellites, but some permit the consideration of any orbit. Included in this group is an extensive analysis, original to the Rand authors, of interference problems in nongeostationary systems. Codes and probability considerations are described, with mathematical details in Appendix B. The fifth category, electromagnetic vulnerability analysis, considers the behavior of complex communication networks under stress caused by intentional and unintentional interference, and the final group, multipurpose, describes programs which partake of several of the previously indicated categories.

The subject matter of these subsections was initially provided by persons from the companies or agencies where the analyses and codes were developed. The level of detail provided ranged from carefully structured presentations to simply sending programmer's manuals. The material was then modified, revised, and adjusted by the Rand authors to bring all presentations to approximately the same level of complexity. The revised versions were submitted to the originating authors for approval. Each subsection acknowledges the provider of the original material. If no individual is cited, the Rand authors either extracted the information from books or equivalent or are presenting their own investigations.

The subsections follow the same format, as listed below, although there are many differences in detail.

Program Source and Purpose

- Who developed it for whom
- When it was developed or became available
- Program users

Code Description and Capabilities

- Analytical material
- Required inputs
- Detailed code structure
- Typical outputs
- Special features and limitations
 - Orbits
 - Frequency limitations
 - Antenna patterns included
 - Propagation models
 - Special algorithms

Program Software

- Language
- Computer type
- Size of program
- Support software required
- Computer storage and memory

Execution time for particular runs

Problem size limitations

Documentation

Individuals to Contact for Additional Information

The character of the original material did not always permit adjustment to the format, so some sections are primarily analytical, others mainly code detail. The Rand authors take responsibility for the description of the subject matter, but are not in a position to define or guarantee the accuracy of the various codes when they are used for specific investigations.

B.2 CULL AND COORDINATION MODELS

Cull models are procedures for excluding clearly non-interfering cases from extensive investigations of interference. Coordination models pertain to the coordination of frequency assignments among potentially interfering systems. Since culling of non-interfering cases is employed in every treatment of interference problems, we shall not consider cull models separately, but only describe coordination models in this section.

B.2.a ITU RADIO REGULATION APPENDIX 28, AUTOMATION¹

Introduction

Before a new satellite communications system is placed in operation, it is necessary to coordinate its proposed frequency usage with any other system which might be affected. The potential interference may involve space systems in mutual interference with terrestrial systems, or space systems interfering with each other. The International Telecommunication Union (ITU) has developed regulations for such situations (ITU Radio Regulations, Chapter IV, Article 11), and procedures for determining if the interference may be significant (ITU

¹Original material was supplied by T. M. Sullivan, IIT Research Institute, DoD, Electromagnetic Compatibility Analysis Center (ECAC), Annapolis, MD 21402; published in the ECAC *Proceedings of the Conference on Space Systems Data Bases and Analysis Capabilities*, November 17-19, 1981.

Radio Regulations, Appendices 28 and 29). We shall describe the required calculations and the techniques for automation that have been developed at ECAC. The material presented here is specifically applied to the procedures associated with ITU Appendix 28.

Appendix 28 applies to coordination of frequency assignments to a satellite system earth station in relation to terrestrial stations, or vice versa. It contains criteria relating only to coordination between earth stations and stations in the fixed or mobile services. Those stations which may interact must coordinate their assignments through the International Frequency Registration Board (IFRB). The necessary information should be sent to the IFRB two to five years before bringing into service each satellite network of any planned system.

The basic concept used for management of frequency assignments is the coordination area. The coordination area around a receiving earth station is the area that contains all transmitting terrestrial stations that are potential interferers. Similarly, the coordination area around a transmitting earth station is the area that contains all receiving terrestrial stations that are potential victims of interference. The cases of transmission and reception by an earth station are treated separately and generally result in differing coordination areas.

The coordination area concept is used to identify potential interference interactions between a specific earth station and environmental terrestrial stations. When a new earth station frequency assignment is planned, the corresponding coordination area is used to indicate the requirements for detailed electromagnetic compatibility (EMC) analyses for terrestrial stations. When a new terrestrial station frequency assignment is planned, it is necessary to determine if the terrestrial station site is within a coordination area for an earth station sharing the same frequency band. These coordination area applications are made on U.S. national and international levels.

The procedure for calculating coordination areas is contained in ITU Appendix 28. This procedure is applicable to all earth station types in the fixed or mobile services (except those that are airborne), regardless of the flight plan of the associated space platform. The Appendix 28 procedure is applicable to troposcatter and line-of-sight systems and to the frequency bands between 1 and 40 GHz.

Calculation Approach

The coordination area is defined as that region on the earth's surface which includes the locations of all possible interferers or interference victims. Many worst-case assumptions are incorporated in the analysis. The calculations result in critical distances for particular azimuths from an earth station. These distances--the coordination distances--measure the maximum range at that azimuth such that interference may be expected from a source within the range, and interference-free behavior may be expected if the separation of source and victim exceeds the range. The locus of points at these coordination distances form a coordination contour that contains the coordination area.

The level of interference at a victim produced by a source depends on at least the following quantities: frequency, power, bandwidth, antenna gain, propagation loss, and receiver sensitivity. In the frequency region under consideration (1-40 GHz), interference may take place along a direct path, line-of-sight propagation and be affected by ducting, superrefraction, or diffraction, or along an indirect path in which the signal is scattered by rain into the victim receiver. The direct path is referred to as Mode 1, the rain-scatter path as Mode 2.

The following calculations result in a coordination contour:

- Determine the maximum permissible level of interference at the victim receiver; the level depends primarily on receiver sensitivity.
- Determine the limiting basic transmission loss for direct-path propagation (Mode 1). This is defined as the transmission loss between the interferer, whose power, transmission spectrum, and antenna pattern are specified, and the receiver such that the maximum permissible level of interference is induced.
- Calculate the range between interferer and victim which produces the limiting basic transmission loss. This range depends on frequency, since the attenuation per unit distance is a function of frequency (the greatest attenuation in the

1-40 GHz region for these terrestrial paths occurs near 22 GHz). It also depends on the presence of ducting or super-refraction, which occurs most frequently for over-water propagation, and of diffraction, which results from obstacles in the beam. If the earth station is pointed toward a satellite, its antenna pattern for interference will be azimuth-dependent, as will that of the terrestrial interferer. The coordination range will depend on all of these parameters. Since satellite communications systems generally transmit on one frequency and receive on another, the coordination ranges for transmission and reception will be different. The greater of the two ranges is used to calculate the contours.

- Repeat the calculations for hydrometeorological scatter propagation (Mode 2). This will depend on frequency (the scattering cross-section of rain varies with frequency), and on the position of the rain cell with respect to the transmitter and receiver, which requires a suitable averaging process. The occurrence of rainfall sufficiently intense to produce scatter propagation is dependent on geography. These quantities permit the calculation of a Mode 2 contour.
- Compare the Mode 1 and Mode 2 distances for each azimuth. The greater of these distances is the coordination distance for that azimuth.
- Determine the envelope of the coordination distances; it will be the coordination contour.
- The types of path geometry for the two modes are depicted in Figs. 4 and 5, the corresponding coordination contours in Figs. 6 and 7, and the envelope contour in Fig. 8.

Permissible Level of Interference

The interference criteria used in Appendix 28 are an interference-to-noise power ratio (INR) and a percentage of time for which the INR may be exceeded. The noise used in the INR is thermal noise only, which is typically only a small part of the total system noise. Consequently, fairly large INR values (e.g., 33 dB) are prescribed in Appendix 28, but these may be exceeded for only small percentages of time (e.g., 0.01).

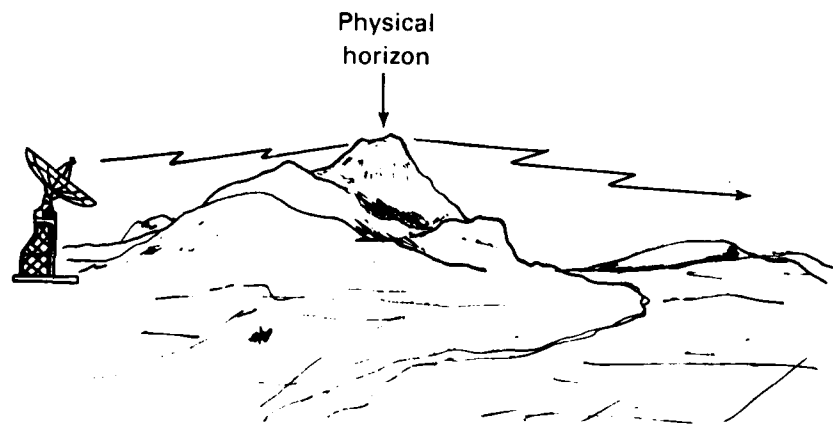


Fig. 4 — Signal path geometry—propagation Mode 1

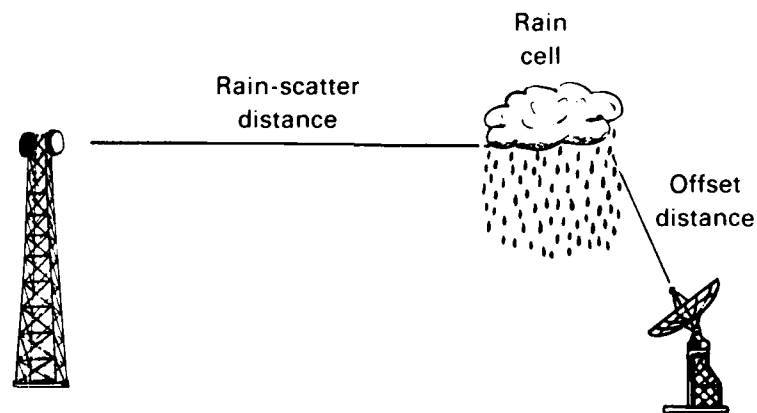


Fig. 5 — Signal path geometry—propagation Mode 2

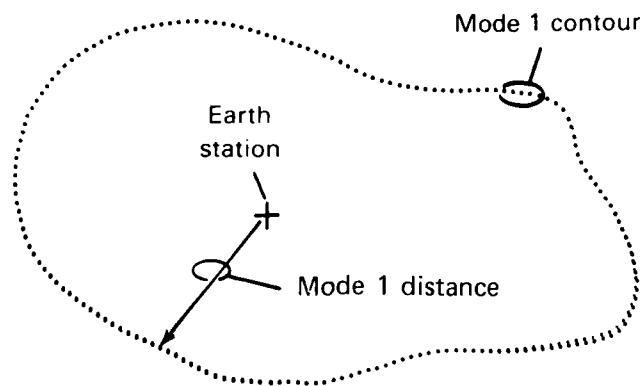


Fig. 6 — Coordination contour—propagation Mode 1

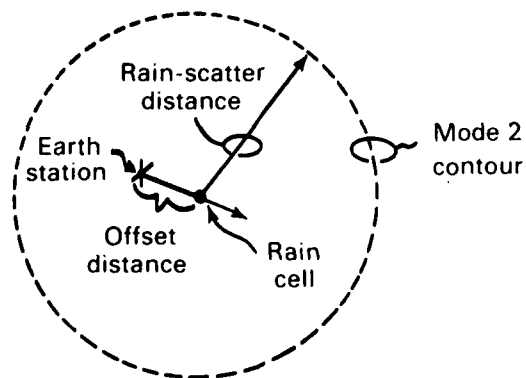


Fig. 7 — Coordination contour—propagation Mode 2

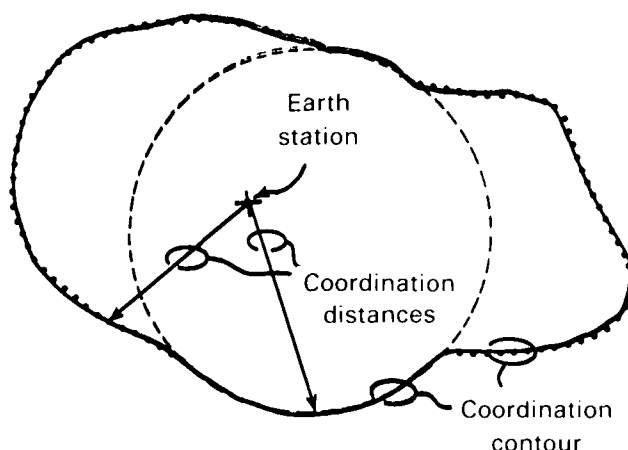


Fig. 8 -- Envelope coordination contour

In the calculation of the maximum permissible level of interference, the percentage of time associated with the INR is divided equally among an assumed number of uncorrelated interference entries. This prevents the depletion of the entire interference budget by a single interferer in cases where more than one interference source is anticipated.

The interference criteria for a typical terrestrial radio-relay receiver must be assumed since the actual station-specific parameter values are not known when coordination areas are calculated. These typical terrestrial station interference criteria are prescribed in Appendix 28. Typical INRs and associated time percentages are provided for receiving earth stations. The thermal noise temperature must be supplied for the earth station receiver under consideration. For receiving earth stations, departures from the prescribed typical INR time percentages and reference bandwidths are permitted. The interference criteria for typical receiving earth stations and terrestrial stations are taken from noise budgets for the hypothetical reference circuits in the International Radio Consultative Committee (CCIR) Recommendations.

Propagation Analyses

The Mode 1 propagation analysis considers interfering signals traveling over great-circle paths. The Mode 1 propagation mechanisms consist of ducting, superrefraction, and diffraction and are the dominant means of propagation for the small time percentages associated with the interference. Loss is calculated for several azimuths from the earth station site using the maximum permissible level of interference, an assumed typical terrestrial station antenna mainbeam gain, and a CCIR reference antenna pattern or a measured antenna pattern for the earth station. The use of the typical terrestrial station antenna mainbeam gain is a worst case provision. Typical spectral power densities are assumed for terrestrial transmitters for the case of receiving earth stations. Actual earth station spectral power densities are used for the case of transmitting earth stations. Mode 1 distances are calculated using a simplified, but conservative model for the Mode 1 mechanisms. The diffraction losses are determined as a function of frequency and the physical horizon angle (i.e., the angle between the visible terrain horizon and a horizontal plane tangent to the earth at the earth station site). The ducting and superrefraction losses are dependent on the radio climatic zones through which the interfering signal may propagate. The earth has been divided into three radio climatic zones that are characterized by typical atmospheric water vapor concentrations and duct-leakage parameter values. The locus of points at Mode 1 distances from the earth station forms a Mode 1 contour.

The Mode 2 propagation analysis considers rain-scatter paths, which consist of two components: the path from the earth station to the (hypothetical) rain cell and the path from the rain cell to the terrestrial station. A minimum required normalized transmission loss is calculated under the assumption that the entire earth station antenna mainbeam is intercepted by the rain cell. The required transmission loss is normalized to 4 GHz, a terrestrial station antenna mainbeam gain of 42 dBi, and 0.01 percent of time. The distance between the terrestrial station and the rain cell is calculated first using radiometerological parameter values for the rain climate of the earth station site. The earth has been divided into five rain climate zones

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TECHNIQUES FOR THE ANALYSIS OF SPECTRAL AND ORBITAL
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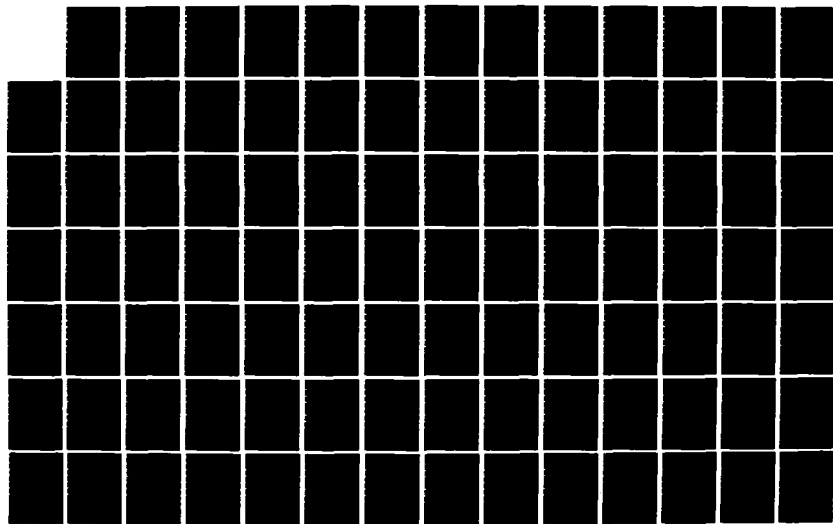
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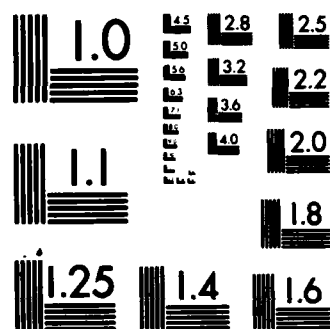
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that are characterized by typical rainfall rates, rain cell heights, rain attenuation coefficients, and rain cell diameters. Only the backscatter distance is calculated and used as the worst case distance for all azimuths from the rain cell toward possible terrestrial station sites. The distance between the rain cell and the earth station is then calculated using the earth station antenna mainbeam elevation angle and the rain cell height. This distance is measured from the earth station in the mainbeam azimuth to locate a hypothetical rain cell location. The locus of points at the backscatter distance from the rain cell forms a Mode 2 contour (i.e., a circle centered on the rain cell).

Coordination Area

The envelope of the Mode 1 and Mode 2 contours form the coordination contour that contains the coordination area. Any terrestrial station that operates in this coordination area in the frequency band of the earth station could cause or experience interference. Detailed EMC analyses are required to determine the actual possibilities for interference.

Automation of Calculations

The preparation of Appendix 28 Coordination Contours is a complex, time-consuming task if done by hand. At the National Telecommunications and Information Administration (NTIA) the preparation of some 300 contours will be required to up-date the NTIA Manual in accordance with the post WARC-79 Radio Regulations. Considerable amounts of time can be saved by computerized automation of the following activities:

- Repetitive calculations
- Determination of horizon elevation angles from terrain surrounding the earth station site
- Assembly and look-up of data from tables
- Determination of climatic zones
- Plotting of contours on maps

Propagation Analyses

The Mode 1 propagation analysis considers interfering signals traveling over great-circle paths. The Mode 1 propagation mechanisms consist of ducting, superrefraction, and diffraction and are the dominant means of propagation for the small time percentages associated with the interference. Loss is calculated for several azimuths from the earth station site using the maximum permissible level of interference, an assumed typical terrestrial station antenna mainbeam gain, and a CCIR reference antenna pattern or a measured antenna pattern for the earth station. The use of the typical terrestrial station antenna mainbeam gain is a worst case provision. Typical spectral power densities are assumed for terrestrial transmitters for the case of receiving earth stations. Actual earth station spectral power densities are used for the case of transmitting earth stations. Mode 1 distances are calculated using a simplified, but conservative model for the Mode 1 mechanisms. The diffraction losses are determined as a function of frequency and the physical horizon angle (i.e., the angle between the visible terrain horizon and a horizontal plane tangent to the earth at the earth station site). The ducting and superrefraction losses are dependent on the radio climatic zones through which the interfering signal may propagate. The earth has been divided into three radio climatic zones that are characterized by typical atmospheric water vapor concentrations and duct-leakage parameter values. The locus of points at Mode 1 distances from the earth station forms a Mode 1 contour.

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ECAC has developed a batch computer program for the repetitive calculations and the determination of horizon elevation angles by using a terrain data base. NTIA is using this batch program as a basis for an interactive on-line capability that incorporates the automation of all the above mentioned activities. The use of the program has been simplified to the point that a coordination contour can be generated from seven basic data items. The user provides inputs to the program by answering English language questions on a cathode-ray tube (CRT) terminal.

Some of the important features of the ECAC batch program are:

- It performs the repetitive calculations required for each of 360 azimuths around the earth station;
- It accesses the terrain data base to obtain horizon elevation angles;
- It automatically calculates the auxilliary contours described in annex 1 of Appendix 28;
- It provides tabular output;
- It requires batch (punched card) input;
- It handles mobile earth stations.

Among the additional features of the NTIA interactive program are the following calculations and retrievals that are performed once per earth station analysis:

- Calculation of antenna diameter approximation given antenna gain;
- Calculation of antenna azimuth and elevation pointing angles given earth station location and satellite location;
- Retrieval of interference and terrestrial station parameters for Tables 1 and 2 of Appendix 28;
- Determination of radio climatic zones;
- Determination of rain climatic zones of earth station location;

- Interpolation of horizon elevation angles to fill in missing data points;

and these enhanced outputs:

- Automatically scaled plots of coordination contours on map (your choice of any combination of contours);
- CRT preview of the plot;
- Computer disc file storage of all parameters and results, allowing recreation of the complete run environment any time and rerun of an analysis with the change of a single data item.

The incorporation of the above calculations and retrievals allows the simplification of the input to the point that a complete analysis can be performed with only seven basic data items input by the user. The seven basic data items,

- Earth station name,
- Earth station location,
- Earth station operating frequency,
- Service designation/station class,
- Receiver noise temperature or transmitter power,
- Earth station antenna gain, and
- Earth station antenna pointing angles or satellite location,

are supplied by the user as responses to English language questions. Included with the questions, as needed, are descriptions of the data items and how they should be entered. Extensive error checking is performed on the data items as they are entered. All parameters, other than the seven above, needed for the calculation are obtained automatically from internally maintained tables, data bases, or calculations.

Since only seven basic data items are required to activate this analysis system, it is ideally suited to linkage with a data base as long as that data base contains data for each of the seven required inputs.

Because of the numerous worst-case assumptions, the coordination areas established by these procedures should be regarded as outer limits, that is, an interferer located outside the contour is very unlikely to produce significant interference. A transmitter inside the contour, which would nominally be a source of interference, may actually not be significant if the worst-case conditions are not met.

For further information on Appendix 28 automation, please contact Thomas M. Sullivan, IIT Research Institute, DoD Electromagnetic Compatibility Analysis Center (ECAC), North Severn, Annapolis, MD 21402.

B.2.b ITU RADIO REGULATION APPENDIX 29, AUTOMATION²

Introduction

The International Telecommunication Union has established procedures for coordinating frequency assignments among communications systems to reduce and if possible eliminate mutual interference. The circumstances under which coordination is required are specified in the ITU Radio Regulations, Article 11, and the detailed techniques for calculating interference appear in Appendices 28 and 29. Appendix 29, the subject treated here, pertains to mutual interference among satellite networks.

All geostationary and nongeostationary systems must publish their frequency assignments in advance of operation. Coordination is required for certain geostationary networks and for earth stations with coordination contours (Appendix 28) extending into the territory of a foreign country. Agreements on frequency use must be reached by the several countries, and the ensuing assignments must be registered with the International Frequency Registration Board.

This section discusses the specific calculations in Appendix 29, and the procedures for automation which have been developed at NTIA.

²Original material was supplied by P. C. Roosa, Jr., NTIA; published in the *ECAC Proceedings of the Conference on Space Systems Data Bases and Analysis Capabilities*, November 17-19, 1981.

Calculations Required for Coordination

Appendix 29 was developed and incorporated in the Radio Regulations at the 1971 World Administrative Radio Conference (WARC) and modified by the 1979 WARC. It includes procedures for two cases: networks which share frequency bands in the same direction, i.e., up-paths and/or down-paths in the same direction, by far the most common case; and networks which share frequency bands in the opposite direction, e.g., the 8025-8400 MHz band is allocated to the fixed-satellite service for an up-path and to the meteorological-satellite service for a down-path. The Appendix provides procedures for calculation of apparent increase in receiver noise temperature due to interference from other satellite networks. The interference is assumed to be noise-like and, hence, to cause an increase in the noise level. The increase in noise temperature or ΔT is then compared to the appropriate receiver noise temperature, T , before the interference is included.

The interference may enter the system in several ways. Up-path interference occurs when a signal from an interferer is received at the satellite associated with the victim, and is then transmitted directly to the victim earth station. The interfering source is usually an earth-based transmitter, but may be another satellite. Down-path interference occurs when a signal from an interfering satellite is transmitted (usually via antenna sidelobes) to a victim receiver. Appendix 29 provides equations for calculating the interference received and converting that to an equivalent change in receiver noise temperature.

The regulations state that coordination is necessary if the fractional change in receiver noise temperature ($\Delta T/T$) exceeds 4 percent. This is equivalent to a signal-to-interference ratio of -14 dB. The theory of Appendix 29 shows that the equivalent noise temperature depends upon the transmitted powers, antenna gains in the relevant directions, and free space transmission losses. The satellite system may be either a simple receiver, which usually carries either commands or data, or a frequency-changing transponder, in which the signal is received, translated in frequency by a fixed amount, amplified, and retransmitted. The latter is the normal system for fixed-satellite service networks. Appendix 29 gives the appropriate equations

for the two cases, and provides algorithms for polarization isolation, topocentric and geocentric angles for antenna calculations, distances to satellites and between satellites, free space path loss, and the standard CCIR antenna radiation patterns for mainbeam sidelobes.

The calculations involved in Appendix 29 are in reality quite straightforward. The only complexity is due to the large number of calculations that must be made for every geostationary satellite network. Each network in the fixed satellite service involves many transponders and each transponder can serve many earth stations. Each earth station or space station of a network must be analyzed to determine whether coordination is necessary with any of the networks whose earth and/or space stations can be "seen" by the interfering network stations. The calculations are virtually identical to those of the programs employed for intersystem EMC analysis.

NTIA Automated Appendix 29 Procedures

To assist EMC analysts and others who are trying to determine if coordination is required between space systems, NTIA has developed two Appendix 29 automated aids. The first is implemented on a TI-59 programmable calculator. The program provides only the basic calculations and does not yet include on-line calculation of interim values. The names of the variables are as similar as possible to those used in Appendix 29 itself. All variables are entered in decibel notation except for the noise temperature, which is entered in degrees Kelvin. This program is appropriate for analysis of single paths or proposed changes to a network.

The second automated version is a data-base-oriented, Fortran-coded series of programs implemented on NTIA's HP-1000 mini-computer. It provides automatic calculation of all the variables in Appendix 29. It is interactive and will automatically calculate all possible interactions of the networks being investigated. There are two main programs. The first creates a data base containing all the necessary characteristics for each network except those which are peculiar to the particular interference interaction to be analyzed. The data base permits all interactions involving a particular network to be analyzed after the data have been entered once. The second program performs the

Appendix 29 calculations and requires only the specific characteristics peculiar to that interaction to be entered to supplement the existing data base.

It is expected that both the HP-1000 and TI-59 programs will be very useful in processing new foreign and domestic geostationary satellite systems. The HP-1000 program will be used primarily to provide detailed calculations for all interactions involving a new geostationary network, whereas the TI-59 version will be most useful for analysis of parametric changes to specific interactions.

For information on how to obtain and use these programs please contact Paul Roosa or Edward Davison at NTIA, Herbert C. Hoover Building, Rm 4600, 14th and Constitution Avenue, NW, Washington, D.C. 20230.

B.2.c GROUND MOBILE SATELLITE TERMINALS³

Introduction

An automated coordination procedure has been developed for performing the detailed area interference analysis necessary to site a mobile or transportable earth terminal. The procedure is based on the International Radio Consultative Committee (CCIR) protection contour concept, but has not been accepted internationally. National acceptance has been achieved in the United States and the Federal Republic of Germany (FRG), and the procedure is now being used to coordinate and site Ground Mobile Forces Satellite Communication (GMFSC) earth terminals in these two countries for training operations.

The automated area coordination procedure is described here. After a brief overview of the basic system parameters of the GMFSC Multi-Channel Initial System (MCIS) SHF earth terminals, the need for a new coordination and site selection procedure is explained. The description of the procedure developed, the Protection Contour Map program, includes how the analysis is performed, its outputs, and how the outputs are used.

³Original material was supplied by G. J. Romanowski, ECAC/IIT Research Institute; published in the *ECAC Proceedings of the Conference on Space Systems Data Bases and Analysis Capabilities*, November 17-19, 1981.

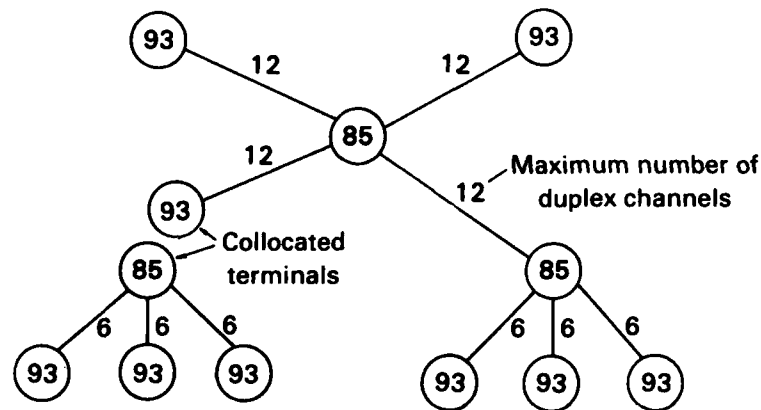
GMFSC MCIS Overview

The MCIS earth terminals are in the Low-Rate Initial Production (LRIP) phase of development. There are three basic LRIP earth terminal types: the AN/TSC-85 and AN/TSC-93 Army terminals and the AN/TSC-94 Air Force terminal. Other terminal types will be added in the full production phase. Some of the key points of the system parameters are the commonality of RF characteristics, the small antenna dimension, and the multichannel capability. All equipments receive in the 7.25-7.75 GHz band and transmit in the 7.90-8.40 GHz band.

The MCIS earth terminals are housed in truck-mounted shelters with ground-deployed antennas. The antenna is designed for rapid installation and disassembly to meet the rapid deployment requirements for a tactical system. This makes the system highly transportable, but not mobile.

The basic link configuration for the Army earth terminals consists of a hub/spoke arrangement. The AN/TSC-85 earth terminals are the hub terminals and can support one uplink signal and four downlink signals, for a total capacity of 96 channels. The AN/TSC-93 terminals are the spoke terminals and can support one uplink and one downlink signal of up to 24 channels. The earth terminals can also operate in a point-to-point mode, as the Air Force LRIP earth terminals are limited. Figure 9 shows a typical link configuration.

The GMFSC MCIS earth terminals operate with the Defense Satellite Communications System (DSCS) Phase II satellites. In the future, the DSCS Phase III satellites will be used. The MCIS earth terminals must operate with the satellite transponders that are connected to the high-gain satellite antennas for the uplink and downlink because of the small earth terminal antennas. Therefore, the 185 MHz transponder is shared for Phase II operations and the 60 MHz transponder is used for Phase III operations.



Key: 85 = AN/TSC-85 terminal and 93 = AN/TSC-93 terminal

Fig. 9 — Typical GMF earth station link configuration

Coordination and Site Requirement

The frequency ranges allocated to the GMFSC earth terminal are not within the exclusive satellite bands. The bands used by the GMFSC system are shared with terrestrial fixed and mobile stations. Therefore, coordination is required with these in-band systems for host country frequency coordination and for selection of compatible operating sites.

Although ITU Appendix 28 procedures can be used to develop coordination contours about the operating areas, no internationally accepted procedure exists for performing the detailed coordination for selecting operating sites. An automated interference model was developed by ECAC to perform the required terrestrial station versus earth terminal analyses. This model was based on the protection contour concept documented in CCIR Report 773, and is referred to as the Protection Contour Map (PCM) program.

PCM Program Description

The terrestrial-station environment must be identified before the PCM program can be brought into play. Coordination contours are developed around the specified operating area for earth terminal transmitting and receiving. Then the terrestrial station receivers (for the earth terminal transmitting) or the terrestrial station transmitters (for the earth terminal receiving) located within the appropriate contour will be compiled for analysis by the program. The RF and site characteristics of the terrestrial stations are required by the program for accurate computation of the interference-to-noise ratios (INR).

The program must analyze the electromagnetic interaction of the earth terminal versus the terrestrial station environment for the earth terminal anywhere within the operating area. This is accomplished by analyzing the potential EM interactions for the earth terminal at a large number of discrete locations. The program constructs a grid of hypothetical earth terminal locations within the operating area. Then, each grid point is separately analyzed for potential EM interactions with every terrestrial station. For example, a 16 row by 16 column earth terminal grid and 17 terrestrial stations yield 256 earth terminal locations considered and 4352 separate interactions analyzed (i.e., 256×17). This configuration is depicted in Fig. 10.

Considering one particular grid location, the program computes the INR level versus each terrestrial station. If the earth terminal is transmitting, the INR level at each terrestrial station is computed and the largest value is stored for that grid point. For the reverse case, the program will either store the largest INR value computed or a composite INR value obtained by a summation of all the received power levels.

The INR values are computed by considering the transmitter power, transmitter and receiver antenna gains, propagation loss, frequency-dependent rejection, and receiver noise level. The ECAC terrain dependent model is used for computing propagation losses over great circle paths. A rain scatter model computes propagation losses due to precipitation scattering.

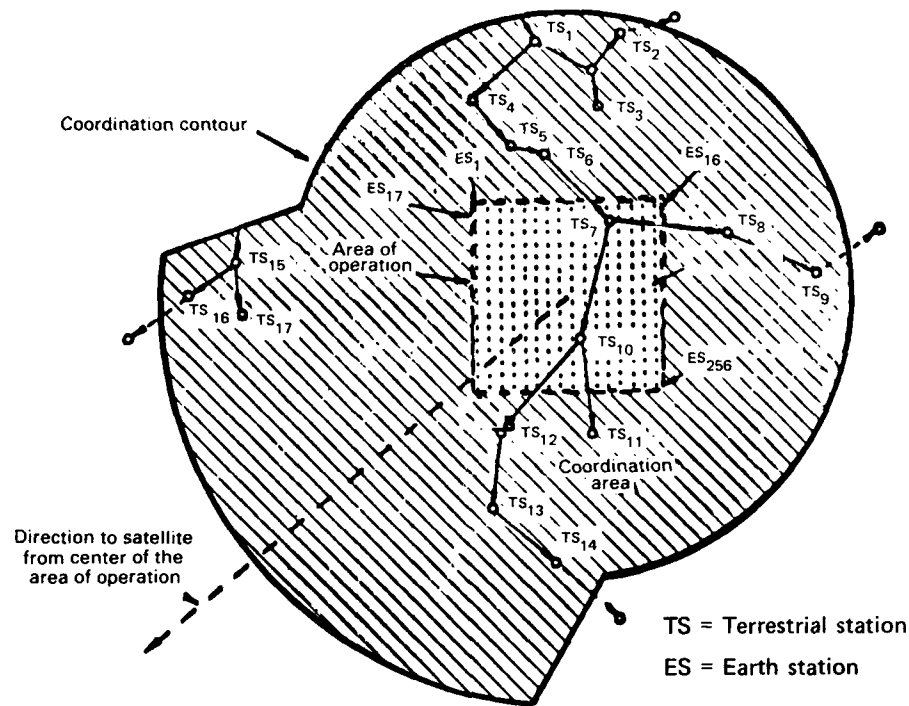


Fig. 10 — Coordination contour for transportable earth stations

When all the grid locations have been considered, there will be a resultant INR value associated with each grid point. An INR threshold will be selected, and a continuous contour will be drawn within the operating area such that the regions above the threshold will be separated from those below the threshold. The former regions will be cross-hatched and are referred to as protection areas. The latter regions are denoted as clear areas, where the earth terminal can compatibly operate for the operating parameters used to develop the output. The contour map outputs are referred to as PCMs. The contours are envelopes within which the system earth terminals will be free from interference.

The frequency-dependent rejection between a transmitter emission spectrum and a receiver selectivity causes the PCM protection regions to be very frequency sensitive. Small changes in the operating frequency

of the earth terminal may cause large changes in the computed protection areas. Similarly, changes in the bandwidth of the earth terminal emission spectrum or receiver filters may result in large protection area changes. Therefore, PCMs are made for all anticipated operating frequencies, using operating characteristics which will yield conservative protection areas to produce PCMs which will provide user flexibility and realistic clear areas. Figure 11 shows an example of the change in the coordination contour produced by an increase in data rate, which requires greater bandwidth and thereby brings more terrestrial stations into potential interference.

PCMs are currently being produced for operating areas in the U.S. and the FRG. A PCM set is generated for each area considered, where a set consists of a PCM for each uplink and downlink frequency of the GMF frequency plan. As stated previously, the production of PCM sets provides the user with the maximum flexibility for frequency and site selection.

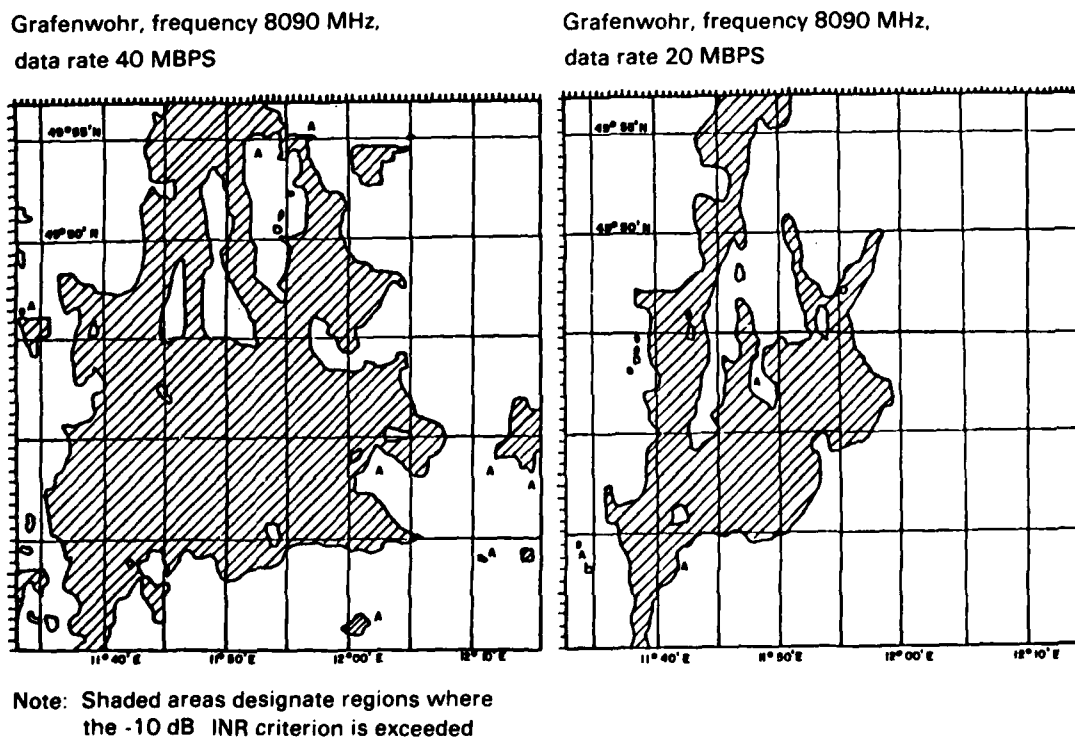


Fig. 11 — Protection contour map examples

With the PCMs, users can effect any required national or international coordination. The PCMs establish that there are or are not compatible operating locations within the specified areas. Then the users can use PCMs to select specific operating frequencies and locations for deploying earth terminals within the appropriate operating areas.

For U.S. and FRG training deployments, the PCMs have supported coordination and site selection, as described above. The only problem encountered is the inability of the initial PCM model to produce PCMs at the rate requested by the user community.

When it became apparent that the PCM approach was successful and that the initial capability was inadequate for operational support, a new capability was designed. The new system, called the Operational Spectrum Support Cell (OSSC), consists of an improved PCM generation program operating on a computer system dedicated for this effort. Although the OSSC VAX 11/780 computer is slower than the ECAC UNIVAC 1100/EC computer (the computer used for the initial capability), the dedicated system and enhanced software tailored to the VAX 11/780 yield faster program execution. Also, additional steps of the PCM generation process have been automated to yield even greater time savings.

The OSSC is expected to meet the GMFSC deployment and contingency engineering support needs for the MCIS earth terminals through 1983. Efforts are under way to determine if an additional or enhanced capability is needed to meet future the support requirements.

For further information on mobile terminal coordination contours, please contact Richard Larson, DoD Electromagnetic Compatibility Analysis Center (ECAC), North Severn, Annapolis, MD 21402.

B.3 SPACE SYSTEMS AND COSITE ANALYSIS⁴

Cosite Effects

This section provides a brief introduction to cosite analyses and discusses their relationship to space systems. "Space systems" are the

⁴Original material was supplied by L. Apirian, ECAC/IIT Research Institute; published in the *ECAC Proceedings of the Conference on Space Systems Data Bases and Analysis Capabilities*, November 17-19, 1981.

ground segment (earth terminals), mobile segment (airborne or shipborne terminals), and space segment (satellites).

Cosite analysis is concerned primarily with system proximity interactions. Only radiated (far-field) interference interactions are considered; they include intermodulation, spurious responses and emissions, desensitization, gain compression, cross-modulation, cochannel and adjacent channel effects, burnout, case penetration, and external intermodulation. These effects are all produced by nonlinear devices in the system; nonlinear devices can usually be represented by power series, which permit classification of the effects. The usual nonlinear device is a mixer or sequence of mixers, but nonlinear interaction can also occur in junctions outside the transmitter or receiver.

The first nonlinear effect, intermodulation, can occur in two ways. Interfering signals can mix to produce a signal at the tuned frequency that mixes with the local oscillator to produce a response at the intermediate frequency. For this to happen, a linear combination of positive or negative integer multiples of the interfering signal frequencies must match the input frequency. Or, the interfering signals can mix with the harmonics of the local oscillator frequency to produce a response at the intermediate frequency. The power series expansion produces these intermodulation terms, since the product of a number of sinusoidal functions can be expanded into a sum of sinusoids whose frequencies are linear integral combinations of the input frequencies.

Spurious responses are unwanted responses of a receiver to a signal at other than the tuned frequency. They result from nonlinearity in an early stage giving rise to harmonics of incoming signals, mixer nonlinearities giving rise to local oscillator and signal frequency harmonics, and from frequency multiplication in the local oscillator. Tuned radio frequency amplifiers or bandwidth limitations on antennas tend to eliminate such problems, but the interference may be caused by pickup which bypasses the input stages.

Desensitization and gain compression, which are closely related, reduce the desired signal output level due to nonlinear effects among the input signals. Desensitization is due to the interfering signal; gain compression is due to the desired signal. If the power series contains a third degree term with a negative coefficient, the output at the desired frequency will contain a term whose amplitude is proportional to the cube of the amplitude of the desired signal and has a negative coefficient, representing gain compression. Another term at the desired frequency has an amplitude proportional to the amplitude of the desired signal, and to the square of the amplitude of the undesired signal. This term also will have a negative coefficient, corresponding to desensitization, since the response to the desired signal is reduced by the presence of the interference. Furthermore, if there is modulation on the undesired signal, the third degree term will cause this modulation to appear on the desired signal, corresponding to cross-modulation.

Another nonlinear effect is external intermodulation. Also called the "rusty-bolt" effect, it occurs when signals combine in junctions outside the transmitter or receiver and are reradiated. The effect also occurs in ferromagnetic materials, whose nonlinear response, usually associated with hysteresis, produces signal mixing.

Burnout and case penetration effects result from high undesired signal levels. Burnout occurs when the input power to a device is sufficient to cause physical damage. Case penetration occurs when the electromagnetic field density incident at a receiver is high enough to couple with the internal circuitry, without passing through the antenna.

Two linear effects, not limited to cosite situations, may arise. Cochannel interference can occur when the emissions of two systems overlap such that the undesired carrier frequency falls within the receiver passband. Adjacent channel interference can occur when the systems do not actually overlap but the out-of-band emissions of one affects the selectivity of the other.

Cosite Analysis

Cosite analysis involves a quantitative assessment of the effects discussed above and includes computation of antenna coupling, propagation losses, interference thresholds or receiver performance, and interaction levels.

Nonlinear effects may be evaluated empirically or theoretically. In either case, the coefficients of the transfer functions of the nonlinear device are assessed. In theoretical analyses the power series expansion is frequently an oversimplification and a time varying transfer function must be used, particularly for strongly driven systems.

High power effects may be evaluated by comparing RF field levels with thresholds established for the device under investigation. The thresholds may be derived from measurement programs or from knowledge of the physical structure of the device.

Cochannel and adjacent channel effects can be evaluated by a consideration of relative bandwidths and off-tuning. The amount of the transmitted signal which is accepted through the receiver selectivity is assessed by convolving the emission spectrum with the receiver selectivity curves.

One way of studying cosite situations is through frequency analysis. In this manner, interaction levels are not evaluated but frequencies which may occur are computed. These data can be used to make compatible channel assignments and to identify problems.

Automated Models

Automated analysis techniques involve modeling one or more of the above procedures, most of which are complex and tedious to perform manually. Computer models are used to calculate nonlinear interaction levels, propagation losses, receiver degradation, interference frequencies, and antenna coupling in support of cosite analyses. Table 2 lists some of the automated models available at ECAC and useful for cosite analysis. The table describes their basic functions.

Table 2

ECAC AUTOMATED MODELS USEFUL FOR COSITE ANALYSIS

Automated Model Name	Functions and Comments
Avionics Interference Prediction Model AVPAK3	Computes coupling levels between antennas on an airframe. Models airframe as a group of perfectly conducting cones, cylinders, and planes.
Channel Assignment Analysis Algorithm C3A	Chooses compatible frequencies from a user-supplied list based on input constraints (i.e., minimum frequency separation, avoiding harmonics).
Cosite Analysis Model COSAM	Calculates receiver performance. Accounts for adjacent channel, spurious, and intermodulation effects, based on measured data. Environment can include up to 50 equipment units. Frequency range from 2-400 MHz for antenna coupling.
Frequency List Analysis Program FLAP	Searches for potential interference interactions among assigned frequencies (or frequency lists). Accounts for adjacent channel, spurious, and intermodulation effects based on user input constraints.
Nonlinear Communications Receiver Model NLRX	Determines intermodulation and spurious response levels. Also assesses transfer function coefficients, which are related to the measured data used in COSAM.
Performance Evaluation Communications Algorithm PECAL	This version of COSAM has been modified to account for propagation on a shipborne environment.

Fundamental limits of the models are based on the validity range of the underlying assumptions, allocated storage space, and required computer time. These manifest themselves as limits on:

- the number of equipments allowed in an environment,
- the number of available frequencies,
- the allowable frequency range,
- the effects evaluated,

the allowable orders of interactions, and
the types of equipment considered.

No single model can perform a complete cosite analysis, just as no single model is applicable to every cosite analysis. To perform a comprehensive cosite analysis the appropriate models in Table 2 are used in conjunction with each other.

Space Systems Cosite Analysis

It is not expected that space systems will cause fundamentally new types of cosite problems, although the characteristics of space systems make them particularly vulnerable to communications interactions. New technology developments and modulation techniques will also require new methods of analysis.

Fixed and mobile earth terminals tend to have large, high gain antennas and low noise temperatures and therefore extreme sensitivities compared with most nonspace systems. For example, shipborne and airborne satellite terminals require very careful coordination to operate compatibly with other on-board equipment.

Mobile platforms impose severe cosite constraints. Many transmitters and receivers are proximal, leading to high coupling levels. Additionally, propagation analysis may be difficult due to platform construction, e.g., reflections, diffractions, and skin effects. External intermodulation may occur and is generally unpredictable. Channel assignment will be difficult due to the high number of interactions that must be considered.

Satellite cosite analyses are currently left to the developers--all elements of a system must work together. Concepts now under consideration may change the situation, however. Specifically, if satellite clusters and antenna farms are developed, cosite analysis will be required. If these systems have several developers, the government may take overall responsibility for electromagnetic compatibility, a case analogous to mobile platforms.

If further information on the cosite analysis programs developed at ECAC is desired, please contact Richard Larson, DoD Electromagnetic Compatibility Analysis Center (ECAC), North Severn, Annapolis, MD 21402.

B.4 INTRASYSTEM EMC ANALYSIS⁵

Electromagnetic compatibility considerations can be divided into two generally separated but sometimes overlapping areas: *intrasystem* and *intersystem*. Intrasystem EMC is concerned with compatibility within a system consisting of electrically interconnected equipments and/or equipments in proximity within a describable geometry, such as those within a single aircraft, spacecraft, or ground station. The interference coupling modes are usually varied and complex. Intersystem EMC is concerned with compatibility between systems that generally operate remotely and whose primary interference coupling media is through antennas. Examples are compatibility between spacecraft and ground stations or between an aircraft and its tactical control center.

Intrasystem electromagnetic incompatibilities are caused when unwanted electromagnetic energy from emitters (interference) finds its way to circuits that are undesired receptors (susceptible) to this energy. While interference is always undesirable to the susceptible circuit, this same energy may be required as functional energy by some other circuit in the system. A digital signal can be a desired functional signal and at the same time appear as interference to a susceptible circuit, such as an analog circuit. Thus, interference energy within the system can result from functional signals or from extraneous signals, such as the harmonic of a transmitter. Extraneous signals are generated as byproducts of the functional signals and are of no use to any other circuit. An EMC Intrasystem Analysis Program (IAP) has been developed by the Air Force Systems Command, Rome Air Development Center (RADC/RBCT), with contractor support. The EMC/IAP is a set of computerized mathematical models, listed and described below, which provide effective methodology for ensuring EMC among components of

⁵Original material for Sections B.4.a-d was submitted by J. J. Dobmeier, A. L. Drozd, and J. A. Surace, RADC/RBCTI. An expanded version was published by RADC in TR-83-101, May 1983. Original material for Section B.4.e was submitted by D. S. Rosen, TRW, Inc.

complex spacecraft, aircraft, and ground systems. The EMC/IAP and required documentation have been maintained by the EMC/IAP Support Center at Griffiss AFB, Rome, NY, operated by IIT Research Institute and sponsored by RADC.

The EMC/IAP Support Center was a contractor-run, government-funded organization operating since August 1978. Current subscribers and code users were furnished the latest updates of the codes, and supported in their usage, by the Center until 30 September 1983, when funding ended. After that date, questions regarding the EMC/IAP should be addressed to RADC/RBCT, Mr. Kenneth Siarkiewicz.

There are four separate programs associated with the EMC/IAP:

- Intrasystem Electromagnetic Compatibility Analysis Program (IEMCAP)
- General Electromagnetic Model for the Analysis of Complex Systems (GEMACS)
- Nonlinear Circuit Analysis Program (NCAP) and
- Wire Coupling Prediction Models

The four programs will be described in Sections B.4.a-d.

An intrasystem EMC analysis program developed by TRW, Inc., Specification and EMC Analysis Program (SEMCAP), will be described in Section B.4.e.

B.4.a THE INTRASYSTEM ELECTROMAGNETIC COMPATIBILITY ANALYSIS PROGRAM (IEMCAP)

Introduction

IEMCAP is a systems-level, computerized analysis program which may be used in analyzing electromagnetic compatibility for aircraft, spacecraft/missiles, or ground stations on both present and future systems. It acts as a link between equipment and subsystem EMC performance and total system EMC and provides the means for tailoring EMC requirements to specific systems. This is accomplished in IEMCAP through detailed modeling of the system elements as well as the various mechanisms of electromagnetic transfer to perform the following tasks:

- Provide a database which can be continually maintained and updated to follow system design changes
- Generate EMC specification limits tailored to the specific system
- Evaluate the impact of granting waivers to the tailored specifications
- Survey a system for incompatibilities
- Assess the effect of design changes on system EMC
- Provide comparative analysis results upon which to base EMC tradeoff decisions.

The IEMCAP program was developed and written by the McDonnell Aircraft Company, St. Louis, MO, for Rome Air Development Center (RADC/RBCT), Griffiss AFB, NY. The program and required documentation were released in 1974 and have been maintained by the EMC/IAP Support Center at Griffiss Air Force Base, operated by IIT Research Institute and sponsored by RADC. (See previous page for change effective 30 September 1983.) The program can be obtained from the Support Center along with supplementary products and services. The program is in broad use, with at least 21 governmental, 45 industrial, and 5 academic users.

The program incorporates state-of-the-art communications and frequency-domain EMC analysis mathematical models into routines which efficiently determine the spectra and evaluate the transfer modes of electromagnetic energy between generators and receptors within a system.

Code Description and Capabilities

The system model for IEMCAP employs the standard EMC approach of identifying all ports in the system having a potential for undesired signal coupling. These ports are divided into arrays of emitter ports and receptor ports having identifiable coupling paths.

All emitters in a system are characterized by emission spectra and all receptors are characterized by susceptibility spectra. All ports and coupling media are assumed to have linear characteristics. Emissions from the various emitter ports are assumed to be statistically independent so that signals from several emitters impinging at a

receptor port combine on an RMS or average power basis. Other waveform parameters that receptor ports are sensitive to include total energy (total energy susceptibility) and peak current (or voltage) and rise time (peak sensitivity considerations for digital-type devices susceptible to instantaneous waveform levels). These latter sensitivities may be included in IEMCAP.

Emitter and receptor ports may be intentional, such as connector pins, or unintentional, such as leakage paths. The signals or responses which are intentionally generated and coupled from port to port are operationally required and lie in a specified frequency range. There may be additional undesired outputs or responses. For example, an emitter may produce harmonics, or a receptor may have an image response, or a signal may be conveyed to the wrong port.

For each emitter port, a two-component spectrum represents the power levels produced over the frequency range. The broadband component, varying slowly with frequency, represents continuous emissions, while the narrowband component, varying rapidly with frequency, represents discrete emissions. A spectrum is determined for receptors that represents the susceptibility threshold over the frequency range. The susceptibility level is defined as the minimum received signal which will produce a desired response at a given frequency.

Outside the required frequency range, military standard levels are used to set the initial maximum emission and minimum susceptibility levels. IEMCAP uses specifications MIL-STD-461A and MIL-I-6181D (6181D has been superseded by 461A which in turn has been superseded by 461B). By adjusting the spectra of emitters and receptors for compatibility, the extreme level specifications are obtained which will produce a compatible system. To prevent the generation of too stringent specifications, each spectrum has an adjustment limit.

The general approach to the analysis is two-fold. First, an emitter-receptor port pair is selected and its type, connection, wire routing, etc. are quickly examined to determine if a coupling path exists. If a path exists the received signal is computed at the receptor and compared to the susceptibility level. In addition to the emitter-receptor port pair analysis, the program computes the total signal from all emitters simultaneously coupled into each receptor.

In conjunction with the above process, IEMCAP uses a sampled spectrum technique in which each spectrum amplitude is sampled at various frequencies chosen by the program and/or by the user across the range of interest. Considering the requirement of MIL-STD-461A of three frequencies per octave from 30 Hz to 18 GHz, this requires approximately 90 sample frequencies. To avoid missing narrow peaks between sample frequencies, IEMCAP samples the spectrum in the interval half-way between the sample frequency and each of its neighboring sample frequencies. For emission spectra, the maximum level in the interval is selected and assigned to the sample frequency in the interval and for susceptibility spectra the minimum level is selected and also assigned to the sample frequency in the interval. This effectively quantizes the spectra with respect to the sample frequencies.

The range of frequencies covered by the analysis is governed by the user. The program will accept any range from 30 Hz to 18 GHz, but if desired, the user may concentrate all 90 frequencies over a smaller interval within this range. These frequencies are applied to a given equipment which contains emitter and/or receptor ports.

Based on the defined conditions and overall analysis approach, an electromagnetic interference (EMI) margin is calculated. An incompatibility is said to exist when sufficient signal from an emitter port, or ports, is unintentionally coupled to a receptor port to exceed its susceptibility threshold.

EMI margins of value greater than 0 dB indicate interference. Values less than 0 dB indicate either compatibility or interference. Currently, IEMCAP spectrum models and transfer coupling models represent a worst-case approach to systems analysis and prediction of EMC/EMI. Although it is uncertain whether compatibility or interference actually occurs aboard a given system, in accordance with the worst-case philosophy of IEMCAP, the uncertainty has been minimized in selecting the interference margins included in IEMCAP.

A new port spectra algorithm is being considered to replace the quantization method in IEMCAP for modeling emitter and receptor spectra. Basically, this new model reduces to a requirement for automated generation of all frequencies and corresponding amplitudes for defining

the port spectra of an equipment. The equipment frequency table is generated by determining the required frequencies from prestored models; harmonics and nonrequired frequencies from appropriate MIL-STDs; and user-specified frequencies from IEMCAP input data. The port spectra amplitudes are computed from prestored emission and susceptibility models, harmonics, user-specified data, and prestored MIL-STD levels. Also, the frequency range for analysis is expected to extend from 0 to 50 GHz and greater. Currently, however, the 30 Hz to 18 GHz limitation is imposed on each port, which is categorized by function into one of six types (RF, signal, control, power, EED, case); each type has its own subinterval of frequencies within the overall range as adapted from MIL-STD-461/462. The nonrequired spectrum model routines will generate zero emission and susceptibility outside these subintervals.

A number of important system-level EMI problems result from nonlinear effects in emitters and receptors. At the present time, however, the IEMCAP considers only interference caused by power transferred linearly from emitter to receptor. To predict accurately all instances of possible EMI, IEMCAP will ultimately be expanded to include interference due to the following nonlinear effects, which are recognized to cause system performance degradation: receiver intermodulation, spurious responses, cross modulation, desensitization, and gain compression and gain expansion.

IEMCAP (currently in release 05) is designed for use by an EMC systems engineer with a minimum of computer experience. The input data requirements, program control, and output formats are engineering oriented and easily learned. The input data are directly obtainable from system and subsystem operational specifications or measured data. They include system types, overall physical dimensions, coordinate system parameters, and basic analysis parameters which apply to the entire system. Also included are common model parameter tables, which describe apertures, antennas, filters, and wire characteristics which have multiple use throughout the system. Subsystems are organized into a hierarchy of equipments (physical boxes such as transmitter units), source or emitter ports, receptor ports, and wire bundles which route signals among ports.

All user program control and data inputs to the program are on punch cards or card images and are in free-field format. Basically, the inputs are in the form of statements in which the parameters may be entered into any columns on the cards (card images). The basic format requires a keyword which identifies the type of data, an equals sign, and the relevant parameters separated by commas. The parameters and subparameters on these cards must be in a prescribed order and may represent numerics, alphabetic codes, or alphanumeric designations.

During execution, a number of printed outputs are generated by IEMCAP. If errors are found in the data during the input decode process, an appropriate error message is printed along with the data card that is in error (preprocessor error checking); additional error messages are printed during initial processing if errors are detected during file updating, generation of initial spectra, or wire-routing descriptions (postprocessing error checking).

After all input data have been read, decoded, and checked for errors, a listing of the input is provided. Also, during initial processing, a report of all the data that comprise the system for which the analysis task is to be performed is printed. This is the Intrasytem Signature File (ISF) report, consisting of a summary of the system, subsystem, and equipment data, followed by each equipment's frequency table and initial port spectra of each port in the equipment and, lastly, the bundle data.

Supplemental and debug output can also be requested. Such output is useful for following the logic in the wire-mapping routines by printing internal flags and messages to aid in software maintenance. The supplemental printout of the wire-mapping routines follows the normal bundle data output.

The first section of IEMCAP is the IDIPR module, which consists of four basic subprograms. The four subprograms are the Input Decode Routine (IPDCOD), Initial Processing Routine (IPR), Spectrum Model Routines (SPCMDL), and the Wire Map Routine (WMR).

The second section of IEMCAP, TART, uses the data compiled by IDIPR to perform the desired analysis task, which is one of the four tasks summarized below:

- *Specification Generation* adjusts the initial nonrequired emission and susceptibility spectra so that the system is compatible, where possible. The user-specified adjustment limit prevents too stringent adjustments. A summary of interference situations not controlled by EMC specifications is printed. The adjusted spectra are the maximum emission and minimum susceptibility specifications for use in EMC tests.
- *Baseline System EMC Survey* searches the system for interference. If the maximum of the EMI margins over the frequency range for a coupled emitter-receptor port pair exceeds the user-specified printout limit, a summary of the interference is printed. Total received signal into each receptor from all emitters is also printed.
- *Trade-off Analysis* compares the interference for a modified system to that from a previous specification generation or survey run. The effect on interference of antenna changes, filter changes, spectrum parameter changes, wire changes, etc. can be assessed from this.
- *Specification Waiver Analysis* shifts portions of specific port spectra as specified and compares the resulting interference to that from a previous specification generation or survey run. From this the effect of granting waivers for specific ports can be assessed.

TART is composed of two basic routines. The Specification Generation Routine (SGR) performs the first task above, and the Comparative EMI Analysis Routine (CEAR) performs the remaining three. These interface with the coupling math model routines to compute the transfer ratios between emitter and receptor ports. The two parts of IEMCAP are executed separately, with data files used for intermediate storage between parts.

IEMCAP determines if a coupling path exists between two ports. If a path exists, the appropriate transfer model routines are used to compute the transfer ratio of all frequencies of interest. The models consist of:

- *Antenna-Coupled Transfer.* This includes antenna-to-antenna and antenna-to-wire coupling on an aircraft (winged vehicle), a spacecraft (wingless vehicle), and over ground. Antenna models and shading (diffraction) models for propagation around wings and fuselage are included.
- *Wire-to-Wire Transfer.* These routines compute coupling within a wire bundle. Transfer models between open, shielded, and double-shielded wires with both balanced and unbalanced configurations are included.
- *Case-to-Case Transfer.* This model computes coupling resulting from electromagnetic leakage from equipment cases.
- *Filter Models.* These routines compute losses due to filters between the emitter and receptor ports and the coupling medium. Models for single-tuned stage, Butterworth, low-pass, and band reject filters are included.
- *Environmental Field Models.* These routines compute the coupling of external electromagnetic fields, if present, to receptor ports.

The TART baseline survey outputs are summaries of transfer ratios, received signal power at receptors, and EMI margins between emitter-receptor port pairs and consider the total received signal from all emitters into each receptor. The margins are printed for each frequency, and an integrated margin is also printed which represents the cumulative effect of coupling across the entire frequency range of interest.

The trade-off and waiver analysis outputs are similar to those of the baseline survey; these outputs illustrate the before and after effects of modifying system elements or shifting portions of the emitter and/or receptor spectra, respectively.

For Specification Generation Runs (SGR), the output format is similar to the baseline survey summary with the addition of emitter spectrum adjustment, receptor spectrum adjustment, unresolved interference, and final adjusted spectrum summaries. These summaries represent adjustments made to the initial nonrequired emission and/or

susceptibility spectra such that the system becomes compatible. The amount of adjustment is controlled by user inputs.

Supplemental outputs for any of the above analysis options may be obtained if requested. These additional outputs consist of antenna coupling propagation path factors involved in computing path loss (antenna-to-antenna), components of the transfer ratio involving coupling through apertures exposing receptor wires (antenna-to-wire), and capacitive and inductive coupling components per frequency (wire-to-wire).

The amount of standard output can be limited by special output control features such as an EMI margin printout limit value and/or port-suppress commands which inhibit the output on ports that are not of interest.

As presently constructed, IEMCAP is not directly related to orbits. The program pertains to the electromagnetic compatibility of the subsystems that comprise a particular system. It may be and has been applied to spacecraft. If the externally imposed fields are derived from the equations of earth-to-space propagation, or vice versa, the effect of orbital variations may be included. As discussed previously, the program covers the frequency range of 30 Hz to 18 GHz in sampled steps. Antenna patterns include low-gain antennas such as dipoles, which are modeled by trigonometric expressions, and high gain antennas such as paraboloids, which are modeled by a piecewise-constant function in the polar angle. The three constant values correspond to main beam, major sidelobe, and backlobe.

Propagation models include ground-wave antenna coupling and intravehicular propagation. For ground waves, a smooth earth surface is assumed, with a $4/3$ earth radius accounting for atmospheric refraction. The model is valid for frequencies between 1 MHz and 1 GHz and moderate antenna height. The height is limited by a plane earth approximation, which permits a two-ray optics solution. The simplified theoretical ground wave model is slightly modified to include the effect of the surface wave.

The intravehicular antenna-propagation model calculates the propagation loss associated with an electromagnetic coupling path when both source and receptor are located on the same aircraft or spacecraft.

Propagation is free-space, with near-field conditions (0 dB transfer gain) for antenna separations which are less than the maximum dimension of the transmitter or receiver antenna, and farfield conditions if the minimum antenna separation exceeds 3λ (for wire type antennas), or $2D^2/\lambda$ (for surface type antennas of diameter D). When a portion of the propagation path is around a curved surface or an edge, allowance is made for shading and diffraction effects.

There are several algorithms employed to calculate wire-to-wire coupling. Couplings are calculated between all wire pairs which lie in the same bundle and have a common run. The wire configurations may be quite complex (shielded, twisted pair circuits, balanced or unbalanced, single or double shield, with single or multiply grounded shields, or any subset of these possibilities). Coupling effects between single wires include interwire capacitance and mutual inductance. More complex circuits are replaced by equivalent single wires.

If there are branches or discontinuities, the emitter current (and the summation of voltages coupled to the receptor port) is computed on the basis of the entire emitter (receptor) configuration, but the coupling is computed on a segment-by-segment basis. All of the coupling components are then summed to determine the total coupling (both capacitive and inductive). This method of segmenting the wires allows the calculation of the effects of environmental fields on the complete receptor circuit at the same time the first emitter circuit is being analyzed.

The case-to-case model uses the emission and susceptibility levels according to MIL-STD-461A or MIL-STD-6181D. These levels are related to the system configuration by modeling each case as though it were a dipole. The source model assumes a $(1/r)^3$ fall off for both the electric and magnetic fields.

The filter models represented in IEMCAP are ideal, lossless networks, made up of only reactive elements (capacitors and inductors). The filter transfer models calculate the "insertion loss" in dB provided by a filter at a given frequency, i.e., the reduction in delivered power due to insertion of a filter. Thus the insertion loss of the single tuned filter at the resonant frequency is 0 dB, i.e., the insertion of the filter does not attenuate the signal delivered to the load at that frequency.

Practical filters are not ideal, lossless networks; there are always dissipative elements that affect filter performance. Consequently the filter models provide for a minimum insertion loss to represent actual dissipation at the tuned frequency or in the pass band. The filter models also provide a maximum insertion loss or isolation to represent the departure from the ideal rejection in the rejection band. The minimum and maximum insertion loss provide lower and upper bounds for the filter transfer function.

The coupling from environmental electromagnetic fields onto wiring is important in the design of USAF systems. Usually, the fields enter the vehicle through dielectric apertures in the system's skin and couple onto wires immediately adjacent. These apertures include radomes, canopies, landing gear doors, camera windows, and air intakes on aircraft and space vehicles, and doors and windows in ground systems.

Exposed wires are assumed to be adjacent to the aperture, and the amount of RF energy coupled depends on the aperture size and location. A transmission line model is then used to compute the currents induced in the wire loads. Worst-case electromagnetic field vector orientation is determined and used for the calculation.

The intrasystem analysis applications of IEMCAP already performed include at least 13 aircraft and 5 spacecraft.

Software Considerations

IEMCAP is a self-contained American National Standards Institute (ANSI) FORTRAN program which consists of approximately 16K lines of code. It has been successfully installed on the CDC/CDC CYBER, IBM, VAX, UNIVAC, Honeywell, PDP, Xerox, and AMDAHL computer types. Central Processing Unit (CPU) core memory to load and execute each part of IEMCAP on a Honeywell 6180 using the FORTRAN J compiler is 91K (decimal) words for IDIPR and 81K words (decimal) for TART.

A typical aircraft, spacecraft, or ground system can contain thousands of ports. If every emitter port had to be analyzed in conjunction with every receptor port, the run time, core memory size, and file storage would be extremely large. Therefore, the maximum system size shown in Table 3 was established. For each equipment, the

Table 3

MAXIMUM SYSTEM SIZE

Equipments	40
Ports per equipment	15
Total ports (40 x 15)	600
Apertures	10
Antennas	50
Filters	20
Wire bundles	140
Total no. of wires	280
Segments per bundle	140
Bundle points per wire	11

15 ports include the required case leakage, and, therefore, 14 intentional ports are allowed.

The amount of file space necessary depends on the size of the system being analyzed. The execution time also depends on the system size. IDIPR time is approximately 0.1 second per input card. TART run time primarily depends on the number of coupled port pairs, which potentially increases as the square of the number of ports. In general, though, each emitter port will not be coupled to each receptor port so the actual time will be less. Also, the TART time depends on the analysis task. Specification generation requires three passes through the emitters per receptor with two passes through the receptors per run and hence runs longer than the other tasks. Table 4 gives the run times and file sizes for two test cases on the CDC 6600.

References for Sec. B.4.a

1. Bogdanor, J. L., R. A. Pearlman, and M. D. Siegel, *Intrasystem Electromagnetic Compatibility Analysis Program*, Rome Air Development Center, AFSC, RADC-TR-74-342, December 1974. In three volumes. Volume 1 provides the user's manual engineering section, Vol. 2 the user's manual usage section, and Vol. 3 the computer program documentation.
2. Baldwin, T. E., et al., *Intrasystem Analysis Program (IAP) Model Improvement*, Rome Air Development Center, AFSC, RADC-TR-82-20, December 1981. Updates IEMCAP since the writing of Ref. 1.

Table 4

EXECUTION TIMES AND SIZE OF PERMANENT AND WORK FILES FOR SAMPLE RUNS

<i>Data Case Size</i>	Test Case 1	Test Case 2
Number of cards		
input to IDIPR	170	241
Total ports	33	56
<i>Execution Times (sec)</i>		
Execution time IDIPR	17.4	24.5
Execution time TART-SGR	176	186
<i>File Size in Words (decimal)</i>		
New ISF	10,862	16,000
Baseline transfer file	35,000	41,000
Emitter spectrum	3,012	4,200
Receptor	1,792	2,670
Emitter equipment	1,634	2,350
Receptor equipment	1,631	2,380
Wire bundle	97	400
Wire map	640	2,390
Array	183	300
Processed input file	3,000	4,200

For further information on IEMCAP, please contact Kenneth Siarkiewicz, RADC/RBCT, Griffiss Air Force Base, New York 13441.

B.4.b GENERAL ELECTROMAGNETIC MODEL FOR THE ANALYSIS OF COMPLEX SYSTEMS (GEMACS)

Introduction

The GEMACS code is the result of an effort to develop engineering tools to support the electromagnetic fields analysis required during the design, development, fabrication, installation, maintenance, and modification of electromagnetically complex systems. It employs the Method of Moments (MON) and geometrical theory of diffraction (GTD) techniques to solve Maxwell's equations for an arbitrary geometry of radiators and scatterers. The program, which possesses inherent growth potential and Air Force wide commonality, provides the capability to model and characterize large systems in terms of near/far-field radiation patterns, predict the coupling between numbers of colocated

antennas, which may be on satellites or at ground terminals, and determine the input impedance of antennas in large radiating systems.

The GEMACS program was written and developed by the BDM Corporation, Albuquerque, NM for Rome Air Development Center (RADC/RBCT), Griffiss Air Force Base, New York. It was approved for public release in 1977. The program is currently maintained by the RADC/RBCT, Griffiss Air Force Base, who provide the program and services. (See Introduction to Section B.4 for change 30 September 1983.) To date there have been at least 12 governmental, 34 industrial, and 6 academic users.

Code Description and Capabilities

GEMACS is a highly user-oriented general purpose code designed for analysis of a variety of complex electromagnetic problems. The user is assumed to be an experienced electromagnetic analyst with a fair understanding of applied linear algebra. The current version (release 3) of the code supports all of the functions necessary for using one thin-wire and one surface patch (Method of Moments) formalism as well as a GTD calculation technique. In addition, these formalisms are completely hybridized. The GEMACS code uses a high-level language and provides flexibility of control over the computational sequence by the user. Error messages, debug and trace options, and other features are included to aid the user in identifying sources of errors.

The thin-wire MOM formalism used in the present code uses the Pocklington integral equation with sine plus cosine plus pulse expansion functions, point matching, and a charge redistribution scheme at multiple wire junctions. The GEMACS code also includes most of the engineering features of other codes, such as loading and ground plane effects. This thin-wire MOM approach can be used to solve general physical problems involving actual wires, wire grid models of conducting surfaces, or a combination of these. The user must reduce the physical problem to a thin-wire model. The GEMACS code includes a highly flexible geometry processor to aid in this task.

A second MOM formalism is the use of the Magnetic Field Integral Equation (MFIE), which treats the surface currents (patches) on wires or other bodies. It is the intent of the code design to allow the

incorporation of other solution techniques, such as Bodies of Revolution and a finite difference frequency-domain formalism.

The GTD formulation is based on work performed by the Ohio State University in the development of their Basic Scattering Code. The structure is modeled as a combination of flat plates and a finite length cylinder with end caps. Near fields and far fields scattered by the structure immersed in an electromagnetic field are calculated.

The present version of GEMACS (Version 03) can be used with confidence only when describing the external phenomena associated with the radiating/scattering structure. The MOM/GTD hybridized solution becomes unwieldy and suspect when applied to the determination of energy distribution interior to the structure's skin or in apertures in the skin. Therefore RADC has recently awarded a contract to BDM Corporation (Albuquerque, NM) to incorporate within GEMACS a Finite Difference Frequency Domain (FDFD) capability, scheduled for delivery in September 1985. It will allow the analysis to describe arbitrarily shaped apertures and interior regions, both of which may contain regions of arbitrary conductivity and permittivity. Interior field distributions and energy coupled to wires and loads will be available. The FDFD technique will be fully hybridized with the MOM/GTD techniques now incorporated in GEMACS.

The GEMACS inputs are in two categories. The command language directs the program execution while the geometry language is used to describe the geometrical properties of the structure being analyzed.

The GEMACS command language is a free-field, keyword-oriented input stream. The order of the inputs is generally not important, and the items on each command are delimited by a blank or a comma. An item is considered to be all of the input associated with a particular parameter. An item may consist of several entries where each entry is referred to as a field. Blanks may be imbedded between fields of an item but not within a field.

The command language consists of a description of the electrical environment of the structure including the effect of loads, external or incident fields, voltage-driven or antenna source segments, ground parameters, frequency, selection of the matrix equation solution technique, and additional commands which permit intermediate

calculations to be performed, stored (checkpointed), resumed (restarted), or purged. In addition, processing time limits, upper limit to the number of processing files available, and checkpoint timing control are specified at this input level.

The GEMACS geometry language is also a free-field language. However, the items must appear in the order specified or an error will occur which may not be detected. The reason for not using keyword-specified items on the geometry inputs is to decrease the effort required by the user since the geometry inputs are usually much larger than the command inputs.

The basic elements of GEMACS are plates, the cylinder, points, and line segments. These in turn may belong to larger data groups with a given name. Any reference to this given name will also reference all the points and segments within that group. In addition, line segments may also be identified as a group by having the same tag number.

The subsection may thus be identified by either a segment number or a tag number. The difference is that the first is unique in the model while the second may be shared by any number (or all) of the subsections within the geometry model.

The geometry data set is the basic source of data for many other GEMACS commands. It must be available before an impedance, excitation, load, or output data set can be generated. Additionally, the accuracy of the results is extremely dependent on the applicability of the structure representation for the analysis being performed.

The user specifies the quantities to be computed from the incident fields and the wire currents, such as impedances, coupling parameters, and near field and/or far fields. These are computed from the incident fields and currents regardless of the solution process specified. In any case it must be emphasized that the user must be familiar with general results from the literature to ensure that the computed solution using the model for the system is of sufficient accuracy for the purposes intended. For example, the far fields can be computed from approximate currents obtained by specifying a weak convergence criterion when solving matrix equations. This will allow the reduction of the required computer resources when large systems are being analyzed. Also, the physical symmetry of the structure may be used to decrease matrix fill time and matrix equation solution time.

The present code generates an interaction matrix from the MFIE, EFIE (Electric Field Integral Equation), and the GTD as discussed in the GEMACS engineering documentation. The wire current is represented by a sine, cosine, and pulse expansion function with redistribution at junctions based on the fractional length of each segment with respect to the total length of all segments connected at the junction. The surface current is represented by a pulse function. The interaction matrix may be modified by loading the individual segments or patches of the model using resistance, capacitance, and inductance in parallel or series configurations.

Associated with the geometric structure and interaction matrix is an excitation matrix which contains the total tangential electric field present at the midpoint of each segment or patch. The electric field may be caused by as many combinations of three types of sources as desired. These types are plane and spherical wave sources for scattering problems and voltage sources for antenna problems. In addition, the user may assign an arbitrary value to the excitation of any wire segment to force the desired boundary condition.

With the interaction matrix denoted by $[Z]$ and the excitation matrix denoted by $[E]$, the primary function of the code is to generate and solve the system of equations for the electric current $[I]$:

$$[Z] [I] = [E]$$

This may be done using direct full matrix decomposition if the structure is electrically small. The Gauss-Jordan algorithm is supported by GEMACS.

For electrically large problems in which use of the GTD is not made, the direct solution method may be prohibitive due to the large amount of time required and the possible roundoff errors. In this case, the BMI (Banded Matrix Iteration) technique is available. When using BMI, the user must provide the convergence measure and value to be used to stop the iterative procedure. Three criteria or measures are available: the BCRE (Boundary Condition Relative Error), the IRE (Iterative Relative Error), and the PRE (Predicted Relative Error).

Once the solution has been obtained, the input impedance of each voltage driven element (i.e., Antenna Feed Point) is output to the user. The currents may also be used as inputs to the field computation routines to obtain the near- and/or far-electric field patterns, and the coupling between pairs of antennas.

There are inherent limitations to the solution techniques available. The user who is not familiar with these techniques is advised to consult the engineering manual [Ref. 2, this section] in order to not waste valuable time and computer resources working an ill-posed problem.

It should also be understood that there are certain limitations and assumptions in GEMACS with respect to wire grid modeling. Regarding geometries that are modeled as wire screen approximations to the actual surface, the currents in the model exist only on the axis of the wires in the grid, whereas physically they are spread over the entire area of the surface. It follows that since the current exists only on the axis of the wire, there is no azimuthal variation of the current around the circumference of the wire, as would exist physically on the antennas. Also, because of the assumed concentration of the current on the axis of the wires there is no radial component of current flow within the wire, which is important in the generation of near-field phenomena at the ends of the wire.

Antenna sources are generally modeled as a delta voltage source placed across a subsection. This may have no counterpart whatsoever in the physical situation. Moreover, the size of the gap in the model usually does not bear any relation to the size of the gap in the physical antenna. The gap in the model is usually the same size as the length of the adjacent subsections, since one of the modeling rules of thumb is to avoid large ratios in the relative lengths of adjacent subsections. The current on a subsection is computed at the center of the segment and the variation over the wire is determined by interpolation between adjacent centers.

Even though all these assumptions are built into a GEMACS analysis, or a MOM analysis in general, good correlation exists between measured data and predicted data, and between other analytical results and the data obtained by using GEMACS.

All the commonly used codes assume that the material of which the system is composed is perfectly conducting. Brute-force techniques can be used to get around this limitation, but they place a heavy burden on the user. Alternative solutions are being pursued and will be included in future versions of GEMACS.

The MOM and GTD models can be used only to solve the external problem. Problems that cannot be treated with confidence include coupling through apertures in the skin of the structure and coupling to objects located within the structure. For example, if the structure is modeled by a wire grid, electromagnetic energy will "leak through" the mesh in the model, resulting in a form of aperture coupling. For the wire-gridded antenna coupling problem, energy will go directly through the body in addition to going around on the surface. Thus, the coupling will be greater than if the surface were modeled as a solid. The solid surface and the GTD models have been implemented into the GEMACS code to eliminate some of these limitations.

The general structure of GEMACS includes a set of executive routines, input, execution, and termination processors, and seven calculation processors which solve the electromagnetic problems. The GEMACS executive routines control the interface of the code with the host computer and perform three basic functions: input/output to peripheral files, taking checkpoints and restarting from these checkpoints, and the compilation of statistical information, which can be used to pinpoint areas for further code refinement.

The input language, task execution, and run termination processors simply read the user's data deck, call appropriate subprocessors based on the user's commands, and terminate the analysis, respectively. These three processors and the executive routines contain all of the file handling capabilities built into GEMACS. New subprocessors, with a proper interface under the task execution processor, can change the field analysis technique or even apply the mainframe code to a different type of problem completely, such as the dynamic load analysis of some structure.

The geometry processor generates the geometry to be analyzed by interpreting the user geometry input commands. The interaction matrix processor generates the elements of the interaction matrix for the frequency and geometry specified by the user. The excitation processor generates the elements of the vector on the right-hand side of the MOM matrix equation. The load processor modifies the interaction matrix to take into account the presence of loads on the wires or of imperfectly conducting materials. The matrix solution processor solves the matrix equation for the currents on the structure. The output processor calculates such quantities as the near and far-field patterns and terminal impedance for antennas or the backscattering from the structure. The direct manipulation processor sets such variables as the maximum CPU time allowed for the analysis, the number of files in the system available to the code, the frequency of the analysis, and the electrical characteristics of the ground (if present). It also performs arithmetic operations, such as modifying the frequency by some factor, a feature which is useful when "looping" is inserted into the command stream.

There are three types of output provided by GEMACS: the standard boiler-plate, those data specifically requested by the user, and error messages and debug information needed by the user when a problem arises during implementation of the computer code.

After the electrical currents have been obtained, the GEMACS code recovers the geometry, load, and source data associated with the currents. It will then compute the impedance, admittance, and power for all voltage driven (antenna source) and loaded elements. Unless specifically directed, no other output will occur. Additional output is obtained by using print, write, and field data commands.

Specialized print and write commands may be used to obtain a list of the currents on the structure as well as the contents of any data set. A print command lists the entire contents of a data set, while a write command lists those data specifically requested by the user. For example, the latter could be used to print out a limited set of elements of the interaction matrix if the currents appear questionable to the user.

The field data command will result in the computation of the near or far electric fields. The output will list the vector components of the field and optionally plot the magnitudes as directed. The near field will be determined for Cartesian, cylindrical, or spherical coordinates. The use of spherical coordinates with the radius parameter omitted will result in the far field being computed. This is the only mechanism to control near and far field output.

The data are preceded by an informative message giving the symbol name, the links to other symbols, and the data type. Since these data are complex, the real and imaginary magnitude and phase are given for the current (amperes) and the excitation (volts/meter) on each segment.

The optional graphic display is controlled by a six-choice item on command. If this item is defaulted, then only a tabular listing of the data will be output by GEMACS. If one of the six choices is present, then the plot will be in either a rectangular or polar form with axes in either a linear or logarithmic progression.

GEMACS is structured to write a checkpoint at specified time intervals, on command, or on detection of a fatal error during execution of any command. To recover from a checkpoint, a restart command has been provided. The restart action is straightforward; on encountering the restart command in the input stream, all previous input is overwritten with the contents of the checkpoint file.

There is an extensive set of messages available to the user that is printed when GEMACS encounters an error during input processing or analysis. These are automatically printed out without the need for a user request.

In addition to the error messages a wealth of information is available regarding actual processing that occurs during execution. These data can be obtained through the use of debug commands. Statistics may also be collected and output which describe what subroutines were accessed, how often, the amount of Central Processing Unit (CPU) time expended in each subroutine and the percentage of the total CPU time spent in each subroutine.

Software Considerations

GEMACS is written in American Standard FORTRAN, X 3.9-1966, and consists of approximately 50,000 lines of code. It is capable of execution with no library subroutines other than those required by the American National Standards Institute (ANSI) standard. The code requires approximately 58K, 85K, 120K, and 50K decimal core locations for each of its four modules (depending on machine and load method) and may be segmented or overlayed. As released, neither of these features is used due to incompatibility with various machines.

GEMACS has been installed on the CDC/CDC CYBER, IBM, UNIVAC, PDP, Burroughs, Honeywell, and VAX computer systems. Although no system library routines are required, some are desirable. The most important is a routine to return the elapsed CPU time in minutes. Such a routine must be available for effective use of the checkpoint command. Auxiliary routines to return the date and time are called by an internal subroutine. In the absence of these routines, zeros should be returned to the calling routing.

The file status function routine is called after each READ to detect an end of the file. If a library function is available to determine this information, it should be called from this routine. If none is available, a zero value for the function should be returned.

Regarding input/output requirements, GEMACS makes extensive use of peripheral file storage and must have several logical units available. The user is responsible for assuring that GEMACS can access these files, whose data sets consist of geometry, excitation, impedance, banded results, decomposed matrix results, current, and field data. If more files are required than are made available, a fatal error will occur and an attempt will be made to write a checkpoint. To this end, a final GEMACS resource requirement is a checkpoint file.

The modular construction of GEMACS has its advantages. First, and most obvious, is that one can plug in any technique which has a proper interface or driver to transfer data between the implementing subroutine and the mainframe. It is therefore possible to have a complete set of techniques stored in separate files. The big difference is that communication with all these techniques is in one common language.

There is no need for the user to be familiar with several different sets of input formats, or limit himself to one specialized code.

Second, and highly significant, is the fact that GEMACS is tied into the Air Force Intrasytem Analysis Program (IAP). It will thus have the full support of the Air Force to provide aid in the loading, use, and maintenance of the code, additions to the capability of the code, updates to eliminate any bugs that may be in the code, and to support a common language among all users of the code.

Execution times on the Honeywell 6180 computer system for a typical system consisting of a variable number of subsections are shown in Table 5. These figures represent analysis times (CPU seconds) using the full matrix solution method as a function of the number of segments.

The problem-handling capabilities of GEMACS are limited by the computer resources available to the user. As presently dimensioned, GEMACS can accommodate up to 20,000 wire segments, 14 plates, and one cylinder with two endcaps. Generally, MOM analyses have been limited to fairly small systems, i.e., those that can be represented by 300 subsections or less. Electrically, this size corresponds to approximately 30 wavelengths of wires or a surface with an area of one square wavelength. This is not a result of a limitation of the theory or the technique, but has been brought about by the computer resources needed to perform a MOM analysis; however, the range of applicability of the moments technique is extended to objects of larger electrical size

Table 5

NUMBER OF SEGMENTS VS. FULL MATRIX SOLUTION TIME

110 segments	255.24 sec ^a
305 segments	2,876.04 sec
500 segments	10,076.76 sec

^aThese numbers are computer-system dependent and apply only to MOM module execution. In this regard, the Honeywell system is fairly slow.

in GEMACS through use of the BMI solution method and the GTD formalism. In terms of wavelengths, an electrically large system is one which has an area of at least 10 square wavelengths for a plane surface, or one which has a linear dimension of at least 200 wavelengths for a single dimension system. The development and recent inclusion of the GTD analysis technique further increases the frequency range capability of the program for a given object size and complexity.

References for Sec. B.4.b

1. Siarkiewicz, K. R., *An Introduction to the General Electromagnetic Model for the Analysis of Complex Systems (GEMACS)*, Rome Air Development Center, AFSC, RADC-TR-78-181, September 1978.
2. Balestri, R. J., T. R. Ferguson, and E. R. Anderson, *General Electromagnetic Model for the Analysis of Complex Systems*, Rome Air Development Center, AFSC, RADC-TR-77-137, April 1977. In two volumes. Volume 1, User's Manual; Vol. 2, Engineering Manual.

Reference 1 provides a general description of GEMACS. Reference 2 presents the detailed studies, with Vol. 1 appropriate for those who would simply use the program, Vol. 2 for the engineering background. For further information on GEMACS, please contact Kenneth Siarkiewicz, RADC/RBCT, Griffiss Air Force Base, New York 13441. The two volumes of Ref. 2 are presently being extensively revised to include the GTD formulation documentation.

B.4.c NONLINEAR CIRCUIT ANALYSIS PROGRAM (NCAP)

Introduction

The Nonlinear Circuit Analysis Program (NCAP) provides the analyst and system designer with a technique for solving weakly nonlinear electromagnetic compatibility (EMC) problems. After a more coarse analysis has indicated a potential EMC problem at the circuit level, NCAP could be used to examine in more detail the nonlinear behavior. NCAP calculates the nonlinear transfer functions of networks made up of interconnections of a standard set of circuit elements. These transfer functions then determine the effects, such as desensitization, intermodulation, and cross-modulation, which in practice can severely degrade system performance.

The NCAP was developed by and for the Rome Air Development Center (RADC) as a part of the Air Force Intrasytem Analysis Program (IAP). It has been available since 1979, and is currently maintained by the IIT Research Institute, EMC/IAP Support Center, Griffiss Air Force Base, New York. (See Introduction to Section B.4 for change 30 September 1983.) The program and related services can be obtained directly from the Support Center. Users to date include at least 6 governmental, 18 industrial, and 4 academic institutions.

Code Description and Capabilities

NCAP employs the Volterra analysis technique, according to which the nonlinear transfer functions are calculated by a power series expansion beginning with the linear first-order system. The nonlinear network problem is solved by forming both the nodal admittance matrix (Y matrix) for the entire network and the linear sources in the entire network. The generators can be located between any node in the network, and can have any desired frequency, amplitude, and phase. Use of Gaussian elimination with the admittance matrix and the current vector results in the first-order nodal voltage vector for the network, whose elements are the first-order transfer functions at all nodes in the network at the given excitation frequency. When there is more than one generator at a given frequency, the first-order transfer function will be the total transfer function due to the superposition of the generators since the first-order transfer function is a linear function. The higher-order transfer functions are solved in an iterative fashion.

The nonlinear transfer functions computed by NCAP are voltage transfer ratios which relate an output response voltage to one or more input excitation voltages. Therefore, to determine a nonlinear transfer function, it is necessary to define the parameters of the input signals of the circuit, including signal levels, and the frequencies at which the analysis is to be performed. In NCAP these input signals are considered to be generated by independent sinusoidal voltage sources. Voltage sources (generators) can be connected between any two nodes in the circuit, and a single source can generate an arbitrary number of frequencies. The order of analysis which the program will carry out is

equal to the total number of defined frequencies in the circuit with the nonlinear transfer functions computed for all $2^n - 1$ possible combinations of n input frequencies.

The user is only required to be able to translate a circuit analysis problem into the appropriate NCAP input language statements. The input statements define the topology of the circuit, the linear and nonlinear devices used in the circuit, the circuit element values, the circuit excitation and the order of the analysis, the desired outputs, the data modification, and the sweeping descriptions. Circuits may be interconnected using the following set of standard electronic circuit element models: independent voltage source, linear and nonlinear dependent sources, linear and nonlinear components, vacuum diodes and pentodes, semiconductor diodes, and bipolar junction and field effect transistors. The first step in the analysis should be the construction of a schematic of the complete circuit, including all of the NCAP elements which can be identified and modeled.

A number of optional features have been incorporated in the NCAP system to increase its versatility and ease of use. For example, to provide the user with a method of analyzing circuits over a range of frequencies or linear component values, an incremental sweep capability has been included in the NCAP program. This feature enables the user to specify numerous analyses for a given circuit in a single computer run. The basic circuit description, together with all sweep definitions, is entered only once. The system then automatically reanalyzes the circuit for all possible frequency and component values.

A modify feature, which allows the user to alter nonlinear device parameters and reanalyze a circuit in a single computer run, has also been incorporated in NCAP. Such modification may also be applied to frequency and component values, either to change the parameters of a previously defined sweep, or to define additional values which may lie outside the range of a sweep.

The program consists of eight phases, numbered 0 through 7. Each phase performs a distinct portion of the circuit analysis and operates independently of the other phases. The only interphase communication is by shared disk files: the driver file, which is a translation of the NCAP input cards (denoted with asterisks) to a machine readable

description of the circuit analyses to be performed, and the data file, which contains all circuit element input data, calculated device parameters, admittance matrices, and transfer function vectors. Although several other disk files are used by NCAP, their function is to conserve core storage and ease the transmission of internally generated data between the subprograms which comprise individual phases.

Phase 0 is the input processor for NCAP. It reads and interprets the input deck mapping the input cards to appropriate driver and data file records. Phase 1 calculates the device parameters for each circuit element, collects and tabulates the circuit's frequencies, and determines the size of the admittance matrices. Phase 2 constructs the admittance matrices, one for each possible combination of the circuit's frequencies. Phase 3 constructs the current vectors and calculates the transfer functions for each frequency combination. Phase 4 prints the results from the circuit analysis performed in Phases 1-3 and controls frequency sweeping. Phase 5 controls linear component sweeping, Phase 6 controls device modification, and Phase 7 controls generator modification.

Since numerous circuit analyses may be specified by a single NCAP input deck, the path of execution through the program phases is not necessarily sequential. Execution always begins at Phase 0 and proceeds sequentially through Phases 1-4 to perform the first circuit analysis. From Phase 4, program execution either reverts back to Phase 1 to initiate a new analysis if frequency sweeping is specified, or proceeds to Phase 5 if frequency sweeping is not specified or after all such sweeps have been satisfied. In a similar fashion, Phases 5, 6, and 7 may either cycle back to Phase 1 or proceed to the next phase depending on the linear component sweeping, device modification, and generator modifications specified in the input deck. Program execution ends with Phase 7 after the last (if any) generator modification has been effected.

Each phase is composed of a principal subprogram which controls its general operation, a group of secondary subprograms which perform specific operations for individual circuit elements or NCAP functions, and in some cases, additional support subprograms which perform operations unique to that phase. The program is organized sequentially

according to the order of the phases. Within each phase, the principal subprogram appears first, followed by the secondary and support subprograms in alphabetical order. A group of shared support subprograms, such as those which perform disk input/output or complex arithmetic, follow Phase 7 and appear in alphabetical order.

The principal subprograms of each phase are subroutines, with the exception of Phase 0 whose principal, in order to satisfy the requirements of FORTRAN, is NCAP's main program. These subroutines are named PHASE0, PHASE1, ..., PHASE7. With the exception of two function subprograms, the remainder of the NCAP subprograms are subroutines.

Whenever possible, subprograms are named according to specific conventions. Subprograms which perform specific functions related to circuit elements are prefixed or suffixed with a device identifier, such as GEN for generator or VD for vacuum diode. Within each phase, the secondary subprogram names contain functional identifiers: IN--read and interpret input cards; CP--calculate parameters; MT--create matrix elements; CUR--calculate current elements. Together, the device and functional identifier describe the purpose of the subprogram: GENIN--input generator card sequence; CPMTVD--calculate parameters and create matrix elements for vacuum diode.

The program code for subroutines PHASE1 through PHASE7 are all organized in a similar manner. Execution through these routines is controlled by reading and processing the driver file records sequentially. Each driver record contains a functional identifier or mode, which serves as the index of a computed "GO TO," selecting the proper code segment to process that record. The coding for each driver function is arranged numerically by mode within the subroutine and begins with the statement number equal to the value of the mode. Additional statement numbers within a code segment are assigned in increments of 100. For example, a section of transistor code would begin with statement 9 (the transistor driver mode), and proceed through 109, 209, 309, and so on.

In a similar fashion, the IN family of subroutines (input card processors) share a common organization. Execution through these subroutines is based on a computed "GO TO" using the card type identifier as an index. The coding for each card type is arranged

numerically within the subroutines and statement numbers are allocated in increments of 100 within code segments.

The narrative descriptions of the NCAP subprograms which follow are arranged in the order in which they appear in the program: by phases and within phases and by alphabetical order. Each subprogram description contains a brief statement of purpose, followed by a variables list, subroutines called, calling programs, and a detailed narrative of the program code. Wherever possible mathematical algorithms are summarized and where possible tables of all possible computed results are presented.

To avoid repetition, variables which are used globally within the program are listed only in the Phase 0 description or in the first principal subprogram in which they are used. In the secondary and support subprogram descriptions, only local variables (or in some cases less frequently used global variables) are listed.

Machine-dependent code is clearly identified in both the program listing and narrative descriptions to ease the adaptation of NCAP to various computer systems.

The output of a typical NCAP run, printed on the computer's line printer, can consist of a large volume of information. In general the output consists of images of all input cards, all circuit devices with their associated parameter values, and all scaled nonlinear transfer functions and node voltages. The transfer functions and node voltages are printed for each node and each order for every possible frequency combination, in both Cartesian and log-polar form.

If errors are detected in the input deck, the printout of the erroneous input card will be followed by an error message describing the type of error encountered. Once such an error has been found, processing of the input deck will continue until the last card is read. At this point, execution of the program will terminate and the output will consist of only the input card images and appropriate error messages.

The successful analysis of a large circuit can result in an inordinately large amount of printed output; therefore, several output control statements in the NCAP language allow the user to specify the desired output and reduce the amount of printout.

The NCAP program, which applies to the analysis of specific albeit complicated circuits, has nothing to do with orbits, antennas, or propagation models, except as they may be used to establish the voltages used as generator inputs. It thus may be used to process the data generated by other programs which calculate interference signals at system or circuit inputs.

A recent application of NCAP predicted radio frequency interference to the 741 operational amplifier (OP-AMP), which was subjected to multiple signal inputs. NCAP was successfully used to predict undesired, low-frequency responses in the OP-AMP caused by demodulation of amplitude modulated RF signals in the range of .05 to 100 MHz.

Software Considerations

NCAP is written in ANSI Standard FORTRAN IV. Although the program is large and its analytical technique complex, the modular structure, adherence to naming conventions for subprograms and variables, and numerous in-line comments allow NCAP to be readily adapted to any computer with an appropriate FORTRAN compiler. Sparse matrix routines decrease core storage requirements and increase computational efficiency of the program.

The program consists of 10,475 lines of FORTRAN code. It has been successfully installed on the CDC/CDC CYBER, IBM, UNIVAC, Honeywell, PDP, and VAX computer systems. The program is self-contained and requires approximately 51K decimal words of core storage (on the Honeywell 6180 computer). Several disk files are required.

Typical execution times based upon implementation on the Honeywell 6180 series computer are shown in Table 6. These figures are in terms of Central Processing Unit seconds and refer to typical sample cases which exercise the various models and specialized analysis features. The number of nodes per model and order of analysis has also been indicated.

NCAP can analyze networks containing up to 500 nodes. It has had a number of applications to EMC problems.

Table 6
TYPICAL EXECUTION TIMES

Analysis Task	No. of Nodes	Order	CPU Time (sec)
Frequency sweeping	4	3	33.84
Component sweeping	3	2	9.0
Device model modification	26	3	63.36
Impedance modification	4	3	15.48

References for Sec. B.4.c

1. Spina, J. F., C. A. Paludi, D. D. Weiner, and J. J. Whelan, *Nonlinear Circuit Analysis Program (NCAP) Documentation*, Vol. I, *Engineering Manual*, Rome Air Development Center, AFSC, RADC-TR-79-245, 1979.
2. Valente, J. B., and S. Stratakos, *Nonlinear Circuit Analysis Program (NCAP) Documentation*, Vol. II, *User's Manual*, and Vol. III, *Computer Programmers Manual*, Rome Air Development Center, AFSC, RADC-TR-79-245, 1979.

These references are self-explanatory. For further information on NCAP please contact Kenneth Siarkiewicz, RADC/RBCT, Griffiss Air Force Base, New York 13441.

B.4.d WIRE COUPLING PREDICTION MODELS

Introduction

The large-scale computer program IEMCAP may indicate a potential wire-coupled interference problem in an aircraft, ground, or space system. Because of the size and complexity of many of these systems, fairly simple models of coupling paths are used to avoid excessive computer run times. A set of seven computer programs has been developed to supplement the analysis capabilities of IEMCAP by performing a more fine-grained analysis of wire-coupled interference. These programs implement the Multiconductor Transmission Line (MTL) model.

The wire coupling prediction models were developed by the University of Kentucky under the sponsorship of the Rome Air Development Center Post-Doctoral Program for RADC's Compatibility Branch. The programs and associated user's documentation became available in 1976 and are currently maintained by the IIT Research Institute EMC/IAP Support Center, Griffiss Air Force Base, New York, who also provide programs and associated products and services. (See Introduction to Section B.4 for change 30 September 1983.) Users to date include 4 governmental, 19 industrial, and 2 academic institutions.

The computer programs described here predict the coupling between wires and their associated termination networks in closely coupled, high density cable bundles and in flatpack (ribbon) cables in modern electronic systems. The effects of shielding and twisting are included. The models are based on a complete and unified consideration of multiconductor transmission line theory as it applies to the prediction of wire-coupled interference. In addition to considering the limitations and advantages of the analysis and prediction techniques, some numerically stable and efficient techniques are used to solve the multiconductor transmission problem for large numbers of closely coupled dielectric-insulated wires. Methods for calculating the per-unit-length parameters are included. All systems are assumed linear, and all calculations are performed in the frequency domain with sinusoidal excitation.

The wire coupling prediction model software tools consist of seven separate codes: XTALK, XTALK2, FLATPAK, FLATPAK2, GETCAP, WIRE, and SHIELD. The first four are closely related. XTALK implements the MTL model, neglecting the presence of wire dielectrics and conductor losses. XTALK2 also neglects the presence of wire insulation but includes conductor losses. FLATPAK includes consideration of wire dielectrics, as in ribbon cables, but neglects the conductor losses. FLATPAK2 includes both wire dielectrics and conductor losses. None of the programs considers insulation dielectric losses. Each program is efficient for the specific problem being investigated.

The program GETCAP calculates the per-unit-length *GE*neralized and Transmission line *CAP*acitance matrices for ribbon cables. The program WIRE is designed to calculate the sinusoidal steady-state terminal currents induced at the ends of a uniform, multiconductor transmission line which is illuminated by an incident electromagnetic field. The analysis and prediction code SHIELD assesses the effectiveness of preventive measures involving cable shielding and also predicts the coupling effects due to pigtailed, which can seriously degrade the effectiveness of braided shielding.

It is difficult if not impossible to write a general computer program which would address all types of transmission line structures which the user may wish to investigate. The programs discussed here form an initial library of specialized analysis capabilities for wire-coupled interference problems.

Code Description and Capabilities

The four programs XTALK, XTALK2, FLATPAK, and FLATPAK2 will be discussed together. They determine the electromagnetic coupling within an $(n + 1)$ conductor uniform transmission line, carrying n wires and a reference conductor for the line voltages. The reference conductor may be a wire, an infinite ground plane, or an overall cylindrical shield which is filled with a reference dielectric. The codes are distinguished by the presence or absence of dielectric insulation and conductor losses.

In all of the programs, the medium surrounding the conductors is assumed to be lossless. Sinusoidal, steady-state excitation of the line is considered, i.e., the transient solution is not directly obtained.

The programs consider the line cross-sectional dimensions as well as conductor impedance via the per-unit-length impedance and admittance matrices which take into account mutual and self-interactions. These basic parameter matrices are used in determining the terminal voltages and currents.

The equations used in the programs for the entries in the per-unit-length transmission line matrices in XTALK and XTALK2 are valid for "large" conductor separations. Generally, this means that the smallest

ratio of wire separation to wire radius should be no smaller than approximately 5. The exact values for these matrices for ribbon cables are computed by GETCAP and used in FLATPAK and FLATPAK2.

The per-unit-length inductance matrix is computed in XTALK and XTALK2 using the "large conductor separation approximations" described above. The per-unit-length capacitance matrix is then determined from the inverse of the per-unit-length inductance matrix since the surrounding medium is assumed to be homogeneous. Terminal voltages are determined using either the Norton Equivalent representation of the terminal networks or the Thevenin Equivalent representation.

The per-unit-length transmission line matrix entries for XTALK2 analysis follows from the developments provided in XTALK taking into account the lossy properties of the conductors.

In the case of program FLATPAK, the relationship between the per-unit-length inductance and capacitance matrices used in XTALK and XTALK2 no longer holds since the surrounding medium about each conductor is assumed to be inhomogeneous. FLATPAK addresses the specific problem of transmission lines consisting of perfect conductors in a lossless, inhomogeneous medium. For example, dielectric insulations surrounding wires result in an inhomogeneous medium (dielectric insulation and the surrounding free space).

By virtue of its permeability, the surrounding medium is considered to be homogeneous; therefore, evaluating the per-unit-length capacitance matrix with the wire dielectric insulations removed is necessary. Hence, one needs to compute the per-unit-length capacitance matrix with and without the wire dielectric insulations. The GETCAP code was written to compute these per-unit-length capacitance matrices of ribbon cables which can be used as inputs to FLATPAK.

FLATPAK2 uses the per-unit-length capacitance and inductance matrices computed by GETCAP assuming perfect conductors as in FLATPAK. The self impedances of the wires are assumed identical since the wires in the ribbon cable are typically identical. The per-unit-length impedance and admittance matrices are appropriately modified to account for the lossy nature of conductors.

The required input data, supplied through cards or card images, are in three groups: transmission line structure characteristics, termination network characterization, and frequency data. The structure characteristics generally consist of specifications of the number of wires, dielectric constant and permeability of the surrounding medium, transmission line length, wire radii, interior radius of shield if present, and any relevant rectangular or polar coordinates which describe the wire system geometry and orientation. The termination network (input and output) is characterized by either the Thevenin (impedance) or Norton (admittance) equivalent representation. Each termination matrix may be full or diagonal. Each of the matrix entries is, in general, complex, so both real and imaginary data inputs are required.

Each program will process the structure and termination data, and compute the response at each frequency specified (one per frequency card). If the termination networks are purely resistive (real inputs, frequency independent), then one may use as many frequency cards as desired and the program will compute the response of the line at each frequency without requiring repetition of structure and termination data. Many of the time-consuming calculations which are independent of frequency need to be performed only once, so this operational mode will save considerable computation time. If, however, the termination networks are reactive (complex inputs, implying frequency dependence), one must run the program for only one frequency at a time.

In the course of the computations, the programs call on four supplemental software routines. These required subroutines are part of the IMSL (International Mathematical and Statistical Library) package, which may be replaced by other appropriate general purpose routines. Subroutine LEQTIC is a general subroutine for solving a system of n simultaneous, complex equations; subroutine EIGCC is used to find the eigenvalues and eigenvectors of an $n \times n$ complex matrix; and subroutines NROOT and EIGEN are a set of subroutines which compute the eigenvalues and eigenvectors of a matrix product. The latter two were a part of the IBM Scientific Subroutine Package.

The outputs for the four programs generally consist of predictions of the terminal voltage for each wire (with respect to the reference conductor) at the end of each wire. The magnitudes and phases of these induced voltages represent the degree of crosstalk within the system.

The prediction of crosstalk in ribbon cables was investigated. Based on the experimental configurations tested, accurate predictions of crosstalk were achieved in controlled characteristic cable circuits. The prediction accuracies were typically within 1 dB for frequencies such that the line is electrically short.

The GETCAP program characterizes a system of wires as a multiconductor transmission line which can be used to predict crosstalk in ribbon cables. The general techniques employed in FLATPAK and FLATPAK2 require that the per-unit-length transmission line capacitance and inductance matrices of the system be determined. GETCAP determines these matrices.

Approximations to the elements of the transmission line capacitance matrix can be obtained for cases with no dielectric insulation, providing the separation between the conductors is at least ten times the conductor radius. These approximations in turn can be used to develop an approximate expression for the transmission line inductance matrix. An approximate method of determining the transmission line capacitance matrix for bare conductors above an infinite ground plane has been postulated where the smallest ratio of conductor separation to wire radius must be greater than ten. In this case, one can assume that the per-unit-length charge on each conductor surface is uniformly distributed around the conductor periphery.

Ribbon cables, however, have a much smaller conductor separation than is required for these approximations to be valid, and in addition have dielectric insulations. It has been shown, in fact, that the approximate formulas based on constant charge distributions are no longer sufficiently valid for close spacing and dielectric material surrounding the conductors. The charge distribution must be represented as a Fourier series in the angle around the periphery of each conductor.

GETCAP is a method for computing the capacitance matrix for dielectric-coated conductors as applied to the case of ribbon cables. Simplifications in the method were made possible by the symmetry of the cable dimensions; the radii of the conductors are all identical, and the center-to-center spacing of adjacent wires is identical. In addition, the wires are oriented in a horizontal plane which is maintained throughout the length of the cable. A method was incorporated to optimize the selection of matchpoint techniques to ensure valid results and reduce computation time. An approximate method for determining the transmission line inductance matrix was also included.

The inputs to the GETCAP code involve the number of wires in the cable, the radii of the conductors and the outer dielectric insulation surfaces, the center-to-center separation of any two adjacent conductors, the dielectric constant of the insulation material, the total number of Fourier series terms to be used to represent the charge distributions around the conductor surfaces and the dielectric surfaces, and the identification of the reference conductor for the transmission line voltages. A program option selector permits the choice of: matrix partitioning to invert the charge distribution matrix, standard full inversion of the charge distribution matrix, and inversions involving removal of dielectric (bare wire cable).

The GETCAP program consists of a MAIN program for inputting data and controlling output of results, a GETCAP subroutine for the actual computation of the capacitance matrix from the input data, and three matrix manipulation routines for inversion (MINV), multiplication (MPC), and output preparation (MPRT).

Typical output from GETCAP consists of the input data (errors are flagged when encountered), followed by the generalized transmission line capacitance and inductance matrices. These matrices are used as inputs for frequency response and crosstalk analyses of cable systems using FLATPAK and FLATPAK2.

The digital computer program WIRE is designed to compute the sinusoidal, steady-state terminal currents induced in a multiconductor transmission line by a single-frequency, incident electromagnetic field. The transmission line consists of n wires (cylindrical conductors) and a

reference conductor. The reference conductor may be a wire, an infinite ground plane, or an overall, cylindrical shield. All $(n + 1)$ conductors are assumed to be perfect conductors and the surrounding medium is assumed to be linear, isotropic, homogeneous, and lossless. The line is assumed to be uniform in that all $(n + 1)$ conductors have no variation in their cross sections along the line length and are parallel to each other.

Two types of incident field specifications are provided. Uniform plane wave excitation can be specified for the wire and infinite ground plane reference structures, whereas nonuniform field excitation can be specified for all structure types.

The primary restrictions on the program validity are that the cross-sectional dimensions of the line, e.g., wire spacings, must be electrically small and the smallest ratio of wire separation to wire radius must be larger than approximately 5. General linear termination networks are provided for at the two ends of the line.

The input data categories above are very similar to those requirements specified for the XTALK, XTALK2, FLATPAK, and FLATPAK2 codes. The only exception is with regard to the field specification. For uniform plane wave illumination of the line, the format of the input data consists of two groups. Group #1 consists of one card containing the magnitude of the electric field intensity vector and the angles between this vector and the appropriately projected coordinate axes. The zero phase of the incident wave is taken at the origin of the coordinate system.

Card Group #2 consists of an unlimited number of cards with each frequency of the incident wave on each card. More than one frequency may be included in this frequency card group. The program will process the input data and compute the response at the frequency on the first frequency card. It will then recompute the response at each frequency on the remaining frequency cards. The analysis technique per frequency is based on the same philosophy as was discussed for programs XTALK, XTALK2, FLATPAK, and FLATPAK2.

For non-uniform field illumination, Group #1 consists of one card which contains the frequency of the field. The remaining cards contain the values of the longitudinal electric field (magnitude and phase)

along the n wires (and reference) and the transverse electric field along straight line contours joining the i -th wire and the reference conductor at the transmission line endpoints. The directions of the transverse field at these specification points are tangent to the contours and directed from the reference conductor to the i -th wire.

The WIRE program contains a MAIN program which controls the flow of input data, provides executive control over all operations, and is responsible for output of results. In the computational portion it uses the previously cited LEQTIC subroutine for solving systems of equations, and two functional subprograms (E1 and E2) which evaluate integrals analogous to Fourier transforms in closed, complex algebraic form. The output data generally consist of basic header information, a summary of the system parameters modeled, and a summary of the magnitudes and phases of the terminal currents (per frequency) induced by the environmental field.

The SHIELD code is a prediction model for accurate simulation of crosstalk to or from braided-shield cables employing transmission line theory. Two main problems are addressed by the SHIELD code: (1) the effect of pigtailed on braided-shield cables which occur when cables are terminated in connectors and can lead to significant degradation in the effectiveness of a shield to reduce crosstalk and (2) the prediction of crosstalk between braided-shield cables.

The distributed parameter, multiconductor transmission line equations are solved for steady-state, sinusoidal excitation of the line. The line consists of unshielded and shielded wires where the wires may be above a ground plane or within an overall, cylindrical shield. Furthermore, the impedances of all conductors are incorporated within the model. The shielded wires may have solid or braided shields (through-braid coupling for braided shields is also included in the coupling prediction model).

During the development of SHIELD for coupling prediction and analysis, two coupling models were considered. A low-frequency model was valid only for a "sufficiently small" frequency. The upper limit to this frequency range was not unique but depended on the load impedances and physical configuration. However, the simplicity of this model allowed considerable insight into the coupling phenomenon and approximate predictions.

The multiconductor transmission line (MTL) model required considerably more computational effort, and the qualitative features of the coupling which were transparent in the low-frequency model were obscured in the MTL model. The advantage of the MTL model is its prediction accuracy. With the MTL model, one need not be concerned about the limitation of the frequency being sufficiently small as was required for the low-frequency model. The prediction accuracies of the MTL model tended to be in the range of 1 to 3 dB when the line is electrically short and 6 to 10 dB when the line is electrically long.

In addition, certain distributed effects which were not predictable with the low-frequency model were accurately predicted with the MTL model. For example, in the case of a single-end grounded shield and high impedance loads, there was a considerable difference in crosstalk depending on which end of the shield was grounded. Clearly, this is a distributed effect not predictable by the low-frequency model. However, the MTL model predicted this result within a few dB.

The input data for SHIELD include the number of shielded and unshielded wires and all of the data per wire required for XTALK. Required specialized shield characteristics include shield thickness and conductivity, braid wire radius, conductivity, angle, and the number of belts in the braid and the number of wires per belt. Pigtail characteristics include length, radius, and number of strands in the pigtail wire, the radius and conductivity of the strands, the radial separation of the pigtail wire from the shielded wire, and the angular position of the pigtail wire. Termination network data include the real and imaginary components of the current sources between each wire and the reference conductor, and the real and imaginary components of admittance between each wire and the reference conductor and between pairs of wires. All termination data are specified at both ends of the transmission line.

The program SHIELD consists of the usual controlling MAIN program, ten functional programs for calculation of self- and mutual-inductance, transfer elastance and inductance, and self- and diffusion-impedance for various types of conductors and shields, and six subroutines for matrix manipulation. All have appropriately chosen names. The calculational

subroutines LEQTIC and EIGCC are also employed. The voltages between each wire and the reference conductor are calculated at discrete frequencies, and provide the output results of the code.

Like the IEMCAP, GEMACS, and NCAP programs, the wire coupling prediction programs have nothing to do with orbits, antennas, or propagation, but those phenomena can be used to provide program inputs.

The seemingly obvious approach to interference analysis is the use of uniform, multiconductor transmission line theory to model the cable bundle. However, this model requires that the wires be parallel to each other along the entire cable length and their relative positions, of course, must be known and should not vary along the cable length. Random cable bundles do not satisfy these criteria. Another difficulty inherent in the application of the MTL model is the computation time required to obtain the response at each frequency. Determining the response of a large number of closely coupled wires at a large number of frequencies can be quite time consuming even on a modern, high-speed digital computer. Furthermore, in cases where the cable responses are sensitive to variations in relative wire position, it may be impossible to predict with any high degree of accuracy in random cable bundles. A more reasonable approach would seem to be the use of simpler models which bound or at least estimate these, perhaps sensitive, cable responses.

Software Considerations

All programs conform to ANSI Standard FORTRAN IV and were originally written in double-precision arithmetic. However, these codes have been converted to single-precision arithmetic. All the programs were originally implemented on an IBM 370/165 computer at the University of Kentucky using the FORTRAN IV, G-level compiler. They also have been implemented on the CDC/CDC CYBER, IBM, PDP, DEC, VAX UNIVAC, Burroughs, and Honeywell computers.

The program sizes and core requirements (based upon implementation on the Honeywell 6180 computer system) are listed in Table 7. The required support software routines (LEQTIC, EIGCC, NROOT, EIGEN) have been described in the discussion of the first four codes.

Table 7

PROGRAM SIZES AND STORAGE REQUIREMENTS

Program	Program Size (lines of code)	Core Required (decimal words)
XTALK	368	17K
XTALK2	534	19K
FLATPAK	474	17K
FLATPAK2	429	17K
GETCAP	932	15K
WIRE	703	20K
SHIELD	1,629	30K

Execution time will depend on the problem size and the choice of compiler. Problem size is limited primarily by internal array sizes which may be modified to expand the analysis capability.

References for Sec. B.4.d

Paul, C. R., *Applications of Multiconductor Transmission Line Theory to the Prediction of Cable Coupling*, Rome Air Development Center, AFSC, RADC-TR-76-101. In eight volumes:

Vol. 1 - *Multiconductor Transmission Line Theory*, April 1976.

Vol. 2 - *Computation of the Capacitance Matrices for Ribbon Cables (GETCAP)*, April 1976.

Vol. 3 - *Prediction of Crosstalk in Random Cable Bundles*, February 1977.

Vol. 4 - *Prediction of Crosstalk involving Ribbon Cables*, February 1978.

Vol. 5 - *Prediction of Crosstalk involving Twisted Wire Pairs*, February 1978.

Vol. 6 - *A Digital Computer Program for Determining Terminal Currents Induced in a Multiconductor Transmission Line by an Incident Electromagnetic Field (WIRE)*, February 1978.

Vol. 7 - *Digital Computer Program for the Analysis of Multiconductor Transmission Lines (XTALK, XTALK2, FLATPAK, FLATPAK2 descriptions)*, July 1977.

Vol. 8 - *Prediction of Crosstalk involving Braided-Shield Cables*, August 1980.

For further information on the wire coupling prediction models, please contact Kenneth Siarkiewicz, RADC/RBCT, Griffiss Air Force Base, New York 13441.

B.4.e SPECIFICATION AND ELECTROMAGNETIC COMPATIBILITY ANALYSIS PROGRAM (SEMCAP)⁶

Introduction

The Specification and Electromagnetic Compatibility Analysis Program (SEMCAP) predicts electronic system compatibility and creates generation and susceptibility specifications for controlling electromagnetic interference. Analysis can waive the specification for any selected interference generator or receptor.

The first version of SEMCAP was developed by TRW for NASA in 1968. It has been frequently revised, and the current standard is version 8. SEMCAP is owned and maintained by the Electromagnetic Environmental Effects Department of the Spacecraft Engineering Division, TRW Space and Technology Group. The EEE Department also provides all installation and consulting services related to SEMCAP, as well as on-site training in its use. SEMCAP is in current use at the Jet Propulsion Laboratory, Martin Marietta (Denver), Nippon Electric Co. (Japan), NLR (Netherlands), MATRA (France), Aeroitalia (Italy), British Aerospace (England), and other sites.

Although SEMCAP is not directly applicable to interference among space communications systems, results of programs that calculate the radiation of signals on space-to-earth or earth-to-space paths may be input to SEMCAP, and the electromagnetic compatibility of the subsystems of a space system application may be determined.

⁶Original material was submitted by Daniel S. Rosen, Defense and Space Systems Group, TRW.

Code Description and Capabilities

SEMCAP calculates the voltage produced at each receptor by a signal from each generator. This voltage is determined as an integral over frequency of the product of the generator spectral density, the transfer function connecting the generator to the receptor, and the receptor acceptance function. All systems are assumed to be linear. Summation over sources yields the total voltage at the receptor, and the voltage may be compared to the susceptibility threshold level.

The generators may be specified as voltage, current, E-field, or H-field spectral density sources. Voltage or current spectral density sources correspond to the time waveforms for a sinewave train of finite length, a trapezoidal pulse train, a ramp step function, or a random trapezoidal pulse. E- and H-field sources are modeled as produced by shielded or unshielded wires or antennas. Lowpass, high pass, and band pass filters may be included to modify the spectra.

The transfer functions simulate close-coupled capacitive or inductive transfer, including all combinations of shielding or twisting, and E- and H-field transfer via antenna gain or wire coupling, including the variation of field with distance. Receptors are characterized by a voltage threshold and filters similar to the sources. In addition, test data can be entered into the program in the form of spectral density curves for generators and passband curves for receptors.

Generators and receptors are divided into required (priority 1) and unrequired (priority 2) classes. The voltage output produced at each priority 1 receiver by each priority 1 generator is calculated and compared to the susceptibility level. Marginal and incompatible pairs are flagged for the attention of the user. The total voltage output at each required receptor is determined by summing the individual voltage outputs (which implicitly assumes steady-state conditions, since the voltage is a number resulting from a frequency integration, and this number contains no time dependence). The compatibility of each receptor with the entire system of generators is thereby established.

Priority 2 (unrequired) generators and receptors can be used as inputs to determine their effects on the required system. The levels of the external sources can be adjusted to match the generation and

susceptibility specification limits. SEMCAP can then be used to determine whether individual generator or receptor waivers can be granted safely.

The code structure permits the transfer of interference from any generator circuit to any receptor circuit via a number of paths. These paths are characterized by the coupling matrix parameters. Transfer may be wire to wire, involving capacitive, inductive, and resistive coupling, and involves the length and separation of the wires in a common run, plus a conduit leakage factor. Field transfer requires specification of the antenna parameters, transfer distance, and bulkhead attenuation.

Inputs to SEMCAP include control cards and data cards. Required control cards include title, geometry data, system data, run compatibility analysis, and end. Optional control cards determine input and output quantity and format. Data cards for geometry modeling describe the physical layout of the system. These cards include harness segment length cards, which give the length of the common runs of wires; system coupling matrix cards, which give the wire separation, conduit leakage, common resistance, and field distance; and bulkhead transmission curve cards, which contain the scalar and vector field attenuation as a function of frequency. Subsystem modeling data cards include wire data, which identify the wires of each type (shielded, unshielded, twisted, and combinations), and subsystem modeling data cards, which list the characteristics of each generator and receptor (voltage or other source type, receiver threshold, etc.).

The G1R1 control card executes the priority 1 generator-receptor compatibility analysis. The transfer matrices are calculated and the output voltage of each receptor (as produced by each generator) is found as a function of frequency, integrated, and summed as described above. If waiver cards are present, the indicated priority 2 generators and/or receptors are analyzed to determine whether the generation or susceptibility specifications can be waived.

SEMCAP provides a variety of print output options and several graphic outputs. The input program constants, geometric data, and subsystem modeling data may be listed. Error comments may appear for such items as wrong card format, missing wire types or data, or modeling

parameters which are out of their permissible ranges. The distance matrices for wires or antennas may be printed.

The calculation program determines the voltage and current amplitude and phase at each generator and receptor as a function of frequency. These quantities and their integrals over frequency may be printed. The G1R1 routine prints the fraction of the sensitivity limit voltage received by each priority 1 receptor (R1) from each priority 1 generator (G1) in each of the four modes (voltage, current, E- and H-field). Flags are printed to draw attention to possible compatibility problems. An optional output is a compatibility matrix, which has as each element a letter which indicates how serious is the compatibility problem, if any, for each G-R pair.

For priority 2 equipments, information is provided on how much the G2 output had to be decreased to be acceptable to all receptors, and how many iterations were required by the decreasing program. If waiver specifications are called, the output contains information on the interference received by each R1 terminal from each G2 terminal for which the waiver analysis is performed, and also on the interference received by the appropriate R2 receptors. A message is printed telling whether the specification can be waived for each generator or receptor.

Graphical outputs for generators show as functions of frequency the generation specifications for voltage, current, E- and H-field excitation. Graphics for receptors include eight susceptibility specification plots; four are the voltage specification spectra induced in receptors by the four types of interference excitation, and four are the running integrals of the susceptibility spectra. The total interference produced at each receptor in each of the four modes may also be plotted as a function of frequency.

Software Considerations

SENCAP consists of FORTRAN and assembly language subroutines. It is available for CDC CYBER/6600, IBM 360/370/3033, and DEC VAX machines. A Cal Comp or compatible plotter is required for the graphical outputs. Printer plots are also available. The program is self-contained and requires no support software save the standard system utilities from each machine. Approximately 40K words of storage are required.

For a small case--nine priority 1 generators and 11 priority 1 receptors--calculation of the receptor voltage matrix required about 4 CP seconds on the CDC 6600, determination of the compatibility matrix required about 20 seconds, and preparation and plotting of generator and receptor susceptibility specifications required about 32 seconds. For a larger case, 49 generators and 40 receptors required about 11 CP seconds on the CDC 6600 to calculate the receptor voltage matrix, and 311 CP seconds for the compatibility matrix. Execution time for the compatibility matrix increases approximately as the product of the number of generator terminals and receptor terminals, whereas the execution time for susceptibility specifications increases linearly with the number of terminals. The model types and model parameters used also affect execution time.

The number of generator and receptor circuits that can be modeled is limited primarily by the available computer resources. It should be possible to model several hundred circuits on most medium or large computers.

References for Sec. B.4.e

1. Johnson, W. R., et al., *Development of a Space Vehicle Electromagnetic Interference/Compatibility Specification*, Vol. 1, TRW Systems, Engineering Report 08900-6001-T000, June 1968.
2. Haidebrecht, J. B., *Program Description Document, Specification and Electromagnetic Compatibility Analysis Program (SEMCAP)*, Version 7.2, TRW Systems, October 1972, together with the necessary errata sheets and change pages necessary to describe Version 7.4.
3. Rosen, D. S., et al., *Program Description Document, Specification and Electromagnetic Compatibility Analysis Program (SEMCAP)*, Version 8.0, TRW Systems, publication pending.

Reference 1 provides engineering information inherent for the program, Ref. 2 describes the basic program, and Ref. 3 presents the current version.

For further information on SEMCAP, please contact Everett Beran or Daniel S. Rosen, Defense and Space Systems Group, TRW Inc., One Space Park, Redondo Beach, CA 90278.

B.5 INTERSYSTEM EMC ANALYSIS

Intersystem EMC analysis is concerned with compatibility between systems that generally operate remotely and whose primary coupling is through antennas. In particular, the systems to be discussed in the many subsections of Section B.5 involve communications or data links between satellites and earth stations. The satellite systems may be subdivided into geostationary communications satellites, which carry the bulk of space-transported messages, and nongeostationary satellites, which possess telemetry and command links.

Geostationary communications satellites generally act as transponders, which receive a signal from a ground station, amplify and frequency translate it, and transmit it to a second ground station. Interference on such links can occur in two ways. Uplink interference happens when the transmission from a ground station is received at a satellite other than the one associated with that ground station, and then retransmitted to the ground stations associated with the satellite which received the unintended message. Downlink interference occurs when a satellite transmits messages to ground stations other than the designated receiver. Both types of interference require that the satellites and ground stations have overlapping frequency bands and antenna coverages. The level of interference depends on the various system parameters such as power, antenna gain, frequency offset, receiver sensitivity, and geometrical configuration. The geostationary character of the systems implies that the configurations do not depend on the time, unless moving (airborne) ground stations are considered.

Nongeostationary satellites receive commands from and transmit telemetry to ground stations. If two such satellites, with overlapping frequency bands, are in a common antenna beam, they can experience severe interference. The fairly rapid motion of these satellites causes strong time dependence of such interference incidents.

Analytical procedures and computer codes dealing with signal interference on earth-satellite links are treated in this section. The analytical framework for interference on geostationary links appears in Section B.5.a (also see Ref. 1); that for nongeostationary in B.5.f. Computer programs are presented in the seven other subsections.

Undoubtedly there are other computer programs which deal with the subject, but these were all for which we requested and received information.

B.5.a ANALYTICAL INTRODUCTION

Many computer codes have been developed to investigate interference among communications links involving satellites and earth stations. Several of them will be described in the following sections. These programs all treat the same general problem, but with many differences in detail. An attempt to discuss each of them separately would lead to extensive redundancy. Since they are all based on essentially the same analytical framework, a single description of the fundamental analysis will provide the necessary background for all of them.

The model to be used is that of Reinhart.[2] Reinhart's general analysis is intermingled with a detailed treatment of orbit and spectrum sharing between fixed satellite and broadcast satellite services. The analytical material has been extracted and simplified to form this presentation. The theory is based on the principle that the several potential interference sources act independently, so their output powers may be added. This corresponds to linear, nonsaturating receivers. If C_i denotes the carrier strength of the i^{th} desired signal, and X_{ij} the strength of the j^{th} interference signal in the i^{th} receiver channel, then the noise-to-signal ratio at the receiver output is given by

$$\left(\frac{I}{S}\right)_i = \sum_{j=1}^N \frac{1}{R_{ij}} \left[\left(\frac{X_{ij}}{C_i}\right)_{\text{UP}} + \left(\frac{X_{ij}}{C_i}\right)_{\text{DOWN}} \right] \quad (1)$$

Here N is the total number of interfering links, and the prime on the summation indicates the term for $i = j$ to be omitted. The factor R_{ij} denotes the receiver transfer function for telephony, or the interference sensitivity factor for television signals. The subscripts UP and DOWN represent interference entering at the input to the uplink (satellite) receiver, and interference entering the downlink (earth station) receiver.

The receiver transfer characteristic R_{ij} is determined by the characteristics of the receiver and the signal and interference inputs. For multichannel telephony, its numerical value depends on the position of the telephone channel in the wanted signal baseband, the spectral characteristics of the wanted and unwanted signals as determined by the number of channels carried by each and the modulation index or RF bandwidth used, and on the frequency separation or offset between the wanted and unwanted carriers. When the signal on the wanted (i^{th}) link and the unwanted (j^{th}) link are both frequency modulated by a number of telephone channels in frequency division multiplex (FDM), and if the modulations are wideband (rms modulation index greater than unity), then it has been shown theoretically[3,4] that the receiver transfer characteristic for the highest telephone channel in the FDM baseband is given by

$$R_{ij} = \frac{\sqrt{8\pi} m_i^2 m W_n W_p f(n_i)}{\exp[-(1+v)^2/2m^2] + \exp[-(1-v)^2/2m^2]} \quad (2)$$

where

m_k = modulation index on link k ($k = i, j$)

n_k = number of channels on link k

$f_{mk} = .0042 n_k$ = maximum baseband frequency on link k (MHz)

$$m = [m_i^2 + (f_{mj} m_j / f_{mi})^2]^{1/2}$$

= composite rms modulation index

W_n = psophometric noise weighting factor ($10 \log W_n = 2.5$ dB)

W_p = preemphasis improvement factor ($10 \log W_p = 4$ dB)

$$f(n_i) = \frac{f_{mk}}{bg^2(n_i)} = \begin{cases} 1.71 n_i^{0.6} & 12 \leq n_i \leq 240 \\ 42.8 & n_i > 240 \end{cases}$$

b = highest frequency in telephone signal (3.1 kHz)

$$g(n_i) = \frac{\text{rms frequency deviation of an } n\text{-channel baseband signal}}{\text{rms frequency deviation of a single test tone}}$$

$$v = (f_j - f_i) / f_{mi} = \text{normalized carrier frequency offset}$$

The coefficient .0042 in the definition of f_{mk} has been given other values in different treatments of the same problem. The modulation index may be expressed in terms of the Carson's rule RF bandwidth by

$$\begin{aligned} m_k &= [W_k / (2f_{mk}) - 1] / \sqrt{\Lambda_k} \\ W_k &= \text{Carson's rule RF bandwidth on link } k \\ \Lambda_k &= \text{baseband peak to average power ratio on link } k \text{ (10 dB)} \end{aligned} \quad (3)$$

For identical signals ($n_j = n_i$, $m_j = m_i$), cochannel ($v = 0$) signals, a good approximation to Eq. (2) is

$$R_{ij} = (1 + 9.5m_i^3)W_n f(n_i) \quad (4)$$

For television signals, the receiver transfer characteristic takes the same form as in Eq. (2), except for the following replacements

$$\text{In the numerator, } \sqrt{8\pi}m_i^2 \rightarrow 0.2 + 8m_i^3$$

$$\text{In the denominator, } m^2 \rightarrow 1.57 + .85m_i^2$$

These expressions for the receiver transfer characteristic depend only on the type of signal being transmitted on each link. Accordingly, they can be determined at the beginning of a calculation of interference involving numerous links. However, the interference to carrier ratio X_{ij}/C_i depends on the radiated power of each transmitter, the antenna pattern of each transmitter and receiver, and the location of all link terminals (space and ground). The calculation of these interference to carrier ratios is the main task of the various computer programs. The interference to carrier ratio is given by

$$\frac{X_{ij}}{C_i} = \frac{P_j \pi_{ij} L_{ii}}{P_i \pi_{ii} L_{ij}} \quad (5)$$

where P_k is the power of the k^{th} transmitter ($k = i, j$), π_{ij} is the product of the gain of link j (interference) transmitting antenna and link i receiving antenna in the direction along the transmission path between them, L_{ij} is the transmission loss along that path, and π_{ii} and L_{ii} are corresponding expressions for the signal path. The powers are initial specifications. The transmission loss is proportional to the square of the range, inversely proportional to the square of the wavelength, and depends on any fading or attenuation along the path. The fading on most 4-6 GHz channels is not significant, but rain effects at 12-14 GHz or higher frequencies may cause appreciable reductions in either signal or interference if rain occurs on the appropriate path. Models have been developed for rain attenuation, [5] and they may be included in the computer program. The rain attenuation effects are generally regarded as probabilities that the attenuation will exceed a certain level for a certain duration, and are strongly dependent on geography. These models are really adjuncts to the main problem of interference calculations, which is to determine the antenna patterns in the directions of the lines of sight.

Consider the geometry of Fig. 12. The ground transmitter of link i is located at T_i and is pointed at satellite S_i . The receiver of link i is located at R_i , and it also is pointed at S_i . The antenna of satellite S_i is aimed at the point A_i . Corresponding notation applies to equipment j . There are two possible interference links. On uplink interference, leakage signal from transmitter T_j is received at S_i and retransmitted to R_i . On downlink interference, leakage signal from the transmitter on satellite S_j is received at R_i . The antenna gains depend on wavelength, polarization, and the angles between the appropriate lines of sight. A double subscript will be used to identify antennas, the first letter denoting the location, the second, U or D, whether it is part of an uplink or a downlink. The argument of an antenna angle will be designated by two letters, representing the points to which the antenna location, marked by the first subscript, is connected to form

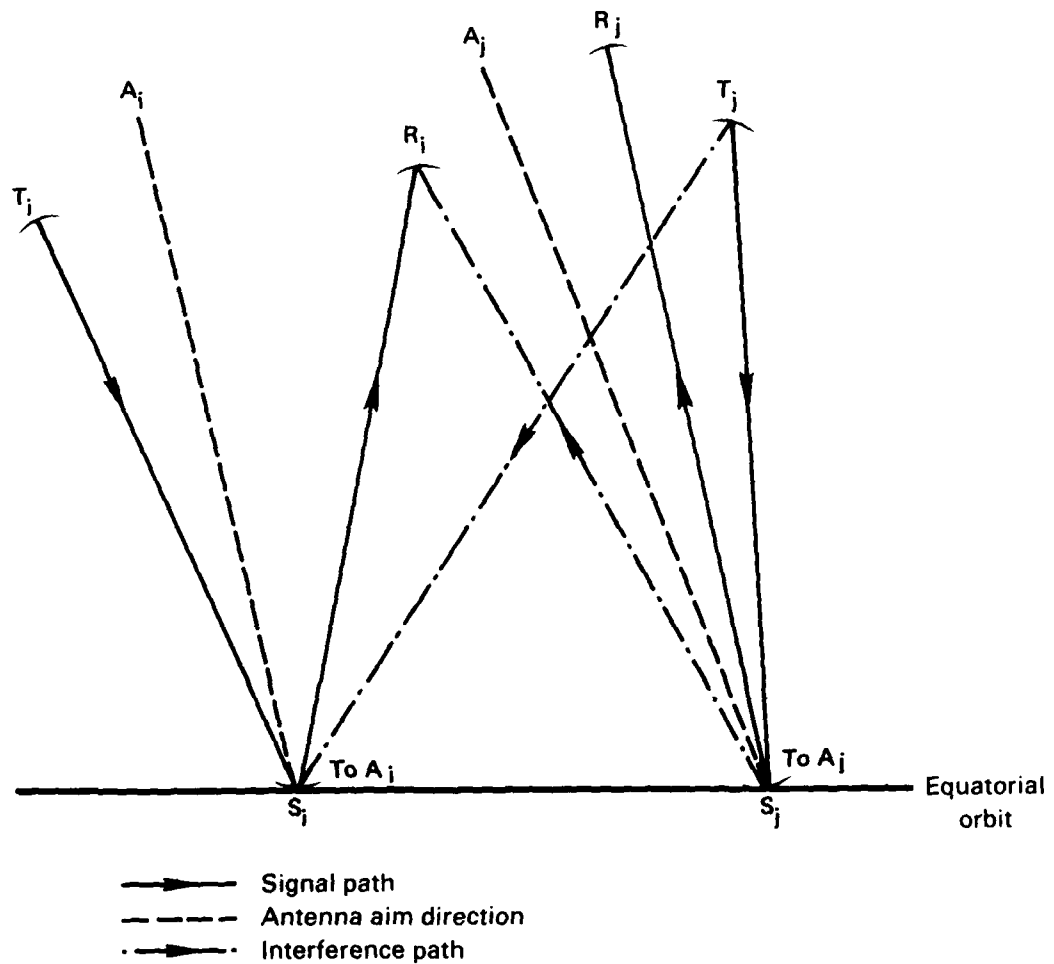


Fig. 12 — Interference configuration

the angle. Thus, the gain of the satellite antenna S_i when receiving a signal from the transmitter T_j is $G_{S_i, U}(T_j, A_i)$. Similarly, the range between two points will be indicated by r and designated by the two connected points. With this notation, the uplink and downlink interference ratios are given by

$$\left(\frac{X_{ij}}{C_i}\right)_U = \frac{P_{T_j} r^2(T_i, S_i) G_{T_j, U}(S_i, S_j) G_{S_i, U}(T_j, A_i)}{P_{T_i} r^2(T_j, S_i) G_{T_i, U}(0) G_{S_i, U}(T_i, A_i)} \quad (6)$$

$$\left(\frac{X_{ij}}{C_i}\right)_D = \frac{P_{T_j} P_{S_j} r^2(T_i, S_i) r^2(S_i, R_i) G_{S_j, U}(T_j, A_j) G_{S_j, D}(R_i, A_j) G_{R_i, D}(S_i, S_j)}{P_{T_i} P_{S_i} r^2(T_j, S_j) r^2(S_j, R_i) G_{S_i, U}(T_i, A_i) G_{S_i, D}(R_i, A_i) G_{R_i, D}(0)} \quad (7)$$

The argument 0 indicates the on-axis gain.

Communications satellites use different frequencies for uplinks and downlinks. In the 4-6 GHz band, the uplink frequency of a given channel exceeds the downlink frequency by 2225 MHz, in the military 7-8 GHz band the uplink frequency exceeds the downlink by 725 MHz, and in the recently developed 12-14 GHz band the uplink exceeds the downlink by 2,300 MHz. The antenna gain for an antenna of specified dimension is proportional to the square of the frequency, while the beamwidth is inversely proportional to the frequency. Hence, the uplink and downlink gains of a given antenna will differ, and the subscripts U and D on the gain functions are necessary.

Equations (6) and (7) have assumed that all signals have matched polarization. Although an antenna may be described as being either vertically or horizontally polarized, in practice there is some transmission or reception in the other polarization direction. Thus, in addition to the conventional antenna pattern $G^+(\psi)$ which shows the angular sensitivity in a specified plane (ψ) through the antenna axis to radiation of the polarization for which it was designed, there is a pattern $G^-(\psi)$ showing the response to the opposite polarization. This cross-polarization component is expected to be 30-35 dB below the copolarized pattern in the main beam, and 10-15 dB below copolarized in the sidelobes. As an example, if transmitter T_j is cross-polarized with respect to satellite S_i , then the gain product in the numerator of Eq. (6) is reduced by a factor

$$\frac{G_{T_j,U}^-(S_i,S_j)}{G_{T_j,U}^+(S_i,S_j)} + \frac{G_{S_i,U}^-(T_j,A_i)}{G_{S_i,U}^+(T_j,A_i)} + \sin^2 \epsilon \quad (8)$$

where ϵ denotes the angular misalignment of the polarization axes. Under these circumstances, the satellite transmitter S_j will be cross-polarized with respect to the receiver R_i , and the gain product in the numerator of Eq. (7) is reduced by a factor

$$\frac{G_{S_j,D}^-(R_i,A_j)}{G_{S_j,D}^+(R_i,A_j)} + \frac{G_{R_i,D}^-(S_i,S_j)}{G_{R_i,D}^+(S_i,S_j)} + \sin^2 \epsilon \quad (9)$$

The polarization of the signals is thereby taken into account by including the factors (8) and (9) when the corresponding links are cross-polarized. Alternation of polarization between successive satellites in an orbital arc is being employed to provide additional discrimination and channel reuse.

There is a great variety of antenna patterns which may be employed in communications links. Ground station patterns are almost always of circular cross-section, but satellite antenna patterns, which may be shaped to cover specified regions of the earth's surface, may be circular or elliptical. The antenna pattern may be given as an analytic function of angle, or as a set of points of a measured radiation pattern, or as a set of specified values of signal level on the ground. The analytic patterns must show both the main beam and the sidelobes.

The most frequently used functions for the copolarized main-lobe response of an antenna with circular cross section are the uniformly illuminated aperture pattern, given by

$$G^+(\psi) = G_0^+ [2J_1(x)/x]^2 \quad (10)$$

$$x = \pi D \sin \psi / \lambda$$

and the empirical Rice pattern

$$G^+(\psi) = G_0^+ \left[.9976 \left(\frac{\sin u}{u} \right)^{2.25} + .0024 \right] \quad (11)$$

$$u = \sqrt{\eta} (\pi D \sin \psi / \lambda)$$

where D is the antenna diameter, λ the wavelength, ψ the off-axis angle, G_0^+ the gain on axis, and η is the antenna efficiency. Other patterns include the gaussian, the polynomial fit, and the purely numerical representation.

The CCIR has suggested specific equations to represent the envelope of sidelobe peaks of communications antennas. For copolarized patterns of ground station antennas for fixed service, the formula to be used depends on the diameter to wavelength ratio, D/λ , as follows:

$$\begin{aligned} 10 \log G^+(\psi) &= \max[32 - 25 \log \psi, -10] & D/\lambda > 100 \\ &= \max[52 - 10 \log D/\lambda - 25 \log \psi, -10] & D/\lambda < 100 \end{aligned} \quad (12)$$

Broadcasting satellite service sidelobe patterns are given in terms of the ratio of the off-axis angle ψ to the half-power beamwidth ψ_0 . Antenna gain functions are also recommended for copolarized and cross-polarized patterns for satellite antennas. Besides these standardized patterns, many other sidelobe configurations are possible, and the various computer programs will generally provide several for calculations.

The satellite antennas are frequently designed to produce elliptical beams. To specify the pattern of an elliptical antenna in a plane through the antenna axis that intersects the reflector at an angle

ψ from its minor axis, it is assumed that the directivity $[G^+(\psi)/G^+(0)]$ at an off-axis angle ψ in that plane is the same as for a circular antenna with a diameter which is a function of the angle ψ . The angle ψ is found for a particular interference configuration by a straightforward although tedious exercise in solid analytic geometry. The computer programs generally include a section which performs this calculation.

The antenna patterns involve the off-axis angle ψ , which is to be found from the geometry of Fig. 12, and the range also appears in Eqs. (6) and (7). Most of the computer programs assume that the satellites are strictly equatorial, but some permit other latitudes. Let the latitude and longitude of any location in Fig. 12 be denoted by L and u , respectively. Measure distance in units of the earth radius, and let the satellites be in geosynchronous orbit at radius d (6.61 era). Then the range along a typical path, say from T_j to S_i , is given by

$$r^2(T_j, S_i) = 1 + d^2 - 2d \cos L_{T_j} \cos(u_{T_j} - u_{S_i}) \quad (13)$$

A typical off-axis angle at a satellite, say, the one at S_i between T_j and A_i , is given by

$$\cos \angle T_j S_i A_i = \{d^2 - d[\cos L_{T_j} \cos(u_{T_j} - u_{S_i}) + \cos L_{A_i} \cos(u_{A_i} - u_{S_i})] + \sin L_{T_j} \sin L_{A_i} + \cos L_{T_j} \cos L_{A_i} \cos(u_{T_j} - u_{A_i})\} / r(A_i, S_i) r(T_j, S_i) \quad (14)$$

while the off-axis angle at a ground station, say, the one at R_i between S_i and S_j , is given by

$$\cos \angle S_i R_i S_j = \{1 - d \cos L_{R_i} [\cos(u_{R_i} - u_{S_i}) + \cos(u_{R_i} - u_{S_j})] + d^2 \cos(u_{S_i} - u_{S_j})\} / r(S_i, R_i) r(S_j, R_i) \quad (15)$$

The omission of subscripts in Eqs. (14) and (15) is clear to the reader and simplifies the typography, but a computer program will of course be required to identify all arguments completely.

The formulas indicated here plus the variations on the antenna patterns constitute the basic equations of the theory. The computer programs implement these equations and apply them to vast numbers of special cases. Many programs will be described in the following subsections, but all of them except the two programs involving nongeostationary satellites are covered by this analytic introduction. The two special ones will be discussed separately.

References for Sec. B.5.a

1. Jansky, D. M., and M. C. Jeruchim, *Communications Satellites in the Geostationary Orbit*, Artech House, Inc., Dedham, MA, Parts 2 and 3.
2. Reinhart, E. E., *Orbit-Spectrum Sharing Between the Fixed-Satellite and Broadcasting Satellite Services with Applications to 12 GHz Domestic Systems*, The Rand Corporation, R-1463-NASA, May 1974.
3. Jeruchim, M. C., and D. A. Kane, *Orbit/Spectrum Utilization Study*, Vol. IV, General Electric Space Systems Organization, Valley Forge Space Center, Document No. 705D4293, December 1970.
4. Hamer, R., "Radio Frequency Interference in Multichannel Telephony FM Radio Systems," *Proc. IEE*, Vol. 108B, January 1961, pp. 75-89.
5. Crane, R. K., "Prediction of Attenuation by Rain," *IEEE Transactions on Communications*, Vol. COM-28, No. 9, September 1980.

B.5.b COMMUNICATIONS SATELLITES INTERFERENCE MODEL

Introduction

This program calculates possible interference on geosynchronous communications satellite links. It was originally developed by The Rand Corporation in 1974,[1] and has been improved and extended by the FCC[2] and the Office of Telecommunications Policy of the U.S. Department of Commerce, now the National Telecommunications and Information Administration (NTIA).[3] The program is maintained by NTIA. Program copies are available in Rand and NTIA reports.

The code is a general purpose program for calculating interference. It was originally designed to treat interference effects among broadcasting satellites, but can be applied to any link involving earth stations and geosynchronous satellites. The program calculates the carrier to interference ratio at the receiver input with as little approximation as possible, then uses the receiver demodulation

characteristics to determine the signal impairment. The many variables differ in the several versions of the program. The program is relatively simple to use.

Code Description and Capabilities

The code is designed to treat interference among signals carrying multichannel telephony, telegraphy, or television. It follows the framework of the analytical introduction. Digital signals cannot be treated with this program.

The program inputs include the number of links, satellites, and ground stations, both fixed and broadcasting. Each satellite and ground station has an identification and a latitude and longitude. For each station, the description includes the transmitter power, the dimensions, efficiency, and co- and cross-polarized patterns of the transmitting and receiving antennas, and the receiving system noise temperature. The description of each link includes the identity of the satellite and two earth stations, the uplink and downlink carrier frequencies, the RF bandwidth, and the number and type of message channels.

The original (Rand) version of the program consists of a main routine and three subroutines. For each link of the fixed-satellite system, the MAIN routine computes and prints the output interference in the worst telephone channel in psophometrically weighted output, picowatts (pWOp). This is done by summing the individual contributions entering the uplink and downlink sections, using values of the receiver transfer function computed by subroutine RTC, the effective diameter of elliptical satellite antennas computed by subroutine ELLPS, and the antenna gain products computed by subroutine GAIN. The later version[3] also uses a subroutine VOA which determines the length of arc of the equator visible to a ground station, taking atmospheric refraction into account, and thereby establishes the mutual visibility of the satellites and ground stations. Similar calculations for broadcasting satellites compute and print the effective carrier-to-interference ratio at the inputs to the receivers at the selected receiving sites.

The structure of the code is as follows. After the dimensions of the various arrays are established, the input data on the link characteristics are read and stored. All relevant path lengths and

intersatellite and interstation distances are computed. The uplink wanted signal power for each link i is found, then the uplink unwanted power from each transmitter j into link i . In these calculations, the off-axis angles are found for each link, and used in the subroutines ELLPS and GAIN to find the received power. The subroutine RTC is used to calculate the receiver transfer characteristic R or sensitivity factor Q , and then to compute the uplink output interference contribution from link j into link i . The results are stored for each link, and after all links j have been included, the output interference powers are summed over j to obtain the aggregate interference power. Precisely similar calculations are performed for the downlinks. The results for individual and total interferences are printed as actual power for fixed satellites and as carrier-to-interference ratio for broadcast satellites. In the later version, the subroutine VOA is employed before each link calculation to determine if visibility is possible, and thereby eliminate unnecessary computation.

The normal printout includes a detailed description of the system parameters and link geometry and a link-by-link breakdown of noise and interference levels--uplink, downlink, and combined. If a more detailed look at the interference contributions is desired for diagnostic analysis, a link-by-link listing of all $2N(N - 1)$ interference entries can be commanded. In this printout, the individual interference contributions, link geometry, wanted and unwanted signal power, receiver transfer characteristics, antenna gain products along the interference paths, and carrier-to-noise ratios are all listed for each link contribution.

The program is limited to analog signals. Telephone channels must use frequency division multiplex (FDM) and frequency modulation (FM), and television signals must also employ FM. FDM/FM basebands must include 12 or more channels and employ rms modulation indices greater than unity. All satellites must be geostationary, but there are no frequency limitations.

Ground stations are assumed to use circular cross-section antennas, but the satellite antennas may be circular or elliptical. The long dimension of the footprint of an elliptical satellite antenna can be oriented in any direction. The main beam has the Rice pattern, and any

of the several antenna sidelobe envelope patterns suggested by the CCIR for interference calculations in either fixed or broadcasting service may be specified for any antenna. Antenna pointing errors, amounting to 0.1 deg for satellites and 0.1 of the half-power beamwidth for earth stations, are included in all link calculations in such a way as to diminish wanted signals and enhance unwanted signals.

The expression used in this program for the effective diameter of an elliptical antenna is not correct. The program takes the effective diameter in a plane making an angle ψ with the major axis of the ellipse as the actual diameter in that plane. If a and b are the major and minor axes, then the actual diameter is

$$D(\psi) = 2ab/[a^2 \sin^2 \psi + b^2 \cos^2 \psi]^{1/2} \quad (16)$$

However, the antenna pattern of a uniformly illuminated elliptical aperture can be calculated[4,5] and leads to the true effective diameter

$$D_T(\psi) = 2[a^2 \cos^2 \psi + b^2 \sin^2 \psi]^{1/2} \quad (17)$$

For an ellipse with an axial ratio of 2, which is typical of U.S. coverage elliptical antennas, the true effective diameter at an off-major-axis angle of 45 deg exceeds the actual diameter by 25 percent, with a corresponding change in the beamwidth. This same problem occurs in other satellite interference calculation programs such as SOUP.

The program uses free-space line-of-sight propagation, except for the refraction correction in VOA, and employs the standard algorithms for demodulation and baseband processing, as typified by the receiver transfer function. There are some differences in analytical detail in the several versions of the program, mostly having to do with the coefficients used to relate the maximum baseband frequency and the number of channels, or the peak-to-average power ratios, which are fixed in the original (Rand) version, but are variable in the later versions.

Software Considerations

The program is written in FORTRAN IV G. The original (Rand) version contains 657 lines of code; the later (NTIA) variation includes 963 lines. The Rand version has been operated on the IBM 370, the NTIA version on the UNIVAC 1108. The program is self-contained, except for calls for trigonometric functions, and can be operated on any machine which reads FORTRAN IV G.

Computer storage required to compute the interference among 120 links involving 50 satellites and 35 earth stations was only 86 kilobytes of core. The calculation of nine separate cases (different satellite configurations and/or system parameters) of the indicated size required about 72 seconds of machine time on the 370.

The original version is limited to 52 satellites, 35 earth stations and satellite antenna imprints, and 120 links and sublinks. The later version is limited to 90 satellites, 50 ground points, 90 links, 60 additional broadcast receivers, 150 total ground receivers, and 36 fixed or broadcasting inhomogeneous systems. These numbers were selected arbitrarily. Either can be readily enlarged by changing the dimension statements, which is especially simple for the later version, which only involves changing the indicated number of, say, satellites. The original version requires changing the dimension of all arrays which depend on the indicated parameter. Little increase in size is involved (to increase the number of links from 120 to 240 would only add 12 kilobytes), but the running time would be quadrupled if the number of links were doubled.

References for Sec. B.5.b

1. Reinhart, E. E., *Orbit-Spectrum Sharing Between the Fixed-Satellite and Broadcasting-Satellite Services with Applications to 12 GHz Domestic Systems*, The Rand Corporation, R-1463-NASA, May 1974.
2. Das, S., and G. Sharp, *Satellite System Interference Modeling (11.7-12.2 GHz)*, Federal Communications Commission, FCC Report No. RS-76-04, September 1976.
3. Ng, H., *Satellite Interference Model Program: User's Manual*, U.S. Department of Commerce, Office of Telecommunications, Report TN-77-3, June 1977.

4. Adams, R. J., and K. S. Kelleher, "Pattern Calculations for Antennas of Elliptical Aperture," *Proc. IRE*, Vol. 38, No. 9, September 1950, p. 1052.
5. Spies, K. P., and E. J. Haakinson, *Calculation of Geostationary Satellite Footprints for Certain Idealized Antennas*, U.S. Department of Commerce, National Telecommunications and Information Administration, NTIA Report 80-51, October 1980.

Reference 1 is a complete treatise on satellite link interference. The computer program is clearly described and listed in the appendix. Reference 2 shows the changes introduced by the FCC, and Reference 3 presents further changes, a description, and a complete listing. References 4 and 5 give the correct formulas for elliptical antenna patterns.

For further information on this program, please contact W. Sollfrey, The Rand Corporation, 1700 Main Street, Santa Monica, CA 90406, or H. J. Ng, U.S. Department of Commerce, National Telecommunications and Information Agency, 179 Admiral Cochran Drive, Annapolis, MD 21401.

B.5.c ADJACENT SATELLITE INTERFERENCE MODEL⁷

Introduction

This program has been developed to assess the impact on U.S. domestic satellites of reducing the orbit spacings between satellites. It was developed by and for the Federal Communications Commission (FCC) in 1981. It is maintained and used by the FCC Office of Science and Technology, and is available from G. Sharp of the FCC.

The program was used by the FCC to perform the analysis supporting the FCC's proposal to implement uniform 2 deg geostationary orbit spacings for all U.S. domestic satellites. It determines adjacent satellite interference as a function of orbit spacing, earth station antenna pattern, and modulation. It can compute the interference between the signal formats in common usage on today's domestic satellites.

⁷ Original material was supplied by G. Sharp, Federal Communications Commission.

Code Description and Capabilities

The computer code is based on analyses associated with the communications satellite interference model (Rand, NTIA), and the Spectrum Orbit Utilization Program--SOUT (Sec. III.B.5.d). However, it is quite different in that it deals with the interference among the many signal channels on a specified pair of satellites. Besides the signal types of the cited programs (FDM/FM, TV/FM), the signal formats can include phase shift keying (PSK), single channel per carrier (SCPC)/PSK, SCPC/FM, companded single-sideband AM (CSSB/AM), and spread spectrum PSK. Inputs required for each link include signal type, bandwidth, number of channels, modulation index, top and bottom modulation frequencies, average talker level, compander preemphasis advantage and noise weighting, number of phases, data rate, and channel spacing. The up and down frequencies and polarizations are required for each transponder. The power, antenna diameter, and gain are required for each earth station transmitter, the receiver antenna gain temperature and the transmitter effective isotropic radiated power (EIRP) for each satellite, and the antenna diameter, gain, and system noise temperature for each earth station receiver.

Each of the N selected links is assumed to be the desired link on a domestic satellite. An adjacent satellite X degrees away in geostationary orbit and carrying the same N links provides the interference. In an iterative fashion both the satellite spacing and the earth station antenna sidelobe envelope (several CCIR patterns) are varied. Thus, for each combination of satellite spacing and antenna sidelobe envelope, $N \times N$ interference computations are performed. For each of these $N \times N$ combinations, a carrier-to-interference (C/I) ratio and, if required, a signal-to-interference (S/I) ratio, are computed. This interference ratio is compared to the wanted signal's single-entry adjacent satellite interference objective to determine the margin for that combination of links on adjacent satellites. A typical output is a series of $N \times N$ matrices displaying the links which suffer negative margins.

The program is limited to geostationary satellites. There are no true frequency limitations, but atmospheric losses corresponding to the 6/4 GHz and 14/12 GHz bands are employed at present. All satellite antenna patterns are modeled as a single gain value, with all earth stations located on the -3 dB (relative to maximum gain) contours of the space station antenna gain patterns. Earth station patterns are a Rice model main lobe and several CCIK-type sidelobe envelopes. No atmospheric losses are included in carrier-to-interference ratios, but absorption and path losses for 10 deg earth station elevation angle are included in the calculation of the carrier-to-noise ratio.

The receiver transfer characteristics for FDM/FM and TV/FM are those of the Spectrum Orbit Utilization Program. Flat yellow TV/FM spectral masks are used to determine interference into digital and SCPC signals, with interference into digital channels modeled as thermal noise. Interference values are for the top baseband channel for FDM/FM signals. In cases where there are multiple carriers per transponder, the received interference levels are those caused to the carrier receiving the most interference, and the interference caused to a carrier is the total resulting from the ensemble of carriers in the transponder.

Software Considerations

The program is written in Honeywell Level 66 FORTRAN, and contains approximately 1700 lines of coding. It is installed on the Honeywell 6650 and is self-contained. Computer storage requires 51K words minimum for compilation and 74K words minimum for execution. The input data file contains approximately 13,000 characters. A typical run for 60 links, consisting of a total of 4264 carrier frequencies, required about 10.8 minutes CPU time.

The problem size is limited to approximately 60 links if the output matrix is to fit on a single page. Each link includes one satellite, one uplink and one downlink. Earth stations are the same for a single link. The number of carriers per transponder can range from one to approximately 600-800 for SCPC links. The program is limited to a total of 5000 carrier frequencies for all 60 links.

References for Sec. B.5.c

1. FCC Notice of Inquiry and Proposed Rulemaking, CC Docket No. 81-704, adopted October 1, 1981 (FCC 81-466).
2. Sharp, G., "Reduced Domestic Satellite Orbital Spacings at 4/6 GHz," FCC, Office of Science and Technology, Technical Analysis Division, FCC Report No. FCC/OST R83-2, May 1983.

Reference 1 gives the FCC proposal, Ref. 2 the supporting analysis and description of the computer program.

For further information on this program, please contact George Sharp, Federal Communications Commission, 1919 M Street NW, Washington, DC 20554.

B.5.d SPECTRUM ORBIT UTILIZATION PROGRAM (SOUP)

Introduction

This program is designed to compute the mutual interference among a large number of communications links, operating at the same or overlapping frequencies, between earth stations at specified locations through satellites in specified orbit positions. It was first developed by the General Electric Company, Valley Forge, Pennsylvania in 1969-70, and has been extended and improved by ORI, Inc., Silver Spring, Maryland, from 1971 to the present. The initial development was for the then Office of Telecommunications Policy with substantial funding provided by NASA. Since 1971, most of the funding has been provided by NASA, with some additional funds from the National Telecommunications and Information Agency and the Federal Communications Commission.

Two versions of SOUP, SOUP-3 and SOUP-5, are in current use. Both are maintained by ORI, Inc., and are available from NASA or ORI, with all necessary services available. A partial list of users includes ORI, FCC, NTIA Annapolis, NTIA Boulder, NASA Lewis Research Center, Ohio State University, and the International Telecommunications Union, Geneva, Switzerland.

The two programs employ the same basic analytical framework, but differ considerably in detail. SOUP-3 is designed for both fixed and broadcasting satellite services. It computes carrier/interference ratios as well as total interference power in picowatts for FDM/FM

signals and error rates for digital signals. SOUP-5, developed exclusively for broadcasting service, computes only carrier/interference ratios and margins.

Among the advantages of SOUP-5 over SOUP-3 are that, whereas SOUP-3 can handle 99 links, SOUP-5 can treat up to 800 feederlink transmitters, 2400 earth station receivers, and 80 service areas with only 15 percent of the computer memory requirements of SOUP-3. SOUP-5 has an easily maintained data base, and includes the 1982 CCIR rain attenuation model. Detailed differences involve receivers, with SOUP-3 using receiver transfer constants, SOUP-5 a protection ratio template; the treatment of non-copolarized interferers, with SOUP-3 treating only clear-sky conditions, SOUP-5 including rain depolarization; and antennas, where only the SOUP-3 patterns can treat interpolation, but SOUP-5 includes additional antenna types. Each program provides very extensive output data, available both in summary form and in a detailed systems engineering format.

Code Description and Capabilities

The programs follow the same general pattern, but with a difference in the control routines. SOUP-3 has a single MAIN routine which calls on 43 subroutines to perform the computations. SOUP-5 is broken into three parts, P1, P2, and P3, which in turn provide outputs to the user and inputs to the succeeding part. We shall describe the inputs for SOUP-3, then indicate the differences for SOUP-5. For each link (up or down) one specifies the service type (telephony, television, digital), the frequency, channelization scheme (grouped into families displaying highest and lowest frequency), number of channels, channel spacing, bandwidth coefficient, modulation index, bit rate and number of phases for digital signals, peak to average power ratio, transmitter power, receiver noise temperature, and the co-channel and adjacent channel protection ratio. For each earth station, the latitude and longitude, antenna diameter, polarization discrimination, aperture efficiency, and antenna sidelobe pattern, given as a gain type and as a table code for both the copolarized and cross polarized patterns, are required. The patterns available will be described later. For each satellite, in addition to the above, one specifies the coverage angle, the coordinates

of the antenna aimpoint, and for elliptical antennas, the axial ratio and the coordinates of a reference point on the major axis of the pattern. The information is to be provided for both transmitters and receivers.

For SOUP-5, besides the indicated data, a scenario must be specified that describes the orbit positions, service areas, and special frequency sharing arrangements. Antenna pointing and rotational tolerances are included. The rain model requires the specification of the rain zone, worst-month availability for links to each service area, and antenna height above mean sea level. Protection ratios are introduced as a template, which takes the place of the receiver transfer constant. The transmitter power may be specified as a power, an EIRP, or calculated from a specified power flux density or carrier-to-noise ratio, and there are multitudes of flags to determine input or output options.

We shall first describe SOUP-3.[1] The MAIN program begins by reading all inputs and repeating them to the user. SOUP-3 then calls the principal subroutine SINT1, which calculates the power received at the input to each receiver from all transmitters. SINT1 calls on 13 subroutines, which determine first the bandwidths and wavelengths, beam vectors, and orientation of elliptical antenna patterns. Next, the frequencies and bandwidths of the various signals are compared. If channels are common, the interference is co-channel. If the bandwidths overlap, the interference is adjacent channel. If the nominal bandwidths (Carson's for telephony and corresponding expressions for television and digital signals) do not overlap, the signal pair is regarded as non-interfering, and no further computations are performed for that link. This treatment implies the receivers have a perfectly sharp cutoff and the signals are completely restricted to their nominal bandwidth, an assumption which is not particularly realistic and has been improved in SOUP-5.

If the signals are deemed to interfere, SINT1 continues by calling subroutines which calculate the range from each ground station to each satellite, the relative position of each ground station with respect to the major axis of any satellite antenna with an elliptical pattern, and the off-axis angles of satellite antennas receiving from interfering

ground stations, or ground stations receiving from satellite transmitters directed at other aimpoints. The gain of each antenna in the appropriate direction is calculated, and the copolarized and cross-polarized gains combined, allowing for polarization misalignment. From these quantities, the power delivered at the input to each receiver is determined for all interfering up and down links. SINT1 is then complete, and a data conversion subroutine, GSKPHI, is called to convert the result to the form specified by the input option statements.

The calculation to this point has not considered that the signals may be of various types. The MAIN program calls the second principal subroutine, SINT2, which calculates the receiver transfer constants for the signals in mutual interference on each link. The total interference power, carrier to interference ratio, etc. at the output of each receiver can then be found. These results are then delivered to subroutine OUTPUT to be printed for the user.

The output of SOUP-3 is quite extensive. The input parameters are repeated. A set of intermediate calculated quantities is available for each uplink or downlink. These include coordinates, elevation and azimuth angles of ground station antennas, slant range, off-axis angles, antenna gains in dB, received carrier power, and carrier to interference ratio. Each of these quantities is presented separately as an $N \times N$ matrix (N is the number of links). Since calculations are not performed for non-interfering signals, the results can appear anomalous, i.e., zeroes in the range matrix.

One table of interference analysis results is presented for each link. The computed parameters depend on the service type of the carrier. Results are shown separately for uplinks and downlinks. All service types show the maximum average flux density in dB for downlinks. For telephony links, the table shows the thermal noise power, total interfering noise, total system noise, and noise for each interfering carrier, all in picowatts. For television links, the table shows the thermal signal to noise ratio (S/N), the total interfering S/N , the total system S/N , the reference protection ratio, the equivalent carrier to interference ratio, and the S/N and carrier to interference ratio for each interfering carrier, all in dB. For digital links, the table displays the thermal and total system carrier to noise ratio (C/N) and the carrier to interference ratio for each interfering carrier.

A summary table shows, for each link, the satellite longitude, the carrier to interference ratio up, down, and total, the protection ratio, and the margin. The table identifies the link which causes the worst interference, both up and down. This summary table is prepared for both co-channel and adjacent channel interference.

SOUP-3 is limited to geostationary orbits. There are no frequency limitations. The antenna pattern listing includes seven antenna types. Four of these involve segmented patterns, in which the gain on each segment is expressed as an algebraic or logarithmic function of the off-axis angle or the ratio of the angle to the beamwidth. These include the WARC 77 copolarized, WARC 77 cross-polarized, and CCIR fixed patterns, plus a pattern in which the main beam is an eight-term power series. The fifth pattern type, arbitrary gains, specifies the gain of each satellite antenna in terms of its ground coordinates, up to a maximum of 100 sets of latitude and longitudes. If the earth latitude and longitude for an antenna match a pair of coordinates in the table, the gain is set equal to the corresponding gain value in the table, otherwise the gain is set to zero. The sixth pattern type, primarily for satellite antennas, determines the gain by bivariate interpolation in a table of gain values specified on contours on the earth's surface, up to 100 points. The seventh pattern type is similar to the sixth, except that the points are given in polar coordinates in a plane perpendicular to the antenna axis. Satellite antenna patterns may be circular or elliptical, but ground station patterns must be circular. To specify any antenna, the pattern type must be given, plus a table code, which directs the gain calculation to a table which gives the constants appropriate to each segment for the first four types, or the coordinates and gains for the last three.⁸

In SOUP-3, propagation is free space line of sight, with a correction for the horizon. Standard algorithms are used for received power in terms of the geometrical and gain parameters, and for the

⁸The analysis and interpolation codes for the fifth, sixth, and seventh antenna types were developed by the Department of Commerce, National Telecommunications and Information Administration, Institute for Telecommunications Sciences, Boulder, CO, who also modified type 5 to include an interpolation program similar to that of type 6.

receiver transfer constants. There are no apparent intrasystem applications.

SOUP-5[2,3] is especially designed for broadcasting satellite operations, but is applicable to other services. Calculations are performed for sites within or external to service areas, which are the areas within which service is desired. Feederlink transmitters (FLT) and earth station receivers may be allocated to the service areas in any manner, except that each area may have no more than 50 transmitters and 50 receivers. Sets of service areas may be linked into groups which coordinate their transmissions in frequency blocks. This feature, which is also available in SOUP-3, automatically precludes the calculation of interference between links in the group. The uplink and downlink interference calculations are completely independent, so that a service area may have different channelizations, satellite and earth station positions, satellite and earth station antenna beams and polarizations, and ground test point locations for up and down. For uplink calculations, where the interference is to the satellites, the interference from each FLT is summed on one satellite. Although each service area may have a number of possible FLTs, in reality only one can be operated at the same frequency/polarization at a time. (There could be two mutually cross-polarized FLTs, operating into corresponding antennas on the same satellite, but this configuration is equivalent to running two problems.) Thus, one co-channel FLT from each service area and the appropriate adjacent channel FLTs are used in summing aggregate interference. The FLT giving the weakest signal from the satellite's own service area is used to calculate carrier power, and the appropriate FLTs giving the strongest co-channel and adjacent channel signals from each interfering service area are used to calculate the interfering power. For downlink calculations, the interference on each receiver is summed over all interfering satellite transmitters.

The analytical formulation of SOUP-5 does not differ much from that of SOUP-3, so the inputs are essentially the same. Since SOUP-5 contains the CCIR rain attenuation model, the rain zone, ground station altitude, rain occurrence percentage for the worst month of the year, and allowable rain margin are required inputs. The data which are needed in SOUP-3 to calculate receiver transfer constants are replaced

in SOUP-5 by a set of protection ratio templates, which specify the required protection ratio as a function of frequency offset and channel bandwidth. SOUP-5 uses a card image version of the broadcast satellite R2BCSAT-83 data base, and requires a data scenario in specified format to describe the problem which is to be treated. There is an extensive list of optional data overrides, flags, and debug choices.

SOUP-5 is divided into three parts. Program P1 selects the data from the data base which are needed for the run and assembles them into a form usable by programs P2 and P3, echo printing the selected data, while checking and editing for completeness, correctness, and consistency. Program P2 performs calculations associated with each signal path. Using various subroutines, it reads the control and table files, checks for errors, performs necessary conversions, and writes binary data for program P3. It transforms ground and satellite coordinates, calculates transmitter power and antenna noise temperature if they are to be derived from other inputs, and calculates a nominal wavelength for each channel family. P2 determines interference categories (co-channel, upper adjacent, etc.) between channel families, checks to ensure the Regional Administration Radio Conference (RARC) channelization parameters have not been violated, and calculates the protection ratio for each interference category using the selected template.

Program P2 calculates the on-axis gains and beamwidths of all antennas. It determines the axial directions for all satellite antennas, and, for elliptical antennas, the orientation angle of the beam major axis in the beam plane (the plane perpendicular to the antenna axis). If the user desires, P2 will print a table and a graph of gain as a function of off-axis angle for each gain table used in the run.

Program P3 performs "cross" functions, that is, those involving more than one signal path. It looks up the interference category, and makes no calculations if channels are non-interfering or if both the satellite and the ground station belong to a group sharing a common frequency block. If they interfere, P3 calculates slant range, off-axis and orientation angles, copolarized, cross-polarized, and equivalent antenna gains for each path. It determines the rain

attenuation, and thence the received power. The appropriate FLT is selected, the interference powers are summed taking block allocations into account, the carrier to interference ratios and the margins are found for all interference categories, and the worst interfering service areas are located for each link in all five interference categories.

SOUP-5 provides both hardcopy and binary outputs. Program P1 echoes the input data and transmits it in proper form to P2. Program P2 provides the user with messages to warn of errors in the input data and diagnostic output as requested, and sends to P3 the results of its single link calculations. Program P3 provides diagnostic output, summary reports containing the up, down, and total aggregate interference, and two detail reports, each containing one line describing each link equation calculation. The first detail report provides gains, carrier to interference or carrier to noise ratios, peak flux density, received power, interference category, and polarization information. The second gives frequency, geometric parameters, and rain attenuation parameters. P3 also produces a binary output with one record per link equation calculation containing the data needed for a report generator. If no calculations are made, which would occur if the satellite were over the horizon to the earth station, or if the channels were non-interfering, the report tables are filled with flag values.

The total quantity of data in the input and output of SOUP-5 can be very large. In a test problem run by ORI, the mutual interference was calculated among ten service areas served by ten satellites. Downlink interference was computed for 36 receivers. The scenario description required 12 printed pages, two for RARC parameter values and one for each service area. Only 27 lines of actual values were included, the rest being headings and definitions. Data parameters (channelization, protection ratios, point sets, beams, antenna characteristics, and gain tables) occupied nine more pages. These pages were duplicated as control data, and again as downpath data. Thirty pages of diagnostic data follow, giving innumerable intermediate results of the calculations. Each of the two detail reports occupies eight solidly printed pages, and the aggregate downpath summary (the only one in this case) occupies two more. With the inclusion of debug option listings and control data, the total input occupies 37 pages, the total output 48

pages. If the option to print and graph the gain tables had been included, there would have been 12 more pages.

We include as Table 8 a typical page from detail report No. 1, showing locations, gains, received power, and C/I, and, as Table 9, the aggregate downpath summary. The flag values (e.g., 999.9) correspond to over the horizon conditions, since non-interfering signals have been culled from the presentation. As can be seen from the margin values in the aggregate summary, the configuration treated in this test case is subject to severe interference, since some of the margins are actually negative.

For SOUP-5, the program constants are for geosynchronous orbit, but the orbit can be inclined. The program can be modified to be driven by an orbit generator, so there is no inherent limitation. There are no frequency restrictions except those in the rainmodel. Like SOUP-3, the antenna patterns of SOUP-5 are characterized by a pattern type and a gain table. The type can be a composite of sections, each of which is an algebraic or logarithmic function of the off-axis angle and the beamwidth (Type 1), or by a "fast roll-off" equation, in which the segment boundaries are functions of the beamwidth (Type 3) or of the beamwidth and the minimum antenna diameter (Type 4). (There is no Type 2.) The constants for the segment boundaries and the gain equations are given in the gain table associated with each pattern employed in the run.

The propagation model for SOUP-5 is line of sight with rain attenuation and cross-polarization discrimination based on data contained in the latest CCIR study Group 5 reports. The algorithm used in the program is a modification of Group 5 report 564-1 (Mod F) (Doc 5/5048). It first converts from worst month to annual statistics, then estimates the height of the rain above mean sea level and the slant path length through the rain. The height depends on the latitude, the slant path on the height of the ground point above mean sea level, the elevation of the line of sight, and the rain height. The height and occurrence probability are correlated, so the slant path length is reduced appropriately. The specific attenuation corresponding to the particular climate zone and the desired percent of time is found as a function of frequency, then multiplied by the reduced path length to

Table 8
TYPICAL PAGE FROM DETAIL REPORT #1 FOR CANTEST 1 DOWN

* SERVICE AREA *	SAT LONG DEG-E	* EARTH STA *	C/I DB	PFD W/SQM	RVC-D POWER DBW	*****		ANTENNA GND-X DB	GAINS SAT-CD DB	*****		EQUIV GAIN DB	INTRF CAT	PAGE	4	
						GND-CD DB	SAT-X DB			SAT-CD DB	SAT-X DB					
CANPESTD	-125 0	56 9	-89 0	18 30	-96 73	-122 94	39 56	14 56	40 57	5 82	57 58	UP-ADJ	X			
	CANPESTD	-100 0	56 9	-89 0	38 74	-101 74	-143 38	1 56	1 56	34 51	7 11	36 08	CO-CHNL	CO		
	CANPESTD	-100 0	56 9	-89 0	62 70	-126 14	-167 34	1 56	1 56	12 87	3 29	14 89	UP-ADJ	CO		
	USAPACAN	-175 0	56 9	-89 0	999 90	-999 90	-999 99	-99 00	-99 00	-99 00	-99 00	-99 00	LOW-ADJ	CO		
	USAMOCAN	-155 0	56 9	-89 0	43 03	-106 06	-147 67	1 56	1 56	30 84	7 91	32 43	LOW-ADJ	CO		
	USACTCAN	-135 0	56 9	-89 0	31 42	-104 37	-136 06	11 51	9 56	29 68	5 08	41 19	LOW-ADJ	CO		
	USAEACAN	-115 0	56 9	-89 0	44 30	-117 31	-148 94	11 40	9 56	17 95	5 86	29 52	LOW-ADJ	CO		
CANPESTD	-125 0	52 8	-95 2	22 00	-98 54	-102 19	39 56	14 56	39 51	9 10	79 08	CO-CHNL	CO			
	CANPESTD	-145 0	52 8	-95 2	52 41	-115 44	-154 60	3 89	3 89	22 58	8 37	26 63	CO-CHNL	CO		
	CANPESTD	-145 0	52 8	-95 2	46 40	-110 28	-148 59	3 89	3 89	28 70	10 63	33 62	UP-ADJ	X		
	CANPESTD	-125 0	52 8	-95 2	20 70	-97 67	-122 89	39 56	14 56	39 51	8 22	57 50	UP-ADJ	X		
	CANPESTD	-100 0	52 8	-95 2	50 32	-110 93	-152 51	1 56	1 56	25 21	7 11	26 84	CO-CHNL	CO		
	CANPESTD	-100 0	52 8	-95 2	65 28	-126 04	-167 47	1 56	1 56	12 87	0 00	14 66	UP-ADJ	CO		
	USAPACAN	-175 0	52 8	-95 2	999 90	-999 90	-999 99	-99 00	-99 00	-99 00	-99 00	-99 00	LOW-ADJ	CO		
USAMOCAN	-155 0	52 8	-95 2	43 42	-103 99	-145 61	1 56	1 56	32 80	7 91	34 38	LOW-ADJ	CO			
	USACTCAN	-135 0	52 8	-95 2	31 67	-102 02	-133 86	11 35	9 56	31 91	5 08	43 27	LOW-ADJ	CO		
	USAEACAN	-115 0	52 8	-95 2	51 50	-122 29	-153 69	11 24	9 56	12 86	5 86	24 65	LOW-ADJ	CO		
	CANPESTD	-125 0	49 8	-95 2	20 07	-100 48	-104 12	39 56	14 56	37 52	9 10	77 09	CO-CHNL	CO		
		CANPESTD	-145 0	49 8	-95 2	52 17	-117 16	-156 30	3 84	3 84	20 82	8 37	24 90	CO-CHNL	CO	
		CANPESTD	-145 0	49 8	-95 2	45 59	-111 50	-149 71	3 84	3 84	27 45	10 63	32 46	UP-ADJ	X	
		CANPESTD	-125 0	49 8	-95 2	19 66	-99 06	-123 78	39 56	14 56	38 07	8 22	56 56	UP-ADJ	X	
CANPESTD		-100 0	49 8	-95 2	52 47	-115 12	-156 59	1 56	1 56	20 96	7 11	22 70	CO-CHNL	CO		
CANPESTD		-100 0	49 8	-95 2	63 29	-125 97	-167 41	1 56	1 56	12 87	0 00	14 66	UP-ADJ	CO		
USAPACAN		-175 0	49 8	-95 2	999 90	-999 90	-999 99	-99 00	-99 00	-99 00	-99 00	-99 00	LOW-ADJ	CO		
USAMOCAN	-155 0	49 8	-95 2	40 86	-103 36	-144 98	1 56	1 56	33 40	7 91	34 97	LOW-ADJ	CO			
	USACTCAN	-135 0	49 8	-95 2	27 97	-100 19	-132 09	11 29	9 56	33 69	5 08	44 99	LOW-ADJ	CO		
	USAEACAN	-115 0	49 8	-95 2	46 76	-119 14	-150 88	11 17	9 56	15 95	5 86	27 40	LOW-ADJ	CO		
	CANPESTD	-125 0	70 0	-106 0	19 03	-101 52	-105 16	39 56	14 56	36 83	9 10	76 39	CO-CHNL	CO		
		CANPESTD	-145 0	70 0	-106 0	38 84	-104 98	-144 00	4 17	4 17	33 22	8 37	37 41	CO-CHNL	CO	
		CANPESTD	-145 0	70 0	-106 0	33 44	-99 87	-138 60	4 17	4 17	39 29	10 63	43 78	UP-ADJ	X	
		CANPESTD	-125 0	70 0	-106 0	22 79	-106 54	-127 96	39 56	14 56	30 93	8 22	52 74	UP-ADJ	X	
CANPESTD		-100 0	70 0	-106 0	49 04	-112 76	-154 20	1 68	1 68	23 77	7 11	25 54	CO-CHNL	CO		
CANPESTD		-100 0	70 0	-106 0	62 59	-126 43	-167 75	1 68	1 68	12 87	0 00	14 77	UP-ADJ	CO		
USAPACAN		-175 0	70 0	-106 0	92 91	-127 33	-168 07	1 56	1 56	13 49	7 91	15 95	LOW-ADJ	CO		
USAMOCAN	-155 0	70 0	-106 0	57 33	-121 59	-162 50	1 56	1 56	15 31	7 91	17 60	LOW-ADJ	CO			
	USACTCAN	-135 0	70 0	-106 0	46 25	-120 22	-151 41	11 67	9 56	13 95	5 08	25 95	LOW-ADJ	CO		
	USAEACAN	-115 0	70 0	-106 0	52 69	-126 63	-157 86	11 64	9 56	8 86	0 00	20 83	LOW-ADJ	CO		
	CANPESTD	-125 0	49 8	-95 2	20 07	-100 48	-104 12	39 56	14 56	37 52	9 10	77 09	CO-CHNL	CO		
		CANPESTD	-145 0	49 8	-95 2	52 17	-117 16	-156 30	3 84	3 84	20 82	8 37	24 90	CO-CHNL	CO	
		CANPESTD	-145 0	49 8	-95 2	45 59	-111 50	-149 71	3 84	3 84	27 45	10 63	32 46	UP-ADJ	X	
		CANPESTD	-125 0	49 8	-95 2	19 66	-99 06	-123 78	39 56	14 56	38 07	8 22	56 56	UP-ADJ	X	
CANPESTD		-100 0	49 8	-95 2	52 47	-115 12	-156 59	1 56	1 56	20 96	7 11	22 70	CO-CHNL	CO		
CANPESTD		-100 0	49 8	-95 2	63 29	-125 97	-167 41	1 56	1 56	12 87	0 00	14 66	UP-ADJ	CO		
USAPACAN		-175 0	49 8	-95 2	999 90	-999 90	-999 99	-99 00	-99 00	-99 00	-99 00	-99 00	LOW-ADJ	CO		
USAMOCAN	-155 0	49 8	-95 2	40 86	-103 36	-144 98	1 56	1 56	33 40	7 91	34 97	LOW-ADJ	CO			
	USACTCAN	-135 0	49 8	-95 2	27 97	-100 19	-132 09	11 29	9 56	33 69	5 08	44 99	LOW-ADJ	CO		
	USAEACAN	-115 0	49 8	-95 2	46 76	-119 14	-150 88	11 17	9 56	15 95	5 86	27 40	LOW-ADJ	CO		
	CANPESTD	-125 0	52 0	-100 0	23 39	-97 15	-100 80	39 56	14 56	40 85	8 86	80 41	CO-CHNL	CO		
		CANPESTD	-145 0	52 0	-100 0	50 02	-111 50	-150 82	3 81	3 81	26 46	8 37	30 34	CO-CHNL	CO	

Table 9
AGGREGATE DOWNPATH SUMMARY FOR CANTEST 1

PAGE 1

BLOCK CODE	SERVICE AREA	SAT LONG	TEST LAT-LONG	POINT LAT-LONG	**** WST-INTFR	***** C/I	UPPER-ADJ C/I	UPPER MARGN	NEXT C/I	UPPER MARGN	NEXT C/I	LOWER MARGN	TOTAL MARGN
CANPESTD		145 0	70 0	-141 0	CANPESTD	57.7	26.7	26.2	17.1	48.9	40.4	99.0	16.6
		145 0	70 0	-120 0	CANPESTD	43.3	12.3	19.8	10.7	48.3	39.8	99.0	8.4
		145 0	60 0	-120 0	CANPESTD	46.5	15.5	20.3	11.2	43.5	35.0	99.0	9.8
		145 0	49 0	-114 0	CANPESTD	43.0	12.0	18.1	9.0	25.1	16.6	99.0	6.8
		145 0	70 0	-130 0	CANPESTD	53.5	22.5	24.0	14.9	50.1	41.5	99.0	14.2
CANPESTD		145 0	49 0	-120 0	CANPESTD	56.3	25.3	23.2	14.1	30.4	21.8	99.0	13.2
		145 0	81 0	-145 0	CANPESTD	53.7	22.7	24.4	15.3	46.7	38.2	99.0	14.6
		145 0	70 0	-130 0	CANPESTD	53.5	22.5	24.0	14.9	50.1	41.5	99.0	14.2
		145 0	49 0	-106 0	CANONSTD	53.3	22.3	26.4	17.4	23.9	15.4	99.0	12.8
		145 0	49 0	-114 1	CANONSTD	60.7	29.7	28.8	19.7	22.6	14.0	99.0	12.9
CANPESTD		145 0	70 0	-106 0	CANONSTD	42.0	11.0	44.3	35.2	23.8	15.2	99.0	9.6
		145 0	60 0	-106 0	CANONSTD	42.2	11.2	35.7	26.6	24.6	16.0	99.0	9.8
		145 0	52 0	-110 0	CANONSTD	59.8	28.8	32.3	23.3	25.6	17.1	99.0	15.9
		145 0	70 0	-120 0	CANONSTD	54.3	23.3	46.6	37.6	21.0	12.5	99.0	12.1
		125 0	56 9	-89 0	CANPESTD	38.6	7.6	18.3	9.2	30.9	22.4	99.0	5.2
CANPESTD		125 0	52 8	-95 2	CANPESTD	48.2	17.2	20.7	11.6	31.3	22.8	99.0	10.3
		125 0	49 8	-95 2	CANPESTD	49.3	18.3	19.6	10.6	27.7	19.2	99.0	9.4
		125 0	70 0	-106 0	CANPESTD	38.4	7.4	22.4	13.4	45.0	36.5	99.0	6.5
		125 0	49 8	-95 2	CANPESTD	49.3	18.3	19.6	10.6	27.7	19.2	99.0	9.4
		125 0	52 0	-100 0	CANPESTD	49.7	18.7	24.9	15.8	32.6	24.0	99.0	13.6
CANPESTD		125 0	70 0	-95 0	CANPESTD	36.2	5.2	41.1	32.1	19.0	10.5	99.0	4.1
		125 0	70 0	-80 0	CANPESTD	40.7	9.7	39.6	30.5	20.7	12.2	99.0	7.7
CANPESTD		100 0	70 0	-80 0	CANPESTD	37.1	6.1	24.2	15.1	47.7	39.2	99.0	5.6
		100 0	51 4	-57 0	CANPESTD	62.2	31.2	-3.8	-12.9	34.8	26.3	99.0	-12.9
CANPESTD		100 0	60 6	-64 5	CANONSTD	42.2	11.2	35.7	26.7	-3.1	-11.6	99.0	-11.7
		100 0	47 5	-52 5	CANONSTD	48.0	17.0	40.4	31.3	4.9	-3.6	99.0	-3.7
USAPACAN		175 0	40 0	-111 6	USAMOCAN	30.7	-0.3	54.2	45.1	55.5	46.9	99.0	-0.3
		175 0	49 0	-123 3	USAMOCAN	41.5	10.5	37.2	28.2	47.8	39.3	99.0	10.4
USAMOCAN		155 0	39 0	99 7	USACTCAN	31.1	0.1	51.3	42.3	47.8	39.3	99.0	0.1
		155 0	43 0	-99 7	USACTCAN	31.9	0.9	43.8	34.7	40.8	32.3	99.0	0.9
USACTCAN		135 0	49 0	-104 0	USAMOCAN	33.3	2.3	26.1	17.0	29.9	21.3	99.0	2.1
		135 0	29.7	-85 0	USAEACAN	33.1	2.1	49.8	40.8	48.9	40.4	99.0	2.1
USAEACAN		115 0	44 1	-87 1	USACTCAN	32.7	1.7	40.0	30.9	26.9	18.4	99.0	1.6

AD-A140 841

TECHNIQUES FOR THE ANALYSIS OF SPECTRAL AND ORBITAL
CONGESTION IN SPACE SYSTEMS(U) RAND CORP SANTA MONICA
CA A L HIEBERT ET AL. MAR 84 RAND/R-3046-AF

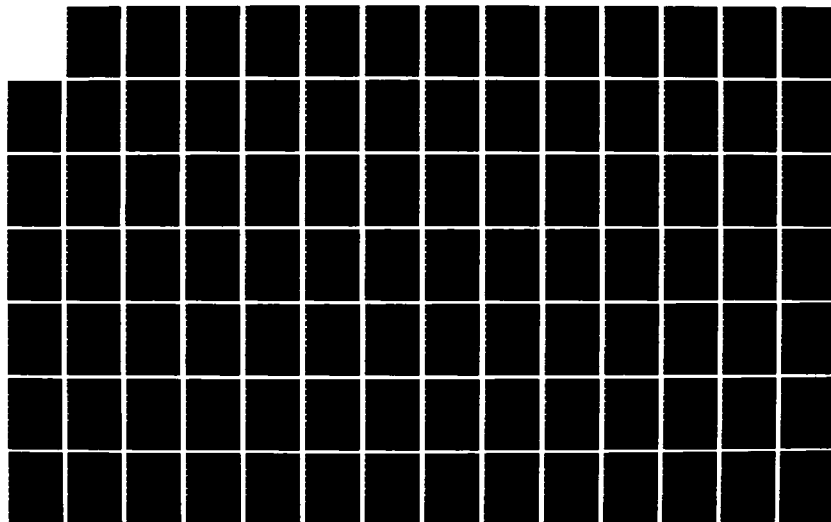
3/4

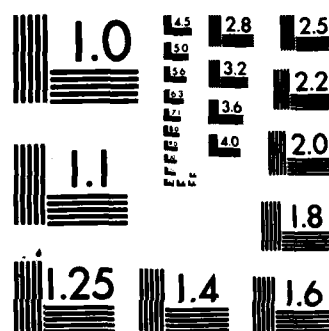
UNCLASSIFIED

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F/G 22/3

NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

obtain the net attenuation. Since scattering by rain affects the polarization of the transmitted wave, the effective depolarization is determined in terms of the frequency, elevation angle, polarization tilt angle, and raindrop canting angle distribution. The attenuation is used to reduce the received signal and the depolarization factor to compute the effective equivalent path antenna gain.

SOUP-5 uses the standard algorithms for received power and the various intermediate quantities, and the CCIR algorithm for rain attenuation. It is applicable to intrasystem problems such as general link power budget calculations, but is particularly designed for intersystem problems. As such it is useful for planning, analysis, and coordination of satellite services at various levels of detail.

The SOUP programs provide a highly developed presentation for fixed satellite interference analysis (SOUP-3) and broadcast satellite interference (SOUP-5). They can give the user the essential results for any likely signal interference problem involving geosynchronous satellites. Furthermore, in preparation for RARC-83, SOUP is undergoing further development and a number of accessory programs have been generated, such as a program that computes elliptical satellite antenna beam parameters for a given satellite position and service area.

Software Considerations

Both programs are written in FORTRAN IV (ANSI-1966). SOUP-3 has 4280 lines of code, SOUP-5 9150 lines. SOUP-3 has been installed on the IBM 370, SOUP-5 on the IBM 370, Prime 400, VAX, and Siemens. SOUP-3 requires 1600K of memory, SOUP-5 only 514K. Typical run execution time is one to five minutes, depending on the number of links and reports.

SOUP-3 can handle 99 links (one link is one satellite and two earth stations). SOUP-5 is limited to 80 service areas, 50 test points (feederlink transmitters) per service area up, 50 test points (receivers) per service area down, 800 test points total up, and 2400 total test points down. Neither SOUP-3 nor SOUP-5 consider EMC properties.

References for Sec. B.5.d

1. Davidson, J. H., and P. Sawitz, *SOUP-3 User and Programmers Manual*, ORI, Inc., 9 September 1981, in two volumes: Volume 1 provides the technical background and a description of the program, Volume 2 contains a detailed listing of the program and a worked out test case.
2. Davidson, J. H., H. R. Ottey, F. S. Zusman, and P. Sawitz, *SOUP-5 Version 3 Technical Manual*, ORI, Inc., Technical Report 2053, 29 November 1982.
3. Ottey, H. R., J. H. Davidson, P. Sawitz, and F. S. Zusman, *SOUP-5 Version 3 User's Manual*, ORI, Inc., Technical Report 2039, 29 November 1982.

Reference 2 presents the technical aspects of SOUP-5, Ref. 3 includes summary descriptions of the programs and detailed descriptions of the inputs and outputs.

For further information on SOUP, please contact Eugene Feinberg, Assistant Vice President, ORI, Inc., 1400 Spring Street, Silver Spring, MD 20910, or Dr. Edward F. Miller, Head Communications Technical Consultant Office, NASA Lewis Research Center, Cleveland, OH 44135.

B.5.e CO-CHANNEL INTERFERENCE ANALYSIS FOR GENERALIZED SATELLITE ORBITS⁹

Introduction

This program calculates potential interference on satellite-to-ground links. It was developed over several years at the MITRE Corporation, and exists in two forms, one for the PDP 11/70, the other for the IBM 3031. The IBM version was developed for NASA Lewis Research Center in 1981, and is maintained at the MITRE Bedford Computer Center. The PDP form is maintained by MITRE Dept. D97, which provides services to run the program when staffing permits. NASA Lewis has used the results in a signal/interference format, and the Electronics Systems Division of the Air Force has used the results in a signal-only format.

⁹Original material was supplied by P. Christopher, formerly with MITRE Corporation, now with Science Applications, Inc., Stow, MA.

At present, this program only calculates downlink interference from many satellites into a single ground station. It is planned to incorporate uplink interference calculations in 1983. The program has been designed for general orbits and includes the effects of atmospheric attenuation. Out-of-channel interference and intermodulation problems are omitted, and the signals are assumed to be of the same type, so receiver transfer functions need not be considered.

The satellite orbits are arbitrary ellipses. It is assumed that satellite position can be accurately predicted without updating for more than one week after orbital elements are determined, which implies satellite altitudes above 3000 n mi, although a Molniya-type satellite, with rapid passage through its 250 n mi perigee, will be well served by the analysis.

The model for atmospheric attenuation includes integrated versions of the gaseous attenuation relations, and a close approximation to the Crane rain attenuation model. The effect of the altitude of the ground station is considered.

The antenna patterns for ground stations correspond to uniformly illuminated circular apertures. Satellite antennas are elliptical, with arbitrary shape and orientation and arbitrary ground reference points for the major axis of the pattern. The main beam and sidelobes are ideal $[J_1(u)/u]^2$ patterns. There are no polarization corrections.

The program is especially suited to airborne earth stations. It calculates the signal received at the earth from the ensemble of satellites and sums the interfering powers to find the total interference to signal ratio. Latitude cuts are provided, which give the interference at a given latitude at a succession of longitude values, corresponding to an aircraft flying east or west.

The two programs are not simple equivalents. The PDP program was intended to be convenient and relatively inexpensive to run in comparison with the IBM version. Instead, the work load of fiscal 1982 led the two programs to different problems. In particular, the IBM program provides a more general elliptical beam shaping than the circularly symmetric spot beams of the PDP version.

Code Description and Capabilities

The PDP and IBM programs are very similar. Each uses a main control routine and subroutines which perform the specific calculations. Required inputs for both versions include the number of satellites and ground stations, the latter limited to one in the present programs. For each satellite the orbital elements (semi-major axis, eccentricity, right ascension of the node, argument and time of perigee, and inclination angle) are required, plus the downlink frequency, power, and antenna diameter. The IBM version also requires for each satellite with an elliptical antenna the major and minor axes and the orientation on the ground of the long axis of the pattern. Corresponding to each satellite antenna is a boresight direction with the latitude and longitude of its projection on the ground regarded as a ground station and required as inputs. For the single true ground station, the location and antenna diameter are required.

After assembling the input data, the main program calls the subroutines ELLIP and PRIME to calculate the instantaneous position of each satellite in rectangular inertial coordinates with origin at the center of the earth. The inertial rectangular coordinates of the ground stations are found, and the ranges and boresight directions established. Subroutine ANGL gives the off-axis angles from the ground stations to each satellite, subroutine GAIN (GAINEL for elliptical antennas) gives the gain of each antenna in the appropriate direction. Subroutine PRTEMP calculates the received power at the ground station from each satellite. The attenuation from rain and gaseous attenuation is determined by subroutine ATMOS, which uses the elevation angle from the station to each satellite, data that give the probability that the rainfall at the ground station exceeds a specified level, and formulas that calculate the attenuation from the rainfall rate and path length through the rain. The calculations of ATMOS modify PRTEMP. Finally, the interference powers are summed to form the total signal to interference ratio.

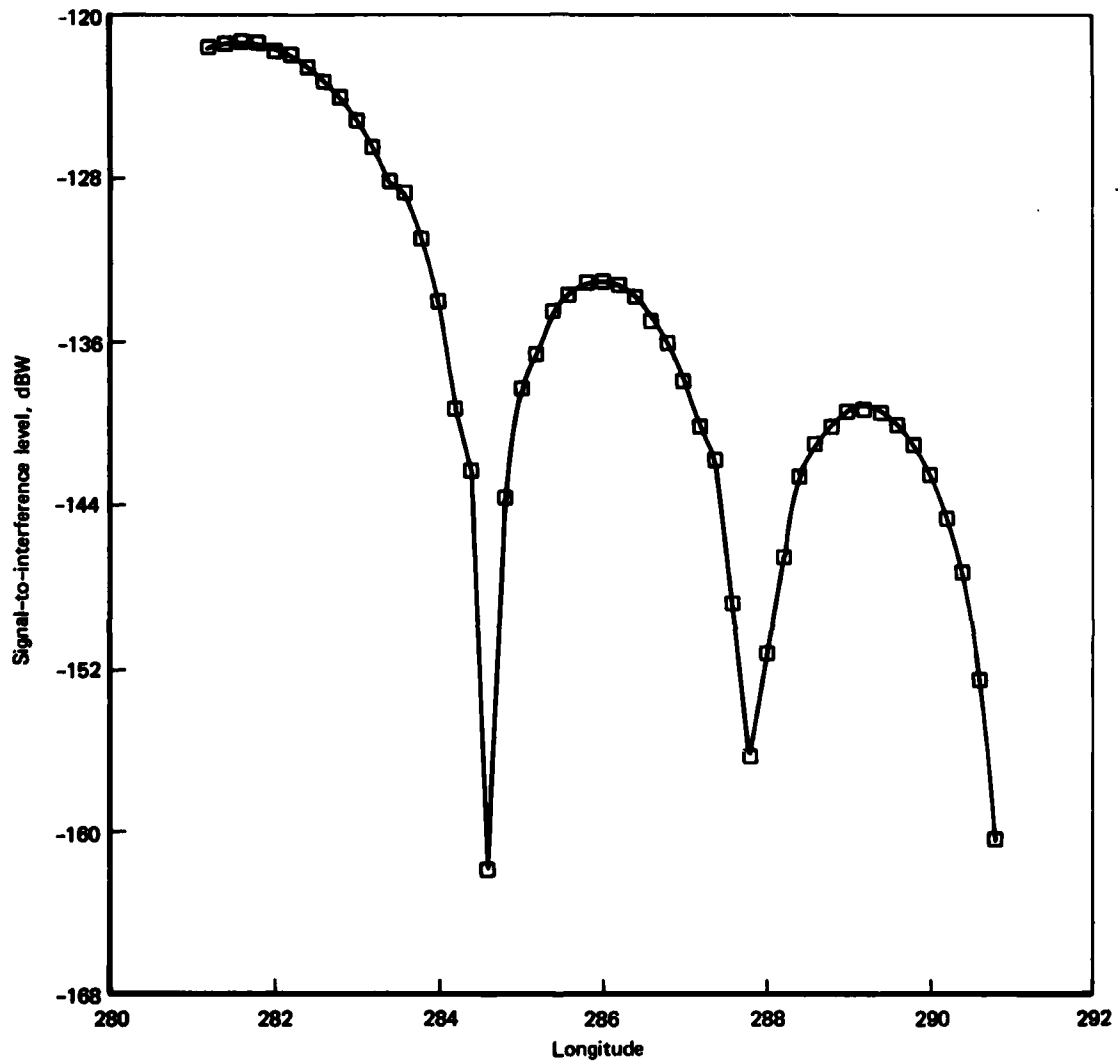
Typical outputs give numerical or graphical data showing the received level at the ground from a particular satellite, or the signal to interference ratio from a set of satellites. The program chooses a

set of values for latitude (typically 5), then cycles the longitude to give the levels for a set of ground points. This is equivalent to tracking the signal level on an eastward or westward flying aircraft. Figure 13 shows a typical case. A geosynchronous satellite, located at 270°E (south of New Orleans), operates at 40 GHz and carries a 2 m by 0.5 m elliptical antenna, boresighted on New York with the long axis of the footprint pointed towards Washington, D.C. An airplane, carrying a 1 m dish, is flying eastward along the 37.6° latitude line from 281° (near Lynchburg, Virginia) to 290°E (over Richmond and out over the ocean). The figure shows the signal level in dBW at the aircraft receiver, and displays the sidelobe structure. It is also possible to show the signal-interference ratio versus position.

No orbit limitations exist if only single precision accuracy is required within a single orbital period. The only real exception occurs for a low altitude satellite (altitude less than 200 n mi) which suffers noticeable atmospheric drag. Useful frequencies for the programs range between 1-50 GHz and 70-90 GHz, limited by the accuracy of the rain model and the strength of oxygen attenuation. A uniformly illuminated dish antenna is used, with the consequence that the sidelobe level is higher than actual, well designed antennas. Propagation includes free space loss, gaseous attenuation, and rain modeling. Algorithms include an analytic integration over an exponential troposphere to calculate the atmospheric attenuation sufficiently rapidly, fast, accurate approximations for Bessel functions, and an efficient procedure for solving Kepler's equation. No obvious intrasystem analysis applications exist.

Software Considerations

FORTRAN 77 is used for these programs. The IBM version contains 650 lines of code, including a main routine of 134 lines and several key subroutines. The two programs are running on a PDP 11/70 and an IBM 3031. No extra software, beyond the subroutines listed here and the Calcomp Plotter, is required. The IBM 3031 used 252K bytes of system memory. The memory requirements would be sharply reduced, perhaps to less than 48K, on a microcomputer. A typical run, with three satellites and 49 (longitude) by 5 (latitude) ground searches, requires 34 CPU seconds on an IBM 3031.



Power (dBW) received by a 1 m dish as it travels East along 37.6° N from 281° E longitude to 290° E. Satellite boresight on N.Y. along axis of elliptical pattern through Washington, D.C.

$D_t = 2 \times 0.5$ m; 40 GHz

Fig. 13 - Power received by airborne terminal

Reasonable run times may limit the program's practicality to 50 satellites and 50 x 50 ground searches. The program is now limited to co-channel interference, and satellites provide the only interference sources. These programs are intended to serve as building blocks for more useful EMC representations. They provide an excellent investigation of the N interferers, 1 victim problem.

References for Sec. B.5.e

1. Christopher, P., S. Maciorowski, and E. R. Edelman, *High Altitude Satellites, with Crosslinks*, MITRE Corporation, MTR-3161, 1976.
2. Kamal, A. K., and P. Christopher, "Communication at Millimeter Waves," *Proceedings of the International Communications Conference*, Session 68, Denver, 1981.

These reports describe most of the analysis and procedures used to construct the programs, especially the portion dealing with atmospheric attenuation.

For further details and information concerning these programs, please contact S. B. Gittleman, MITRE Corporation, Bedford, MA, or P. Christopher, Science Applications, Inc., Stow, MA.

B.5.f INTERFERENCE PROBLEMS FOR NONGEOSTATIONARY SATELLITES¹⁰

Introduction

Most investigations of radio-frequency interference between satellites deal with geostationary communications satellites. There are many other satellites in earth orbit, however, and they also are subject to potential signal interference. The communications circuits with these satellites carry commands on the uplinks and data, tracking codes, and beacons on the downlinks. Since there are many more satellites using certain frequency bands than there are communications channels, the interference problems may be significant.

What investigation techniques are available to treat these interference problems? There are two different procedures, which would be applied by different people.

¹⁰Original analysis by W. Sollfrey, The Rand Corporation.

The personnel who actually operate satellite systems, or collect and interpret the data, are concerned with the specific times and places of interference episodes. They therefore employ computer programs, which produce such answers as "There will be interference between satellite A and satellite B when viewed from ground station C at 3:30 pm local standard time next Wednesday." At least two such programs are currently operational. One, at the Jet Propulsion Laboratory in Pasadena, California, predicts interference for the deep-space net. The other, at the Air Force Satellite Control Facility in Sunnyvale, California, predicts interference for the numerous U.S. military satellites. Computer programs such as these are necessary for satellite network control.

The personnel who plan satellite missions or devise new satellite programs have a different viewpoint. They do not need precise prediction of interference occasions. In fact, they may not even know the launch date. They are concerned with such questions as: How much total interference can be expected? How long will it last when it occurs? How often does it occur? Is there a real interference problem, which perhaps should be solved before launch? For such questions, computer programs do not provide appropriate answers; the methods of the theory of probability are more effective.

To place the situation in perspective, consider Table 10. This table shows that the geostationary communications satellites constituted only about 8 percent of the total number of satellites orbited in the years 1979 and 1980. The other satellites fall into several classes. There are geostationary satellites used for other purposes, such as the synchronous meteorological satellites. The Soviet Union has launched many satellites into the Molniya-type orbit (highly elliptical, 12-hour period, 63 deg inclination). Most of these are communications satellites, but some have different purposes. The USSR and the United States have launched a large number of satellites into low earth orbits (apogee below 1500 km), with low eccentricity ($< .01$). These may be separated by their orbital lifetimes. The 82 short-life (< 30 days) satellites launched by the USSR are associated with their military space program. There are usually two or three of them in space at any time.

Table 10

SATELLITES ORBITED: 1979-80

	USSR	U.S. & Other	Combined
Geostationary communications	9	11	20
Geostationary noncommunications	0	3	3
Molniya type	15	0	15
Low circular, < 30 days	82	0	82
Low circular, 30 days-1 year	15	6	21
Low circular, long life	86	12	98
High circular and other	1	4	5
Total	208	36	244

The intermediate lifetime (30 days to one year) satellites are mostly scientific. The long lifetime (one year to 1000 years) satellites have a variety of purposes. This class includes 40 Soviet communications satellites launched in five groups of eight during 1979-80.

In addition to the satellites listed in Table 10, many satellites launched in previous years are still transmitting. In August 1981, NASA was monitoring the transmissions of 20 satellites in earth orbit and nine deep-space vehicles. The U.S. military was monitoring at least 20 satellites, and the Soviet Union was certainly monitoring more than that. The possible RF interferences between satellites depend upon their orbital and signal characteristics.

Geostationary satellites appear at fixed points in the sky with respect to ground stations. Hence, any interference between them will not be dependent on time. Various interference reduction techniques, such as polarization discrimination, antenna beam shaping, and use of efficient modulation schemes, have been developed. When these techniques are applied, it may be possible to reduce the interference to an acceptable value.

In contrast, interference between nongeostationary satellites is strongly time-dependent. It can only occur when the satellites are in a common antenna beam. Such events are rare, but predictable since the satellite ephemerides can be accurately calculated. When the interference does occur, it may be quite disruptive.

These satellites receive commands on their uplinks. If a pair of satellites are in such directions from their ground stations that a command intended for satellite A is received by satellite B, then the possibility of a false command exists. If both ground stations are transmitting commands, the interference may cause the satellites to fail to receive their proper commands. Since the command interval is usually short compared to the time each satellite is in the field of view of its ground station, the commands may be deferred or repeated until they are properly acknowledged. Hence, uplink interference problems should not be too serious.

The downlink problems are more important. Most of the existing and planned satellites use the 2200-2300 MHz band for data transmission. This band contains 20 channels, each 5 MHz wide. Most satellites have low power levels, and the low-orbit satellites (the vast majority) carry earth coverage antennas. Thus, the power density at the ground from the desired and undesired satellites is comparable. If they are in the same antenna beam, serious interference may result. This may take the form of excess bit error rate and consequent loss of data during the interference interval. Worse, if the communications link employs a phase-locked loop, the interference may cause the lock to break, so that after the interference ceases, the desired signal must be reacquired and the lock reestablished. Still worse, if the interfering signal is somewhat stronger than the desired, it is possible for the antenna tracking system to be captured, so that after the satellites separate in direction, the antenna follows the interferer. Worst of all are the problems of the deep-space tracking net. The receiving systems are so sensitive, and the interferers have such a range advantage (low earth to planetary distances) that a deep-space tracking station may be completely incapacitated if an interferer is anywhere above the horizon, since the interference will come in on the sidelobes.

Since there are many more satellites than there are channels, interference may be quite likely. There are three possible configurations. In the first, a low altitude satellite is being tracked, and the tracking antenna beam crosses the location of a geostationary satellite. In the second, the converse of the first,

communication is taking place between the ground and a geostationary satellite, and a low altitude satellite enters the field of view of the ground-based antenna. This situation is the one most likely to produce antenna capture. For the third configuration, while a low altitude satellite is being tracked, another low altitude satellite enters the field of view, producing a short episode of serious interference.

The determination of when these episodes occur reduces to finding when a low altitude satellite, moving on the surface of an imaginary sphere, enters the cone which defines the critical offset angle of the earth-based antenna beam. The locus of intersection is determined by a complicated mathematical expression which for small antenna beamwidth reduces to an ellipse. The specific times of intersection may be found by a computer program, or the probability of intersection may be found by analytic procedures. We shall describe the two techniques. The mathematical details of the probability calculations, which are original to this paper, are presented in Appendix B.

Computer Programs

Computer programs for calculating interference involving both geostationary and nongeostationary satellites are in operation at the Jet Propulsion Laboratory, Pasadena, California, for determining interference to the deep-space net, and at the U.S. Air Force Satellite Control Facility, Sunnyvale, California, for predicting interference with U.S. military satellites. These programs are described in Secs. B.5.g and B.5.h. The programs employ the same basic logic, but differ considerably in detail, since the satellites to which the programs are applied are very different. At this point, we merely describe the program tasks and ensuing actions.

The first task is to determine whether interference is at all possible. The program first investigates if the satellites have common frequencies (common means lying within the same bandwidth). It then considers the location of the satellites' ground stations, to determine whether satellite A is transmitting when it is in view of the ground station associated with satellite B. If the answers to these questions are negative, the satellite pair is scratched from the list of potential interferers.

If the satellites may interfere, the program determines the degree of interference. Basic receiver theory is employed to determine the threshold levels of interference to signal ratio above which various types of receiver degradation may set in. For the JPL program, these types include telemetry symbol signal-to-noise ratio degradation, telemetry drop lock, receiver interference, and receiver drop lock, arranged in order of lowest to highest threshold. These levels are established as flags which determine the condition of the system. The calculation depends upon the signal types, frequency offsets, antenna parameters, power levels, and other fixed characteristics of the system. This portion of the program need be performed only once for each satellite pair at each ground station.

The interference depends on certain fixed quantities (power level, critical threshold, etc.) and certain time-dependent quantities (slant range, cone angle between satellites). The major part of the program calculates these parameters as functions of time, determines the signal-to-interference ratio, and thereby establishes the condition of the system. This section must be run as often as necessary. Both the JPL and Air Force programs are usually run weekly, with more frequent operation at critical time periods. The JPL program during 1981 was evaluating interference among nine spacecraft, ten potential interferers, and three ground stations. The Air Force program handled 20 satellites and 12 ground stations. Each program is capable of treating greater numbers.

Since these programs are employed to provide information to field personnel concerning potential interference and consequent loss of operation, action is required if interference is indicated. The first action is to inform the user when an interference episode may be expected. He may be able to defer his operation to a noninterfering time. This is especially useful for commands. Then, if the interference episode is very short, the interference may simply be accepted and the information lost. This is only reasonable if the information is not critical. As was remarked in the discussion of another paper at the symposium where the research of this paper was reported (see Preface), if the signal from Voyager had been interfered

with for a particular 45 seconds, the only picture which contained a previously unknown moon of Jupiter would have been lost. If the information is critical, the operator of the interfering satellite may be persuaded to command it off. This was actually done during the Voyager I flyby of Saturn. A Soviet Cosmos satellite, which could have interfered drastically with the Voyager data transmission, was turned off by the Russians during the critical periods.

These computer programs work quite well for the ascertainment of possible interference, determination of when it may occur, and action procedures. There is a difficulty at present in the Air Force operation in that there is no feedback from the field, so it is not known whether the action procedures are effective. This is an operational problem rather than a matter of principle. It appears that both programs provide interference warnings with sufficient lead time.

This completes our discussion of the computer programs. We shall next treat the probability considerations.

Probability Considerations

The mission planner is interested in such quantities as the expected fraction of the time there will be interference, the mean and maximum duration of such occurrences, and the mean spacing between episodes. He would like an analytic treatment, with the results given as simple equations from which he can draw qualitative and quantitative conclusions, rather than a computer program which will give him excessive information about special cases. We have developed such results, valid under the restrictions of narrow antenna beams and near-circular orbits. These restrictions are satisfied for most cases of interest. They are not satisfied for the deep-space net. Although they use very narrow antennas, the great receiver sensitivity and the range advantage of the interferer permits sidelobe interference. The theory may be adapted to cover this situation, although the results are not presented here. Also, the Molniya-type orbits cannot be handled by these analytic procedures.

The general theory and some examples will be presented here. The mathematical details are relegated to Appendix B. Recall that the condition for interference is that the two spacecraft be in the same

antenna beam. Suppose satellite A is being tracked. If all orbits are approximately circular, satellite B is moving on a sphere of radius r_B . The beam from the ground station to A intersects the sphere of radius r_B in a complicated curve which for small antenna beamwidths reduces to an ellipse. If the nodal crossing of the orbit of B is properly located, the orbit track will pass through the ellipse, and if the time of the nodal crossing of B is properly related to the time of the nodal crossing of A, satellite B will actually pass through the beam. The time that B spends in the beam can be calculated. The value of beamwidth is selected by a "cookie-cutter" model, such that there is interference if B is inside, and non-interference if B is outside. The JPL and Air Force computer programs use a beamwidth of 5 deg, which is small enough to meet the requirements that the intersection curve be an ellipse. The duration of interference is to be averaged over the position and time of the nodal crossing to give the mean duration of interference, which is equivalent to the long-term probability of interference. The maximum duration of interference occurs for episodes near the edge of the field of view, for which the ellipse is largest.

There are several possible configurations. The interference may be between a low-altitude satellite and a geosynchronous satellite, in which case interference may occur on either northbound or southbound passes of the low-altitude satellite. If both satellites are low-altitude, their periods may be unrelated, in which case interference may occur for either northbound or southbound passes of either satellite. If two low-altitude satellites have related periods, as occurs for the sun-synchronous satellites, then there is only one possibility for interference, which must be determined separately for each example.

A low-altitude (below 1500 km) satellite of sufficient inclination will make one northbound and one southbound pass through the field of view of a ground station each day. If the ground station is tracking a geosynchronous satellite, then there will be interference if the low-altitude satellite has its nodal crossing in the proper range. The mean time between episodes of interference will be the nodal crossing width which corresponds to entering the field of view divided by the nodal crossing width which corresponds to entering the beam. The result is the same if the low-altitude satellite is being tracked. If the

satellites are both low altitude, then the interval between episodes of interference is directly proportional to the synodic period of the satellites, that is, the time for the faster satellite to gain one orbit on the slower, and inversely proportional to the product of the angular widths along the equator such that either satellite enters the field of view. In general, the probability of interference is proportional to the square of the beamwidth, while the maximum duration of interference is proportional to the beamwidth.

The general theory is next applied to several examples of real satellites, listed in Table 11. These satellites were selected because the information about orbits, frequencies, and other parameters was unclassified and because they display all the indicated interference behavior. Other satellites might have been preferred, such as a Soviet satellite, but the information was not generally available. It is noted that Soviet satellites will usually not be transmitting when they pass over the United States, and thus will not cause interference, but they might interfere with U.S. or other receivers in Europe.

The interference between a Defense Meteorological Support Program (DMSP) satellite and the geostationary meteorological satellite GOES-4 is summarized in Table 12. They have a common frequency, or rather

Table 11
SATELLITES TREATED

Satellite	Altitude (km)	Inclination (deg)
1. Desired signal Defense Meteorological Support Program (DMSP)	825	98.65
2. Geostationary interferer GOES-4	35,790	0.2 (95°W)
3. Low-altitude random P-80	740	72.5
4. Low-altitude synchronized Landsat-3	919	99.11

Table 12

DMSP AND GOES-4

Common frequency:	2207.5 MHz (DMSP)	2209 MHz (GOES-4)
Stations:	Loring AFB, Caribou, ME	DMSP 5° beams
	Wallops Station, VA	GOES-4 5° beams

GOES-4 interferes with DMSP 52 min/yr

	Northbound	Southbound
Episodes per year	48	40
Mean duration	32 sec	39 sec
Max duration	42 sec	50 sec
Episode spacing	4, 5, or 9 days	9 days

DMSP interferes with GOES-4 27 min/yr

	Northbound	Southbound
Episodes per year	32	30
Mean duration	25 sec	28 sec
Max duration	32 sec	36 sec
Episode spacing	9 or 14 days	9 or 14 days

their center frequencies lie well within the 5 MHz bandwidth. Their ground stations are so located that DMSP is commanded on when it is within range of the GOES-4 station, and GOES-4 is always in the sky at the DMSP station. The table shows the interference is at the .01 percent occurrence level, which is comparable to that required of communications satellites, and lasts about 1/2 minute per episode. The 9-day period is the synodic period for DMSP to recur within the nodal crossing range required by the ellipse size. The ellipse is so oriented in the sky at Loring AFB that there are additional northbound episodes of short duration. The ellipse is higher in the sky at Wallops Station than it is at Loring, so it is smaller in size and there is less interference, as shown by all the numerical values.

The interference between two randomly related satellites, DMSP and P-80, is shown in Table 13. The interferer, P-80, is a satellite in the Air Force Satellite Test Program which has not yet been launched, but

Table 13

P-80 INTERFERING WITH DMSP

Nodal positions and times random	
Common frequency: 2207.5 MHz	
Common station: Vandenberg AFB, CA -- 5° beams	

<i>Probability of interference -- 2.15 min/yr</i>	

Episodes per year	9
Mean duration	14 sec
Max duration	30 sec
Mean spacing	40 days

for which information has been released. These satellites have a common frequency and a common ground station. As can be seen, the interference is rare, but when it occurs, the duration is appreciable. For this pair of satellites, each has a nodal crossing width of slightly below 60 deg for it to come into the field of view northbound, and another of the same length for southbound passes. The synodic period is 61 orbits, or about 4 1/4 days. The product of factors gives the 40-day mean spacing, which was then checked by detailed calculations. The probability was calculated using a computer program for the HP-34C hand calculator. This probability would most likely not be regarded as significant.

The third case is the interference between DMSP and its fellow sun-synchronous satellite Landsat-3 (L-3), shown in Table 14.

The times when these satellites cross the equator are so adjusted that they will always be in the proper time phase for interference at 10:30 am local time, at which time both are near 60° N. Their nodal crossings must be so arranged that L-3's southbound crossing is about 38° W of DMSP's northbound crossing. They have a common frequency, and a pair of ground stations such that both can be commanded on and viewed during potential interference intervals. The nodal crossings, separated as above, must be placed so the interference location lies within the mutual field of view. These nodal crossing combinations are quite rare, so the total interference is small, less than 1 minute per year.

Table 14

LANDSAT-3 INTERFERING WITH DMSP

DMSP crosses equator northbound at 11:30 am local time
L-3 crosses equator southbound at 9:30 am local time
Interference only possible with satellites near 60°N
Common frequency: 2267.5 MHz (DMSP), 2265 MHz (L-3)
Stations: Fairchild AFB, Spokane, WA (DMSP)
Fairbanks, Alaska (L-3)

Probability of interference -- 0.88 min/yr

Episodes per year	3
Mean duration	18 sec
Max duration	30 sec
Mean spacing	127 days

However, the duration may be significant, since a full picture may be lost. The mean duration is longer for the case of Table 14 than for Table 13, because the interference episodes for Table 14 all occur in the outer portion of the field of view.

It may be concluded that nongeostationary satellite interference problems are sufficiently important that there are current and planned major field operations for handling them. Existing computer programs provide interference flags with sufficient lead time. Effectiveness of action programs is uncertain at present, because of lack of feedback from the field. Probability considerations enable mission planners to determine if they may be confronted with significant interference problems.

B.5.g AIR FORCE SATELLITE CONTROL PROGRAM--MILESTONE 4¹¹

Introduction

This program determines possible radio frequency interference involving the satellites under control of the U.S. Air Force. It was

¹¹Original material was submitted by K. Hill, Lockheed Corporation.

developed by Data Dynamics, Inc., for the Air Force Satellite Control Facility (AFSCF). The program development began in 1967 and has been updated many times. It is maintained and operated by the Lockheed Corporation, and used by AFSCF, Sunnyvale, CA. No external services are available.

Milestone 4 is used for day-by-day scheduling of command and telemetry transmissions of Air Force satellites. These signals are in the 2200-2300 MHz data transmission band, which contains 20 channels, each 5 MHz wide. Most satellites have low power levels and carry earth-coverage antennas. The power density levels at the ground from desired and undesired signals are comparable. Each satellite may use several channels. Since there are many more satellites than there are channels, interference is quite likely. The satellites are in a variety of orbits, ranging from low-altitude to geosynchronous and beyond (Vela). Hence, the interference at any ground station will be strongly time dependent.

The program uses an ephemeris generator to determine the positions of the satellites versus time, and thence the station events (rise, set, azimuth, elevation). A time sieve finds satellite mutual visibilities, and a frequency sieve investigates whether possible interferers have frequencies in common. Antenna cone angles are then calculated to establish the actual times of interference, if any. Unlike the programs for communications satellites, no receiver transfer functions are involved, since any channel carries the same type of telemetry signal.

Code Description and Capabilities

The code is built as a set of sequential routines. The data base for inputs contains detailed information on the ground stations and satellites. Each ground station is defined by identification, latitude, and longitude. Each ground station antenna has an associated beamwidth, critical cone angle (the angle off axis within which interference may occur), and obscured profile (the elevation angle below which the line

of sight is obstructed, regarded as a function of azimuth). Each satellite has an identification, a frequency set, and sufficient information to compute an ephemeris (rectangular inertial position and velocity at the initial time, or mean element sets).

In operation, each user (the operators of a military satellite system) first updates his satellite inputs, using tracking observations for his particular satellite vehicles. He then uses the routine DEEP to generate an ephemeris. A subroutine, DESERT, establishes the station events, which are the rise and set times over the partially obscured horizon at each station for the time period under investigation. Another subroutine, DRFI, produces card or tape listings of these events at each station, which are hand-carried to the Network Scheduling operations. At Network Scheduling, a routine DRASTIC assembles the station events and frequency sets for the various satellite systems. The interference is then calculated by a routine DLASTIC. Frequency sets are matched for each pair, then common visibility intervals at each station are found. Stored ephemeris data are used to calculate whether the satellites lie within the critical cone angle for any interval during the pass. The sun and moon are included in the satellite list, so vehicle-sun and vehicle-moon conflicts are also found.

Outputs from DLASTIC include a pass span list and a conflict prediction display. The pass span list includes the rise time and midangle revolution of the first and last acquisition of each vehicle at each station. The conflict prediction display is available in either detailed or summary form. In the detailed form, the header presents the station number and name, the station cone angle that was violated, the sun, moon, or vehicles involved in the conflict, the midangle revolution numbers for each vehicle, the rise and set times of each object, and up to 12 conflicting frequencies. The body displays the elevation and azimuth for each object and the cone angle at various times. The times may be internally generated or specified by the user. They include the start time minus the display rate, the end time plus the display rate, and the time of minimum cone angle. The summary form for conflict prediction is a two-line display. The first line contains the two vehicle numbers, the associated midangle revolutions, the start time of the conflict, conflict duration, time to minimum separation, and up to

six conflicting frequency numbers. The second line will be blank unless more conflicting frequencies exist, in which case up to six additional frequencies may be displayed. Besides these DLASTIC outputs, a simpler presentation routine, DGLASS, provides the cone angle as a function of time for each satellite pair in potential conflict.

Another useful output from this program is in the form of a wall-mounted multichannel strip chart. Time is horizontal, and each ground station is assigned to a vertically displaced parallel channel. Each satellite is associated with a color. The rise and set times for each satellite at each station are then used to mark an interval along the corresponding channel with the appropriate color. This enables the user to obtain very easily both an overall picture of the operations and an indication of the times of RFI conflict.

The program has no orbit limitations. Any frequency range could be used, but in practice only the 2200-2300 MHz band is implemented. Antennas are defined only by the beamwidth and conflict cone angle, with no pattern description. Propagation is line-of-sight with refraction correction included in the cone angle calculation. No special algorithms are employed.

Software Considerations

The program is written in JOVIAL-J4. It consists of approximately 300,000 lines of code, and is installed on the CDC-3800. A number of Executive Utility Routines are required as support software to permit operation of Milestone 4. The computer memory involves 128K of core, with the program and data sections maintained on disk and called as required. A typical run would involve about 15 vehicles and a pass span duration of 3 to 4 days, which would take about 1 to 1-1/4 hours for computer processing and the production of four RFI reports.

The program scope is limited to a total of 48 vehicles, 50 frequencies, and 100 ground stations. Any vehicle may be associated with no more than 16 frequencies, 4 signal categories, or 25 stations. The duration of a pass span (total time of a run), may not exceed 48 days, and any single ground station may have only 5000 vehicle acquisitions during a pass span.

Documentation and References

There has been no general release of documentation on this program. Descriptive material on the various routines may be available from the operators under the title Milestone 4, DDI-AOES.

For further information on Milestone 4, please contact A. P. Hall/ROSR, Air Force Satellite Control Facility, Sunnyvale Air Force Station, CA 94086.

B.5.h DEEP SPACE RFI PREDICTION PROGRAM (DSIP2)¹²

Introduction

This program determines possible radio frequency interference (RFI) with the Deep Space Tracking Net. It was developed in 1976-1977 by Jet Propulsion Laboratory with software support from Computer Science Corporation. The program is maintained by JPL and used by NASA/JPL Deep Space Network Operations.

Although the program has not been made available externally, it could be made available under special circumstances. In addition to DSIP2, peripheral software (including DPTRAJ, SATRAP, described later) and a planetary ephemeris file are required for program execution. Special compilation capability may be necessary, as DSIP2 is compiled in a two-step process, starting with the high-level SF3 (structured FORTRAN) and resulting in FORTRAN V code. Programming and consulting services are limited.

The code is designed to predict whether the DSN spacecraft tracking or telemetry operations might be compromised by radio frequency interference from an earth satellite. With reliable predictions of RFI events available, it is possible to change spacecraft operations plans to avoid the RFI or to request those operating the satellite to turn off its transmitter for certain intervals.

Most intersystem EMC programs are devoted to interference among communications satellites. The signals are broadband (typical channel width 34 MHz in the 4-6 GHz band) and come from geosynchronous satellites, which maintain a fixed position in the sky. In contrast,

¹²Original material was submitted by P. E. Beyer, Jet Propulsion Laboratory.

the Deep Space Net signals carry telemetry data, with bit rates ranging from 8 bps to 115 kilobits (Voyager and Galileo imaging data). The transmission frequencies are in the 2290-2300 MHz and 8400-8500 MHz bands, which are shared with other satellites. There are future plans for K-band assignments. The spacecraft are at interplanetary distances, some in orbit around or on the surface of other planets (Pioneer-Venus, Viking lander), some in solar orbit with radii comparable to the earth's distance from the sun (Pioneer 6-9), and some bound out of the solar system (Pioneer 10 and 11, Voyager). At such distances, the angular motion of the spacecraft with respect to the fixed stars is very small, so the earth-based antenna must track the spacecraft as the earth turns. The satellites that can interfere with interplanetary spacecraft downlink transmission are in low earth orbit or in highly eccentric orbits, so they move through the antenna beam very rapidly, or remain within the field of view for hours. Geostationary satellites may also produce interference. Because of the great distances over which the signals must be transmitted, extremely sensitive receivers must be employed, and consequently the Deep Space Net is subject to impairment when the source of interference is in the sidelobes of the antenna.

For instance, Pioneer 10, which is more than 2 billion miles away, has such a weak signal that it is susceptible to frequent RF interference, even by signals coming through the backside of the 64-m antenna. This implies that line of sight is meaningless as a prerequisite for RFI. As another example, the transmission from Pioneer 11 lost a good portion of its only infrared image of Titan during its Saturn flyby in 1979. The source of interference was a Cosmos satellite roughly 90 deg off the main beam axis.

These examples document cases of in-band interference, i.e., signals within the DSN bands. The DSN also has experienced RFI from sources such as the Landsats, operating adjacent to the DSN band. Angular offset becomes more important in these cases, and problems only become real for angular offsets below about seven or eight degrees.

The Deep Space Net has three ground tracking complexes, located at Goldstone, California, Madrid, Spain, and Canberra, Australia. Each provides coverage for about eight hours per day. The antenna beamwidths are very narrow (0.03 to 0.3 deg), but the great sensitivity can cause

impairment of the signal at very large angular offsets, as documented above. The receivers are multichannel telemetry, with each channel typically tens of kilohertz wide. The signals are shifted in frequency by the doppler effect, and a phase-locked loop enables the receiver to track the transmitter frequency. Under these circumstances, the interfering signal waveforms, which also represent telemetry, may be viewed as a set of narrow spikes, and the frequency of each spike must be tested to ascertain if it lies within a receiver channel. Thus, the equivalent receiver transfer function is a bandwidth match rather than an expression involving modulation indices and numbers of channels.

Since the spacecraft and interfering satellites are moving with respect to the ground station, their trajectories must be calculated accurately to find the direction of the line of sight to each. This requires a separate ephemeris calculator, which is a more complicated program than the interference calculator. The ephemeris calculator begins with the initial position and velocity of the spacecraft or interferer, and integrates the equations of motion, taking into account the various perturbations. For a spacecraft in solar orbit, the principal force is solar gravity, with the gravitational effects of the planets as perturbations. For a spacecraft in orbit around another planet, or an interfering satellite in orbit around the earth, the principal force is the spherically symmetric gravitational field of the planet, in which the orbit of the spacecraft or satellite is an ellipse. Perturbations are the nonspherical part of the gravitational field of the central body, which causes the ellipse to precess and distort, and the solar and lunar (for earth orbits) gravities, which have the same effects. The ephemeris calculator determines the position and velocity of the spacecraft or satellite as accurately as possible, and provides this information to the interference program, which will use it to determine the direction of the appropriate line of sight.

With this fuller description of the problem being investigated, we can now consider the computer code itself. The DSIP2 code plus associated programs are more complicated in mathematical detail than the codes that calculate interference among communications satellites. However, since there are relatively few satellites in the DSN telemetry band, and they appear in the field of view quite infrequently, the quantity of output is usually less.

Code Description and Capabilities

The code defines four types of interference: receiver drop lock, receiver interference, telemetry drop lock, and telemetry symbol signal-to-noise ratio degradation. Required inputs are the spacecraft, interferer, and ground station parameters and present locations. Each spacecraft is characterized by a total output power, a carrier frequency, a list of optional subcarrier frequencies, and, for each optional subcarrier, a list of optional telemetry modes (bit rate, modulation index, and coding type). The interfering signal is described as a set of spikes of specified power and frequency. The ground station locations, antenna gains, receiver bandwidths, and effective temperatures are required. The spacecraft and interferer locations are determined by a separate program (DPTRAJ or SATRAP), which calculates the trajectories from initial data. The initial data are provided by the DSN for the spacecraft, and by the NORAD tracking service, the NASA/Goddard Space Flight Center, or the European Space Agency for the satellite interferers. The trajectory data (P-files) are calculated for the duration of the interval during which RFI is to be investigated.

The program logic is as follows. For each satellite of the run, read in the data and compute the view periods at each ground station. Do the same for each spacecraft. Determine for each spacecraft/satellite/ground station triplet all common visibility intervals. For each interval, look for RFI by calculating the relative signal levels from spacecraft and satellite and determining if any threshold is exceeded. Repeat for all intervals for each spacecraft-satellite pair at each ground station, and print any RFI episodes.

A typical output would identify the spacecraft, satellite, and ground station, and those subcarrier signals that suffer interference. The starting and ending time of the interference for each of the four types is given, plus the occasion and level of the peak interference. Detailed printouts provide the signal and interference levels, the frequency separation between the interference spike and the closest subcarrier frequency, the angle between the lines of sight to the spacecraft and the satellite, and the amount of signal degradation, all available at user-specified intervals.

As a typical example, interference between Pioneer 10 and a Cosmos satellite on November 7, 1982, was predicted to last about one hour. The angular offset was between 42 and 43 deg, and the interfering signal level exceeded the desired signal by about 20 dB. The 32768 Hz subcarrier, carrying bit rates of 16, 32, and 64 bps, experienced signal degradation at the higher bit rates when the smallest frequency separation of an interference spike from the signal fell below 400 Hz, and telemetry drop lock below about 200 Hz at any of the bit rates.

The program has no orbit limitations, as it covers the range from low-altitude satellites to interplanetary spacecraft. There are no frequency limitations, but the degradation and drop-lock criteria are based on measurements of interference in the 2290-2300 MHz band, which is one of the operating regions of the Deep Space Net. The ground station antennas follow the CCIR sidelobe pattern ($32-25 \log \theta$) with constant mainbeam gain (56.1 dB to 0.14 deg for 34 m antennas at S-band, 61.7dB to 0.07 deg for 64 m antennas at S-band, and corresponding values at X-band). Only the total output power is specified for spacecraft and satellites. (The spacecraft will be pointed at the ground station. Earth coverage antennas are assumed for the satellites, which is generally satisfactory.) Propagation is free-space line of sight. The program uses special algorithms to calculate receiver gain reduction from saturation, noise temperature equivalent to interference, and drop-lock thresholds, and standard formulas for space loss, doppler shift, and antenna cone angle.

Software Considerations

The program is written in SF3/FORTRAN V UNIVAC. DSIP2 contains approximately 20,000 lines of code, and the associated programs DPTRAJ and SATRAP contain respectively 20,000 and 2500 lines. It is installed on the UNIVAC 1100/81. DSIP2 requires as support software the standard FORTRAN card reader and printer files, a planetary and lunar ephemeris file, and DPTRAJ or SATRAP generated P-files for each satellite and spacecraft to be processed in the run.

Computer storage and memory required is always under 65K. Core block execution time on the UNIVAC 1100/81 for a two-week run with three ground stations, five deep-space spacecraft, and an earth orbiting interferer is about 11 minutes for a 12-hour elliptical orbiter (Molniya or Cosmos), about 16 minutes for a near-earth polar orbiter (e.g., Landsat), or about 4 minutes for a geosynchronous orbiter.

DSIP2 can handle 10 ground stations, 10 interfering satellites, and an unlimited number of spacecraft. The run duration can include no more than 100 satellite view periods or 50 spacecraft view periods for any tracking station in the run. There can be no more than 50 interference spikes per satellite, and no more than 200 interference spikes for the aggregate of interfering satellites. A spacecraft can have no more than 10 subcarriers, no more than 20 bit rate modes per subcarrier, and no more than 40 total bit rate modes. The output is limited to 300 interference intervals total, and no more than 1000 interference changes of state per spacecraft pass for a given interferer. The last two conditions are not under the user's control.

References for Sec. B.5.h

1. Gallagher, J. F., *User's Guide for Deep Space Interference Program (DSIP2)*, Computer Sciences Corporation, Pasadena, CA, November 1977.
2. Beyer, P. E., and D. C. Cain, *Radio Frequency Interference by Earth Orbiting Satellites: Deep Space Interference Program*, TDA Progress Report 42-66, Jet Propulsion Laboratory, Pasadena, CA, September-October 1981.
3. Low, P. W., *Radio Frequency Effects of Continuous Wave Signals on Telemetry Data*, Part I, Deep Space Network Progress Report 42-40, May-June 1977, and Part II, Report 42-51, March-April 1979, Jet Propulsion Laboratory, Pasadena, CA.
4. Brady, F. H., "Radio Frequency Interference Modeling as Implemented in Subroutine CIANSP of Program DSIP2," Interoffice Memo 314.9-835, Jet Propulsion Laboratory, Pasadena, CA, March 1981.

Reference 1 gives a full description of the program showing structure, inputs, and outputs. Reference 2 provides a brief software description. Reference 3 presents the fundamental measurements and analysis, and Reference 4 shows how the analysis was implemented.

For further information on this program, please contact Patrick E. Beyer, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109.

B.5.j SATELLITE SIMULATION, NETWORK EVALUATION, AND COVERAGE PROGRAMS¹³

Introduction

This section describes three programs developed by Computer Sciences Corporation. They have different but related purposes. The first program, Flexible Satellite Communications System Simulator (FSCSS), models multiple end-to-end satellite communications channels including earth transmit and receive terminals, satellite equipment, and the respective up-and-downlink signal propagation paths. The simulation is used to calculate system performance and is primarily for basic system design. The second program, ECCM Network Evaluation Program (ENEP) is designed to evaluate the performance of electronic counter-countermeasures (ECCM) networks under varying degrees of uplink jamming. The third program, Satellite Coverage Program, determines the visibility of satellites from ground locations and the times when satellite antennas are pointed at ground points, and is thus a combined coverage and footprint program.

FSCSS is being developed by Computer Sciences Corporation for the Defense Communications Engineering Center (DCEC), Reston, VA. This system has a phased implementation plan with the initial phase just completed providing basic capabilities. These will be extended in the next phase, scheduled for completion in mid 1983. ENEP was originally developed by Computer Sciences Corporation and the Satcom System Engineering Division, DCEC/R410, for the Defense Communication Agency (DCA) in 1977. It is updated and maintained by the Satcom System Engineering Division and any use of this program must be coordinated with them. The program is in constant use by DCEC in their assessments of the capabilities of the Defense Satellite Communication System (DSCS). The Satellite Coverage Program was developed about 1965 at Computer Sciences Corporation for the Defense Communications Agency. Since then it has undergone extensive modifications, resulting in a

¹³Original material was supplied by W. L. Schummer, Computer Sciences Corporation.

number of versions. It is being maintained by Robert Heppe at Computer Sciences Corporation. It has served several users in addition to the DCA.

The several programs will be discussed in sequence.

Flexible Satellite Communications System Simulator (FSCSS)

The FSCSS simulates multiple satellite communications signals and their respective RF environments. This simulation is then used to calculate system performance (received signal power, error rates, loop slips, etc.). The simulator permits an interactive study of a variety of satellite and earth terminal configurations. Elements which may be simulated include up- and downlink signal processing paths; coding and modulation techniques; up-conversion from IF to RF; transmitter and receiver antenna performance; down-conversion and receiver signal processing; receiver demodulation, decoding, phase tracking, and bit timing; satellite channel modeling, multiple access (TDMA, DA) schemes; and jammer interference. General interference could be modeled and used as an input to the program to determine system performance as a function of various interference parameters. The various channel and signal processing effects are modeled as functional elements, so a user can freely and flexibly build a complex system configuration.

Required inputs include the parameter values of equipment level devices (modulators, filters, antennas, etc.). Typical information for a filter would be type, bandwidth, and number of poles; similar data are required for other devices. There is a data base of standard device groups stored within FSCSS, so a particular device can be used in more than one system element, and can be used several times within one element. Since an element may correspond to an earth terminal or satellite, this feature permits the user to create a file of DSCS stations, which then may be varied interactively to study system performance.

There are eight types of measurement device or outputs available for monitoring any point in the system: Spectral Power Density, Power Meter Display, Bit Error Rate Counter Display, Demodulator Statistics Display, Computed Symbol Error Rate Display, Demodulator Symbol Timing Loop Slips Display, Demodulator Symbol Phase Tracking Loop Slips

Display, and Demodulator Phase Tracking Statistics Display. As a sample, the Demodulator Phase Tracking Loop Slips Display would present the identification of the modulator and demodulator, the number of symbols received, the number of slips and of batch slips, the average number of slips per batch slip, and the average number of symbols and of bits between slips and between batch slips.

The signal representation used in FSCSS is the time series of complex envelope samples of the narrowband modulated signals. This permits monitoring of time functions at many points within the overall model, and verification of individual simulator modules. The carrier simulation is in terms of frequency offsets relative to the center of the total information bandwidth. The minimum relative sampling rate which achieves the desired accuracy is automatically computed. The minimum sufficient number of samples per symbol determines the overall simulation bandwidth.

FSCSS is restricted to geostationary orbits and is limited to a frequency range of 1 MHz to 100 GHz. Antenna patterns are synthesized using bessel functions and include earth coverage, narrow beam, multiple beam, and phased array, with special adaptive antijamming features. A free space propagation model is used with consideration for cloud attenuation, cross polarization, doppler effects, scintillation, and arbitrary fluctuation.

The software comprising FSCSS is in the implementation phase. The development is in PASCAL on a Digital Equipment Corporation VAX-11/780 computer system at the Defense Communications Engineering Center (DCEC) in Reston, VA. The VAX-11/780 hardware configuration is supplemented by a Floating Point Systems, Inc. array processor (AP-120B), which provides approximately 37K word (38-bit) memory. Including input, simulation, and data base management, the executable modules of FSCSS use approximately 1.2 Mbyte memory. Run time for the system depends on the complexity of the problem being solved, and may vary from several minutes to several days. Currently the system can handle up to 60 transmitters and jammers, 50 receivers, and two satellites.

The FSCSS system is described in DSCSS Phase 1A Final Report, Vol. 1-10, Computer Sciences Corporation, July 1979, prepared under CSC Contract DCA-100-77-C-00200.

ECCM Network Evaluation Program (ENEP)

ENEP provides an interactive model to evaluate ECCM networks under varying degrees of uplink jamming. A known ECCM network requirements model and associated link data rate adaptation file are loaded into the program's data base; ENEP will then calculate the realizable network configuration associated with the desired stress condition. ENEP has also been enhanced to characterize networks under specialized user subnet operating conditions; an example is the ability to fix specific link EIRP allocations so as to ensure uninterrupted service for those links under operator-specified uplink jamming levels.

Input data required to operate ENEP include site designators, antenna gains, link margins, SSMA modem characteristics, required link bit-error rate, link data rates, and link EIRP.

The primary network parameters ENEP outputs upon completion of network evaluation include terminal transmit EIRP required, link EIRP apportionment among SSMA links at a terminal, realizable link data rate and/or link connectivity, total SSMA signal composite, interference power, total channel composite power, signal-to-interference ratios per access, small signal suppression incurred, and available downlink carrier-to-noise ratios per terminal.

Special features of this program are its ability to automatically adapt link data rates to meet prescribed operational capabilities, its signal suppression computations for hard-limited satellite transponder operation, and its ability to solve for either achievable link rates or link transmit EIRP. ENEP does not yet handle the soft-limiter condition.

The ENEP is written using the FORTRAN IV level 1-1 compiler for the IBM 370/155 computer and also operates with the ITEL AS-5 operating at the DCEC Hybrid Simulation Facility (HSF). It is designed to function under control of the standard IBM time-shared option (TSO) of OS/MVT. A preprocessor program capable of interpreting FORTSIM pseudo-instructions must be available when compiling the program. ENEP contains about 3000 instructions and requires 160K bytes of core for execution. Running time varies from 3 to 20 minutes depending on the complexity of the problem. The program may be executed either in foreground (TSO

interactive operation), or in background (batch job operation). The model can handle up to 300 terminals, 10 satellite channels, 600 simplex links, 20 modem types, 100 modem records, 10 transponder gain states, and 6 antenna connectivity types.

ENEP is described in the following documents, all published by Computer Sciences Corporation.

Program Summary Description, 31 August 1978

ENEP Coding Guideline and Design Specification, July 1978

ENEP Users Manual, September 1978

Enhanced ENEP Operation, 10 January 1979

ENEP Improvement Plan, October 1982 (available from DCEC).

Satellite Coverage Program

The satellite coverage program calculates the geographic coverage of a satellite antenna considering motion of the earth and of the satellite. It exists in several versions. Input data include the types of output wanted, the number of satellites and earth stations, and the number of locations on the earth (if any) to test for mutual visibility with the earth stations. Visibility constraints, such as minimum and maximum elevation angles, azimuth limits, and satellite antenna beamwidths may be specified. The coordinates (latitude and longitude) of the earth stations and other locations are required inputs. The other locations can be specified or generated internally as a grid covering a desired range of latitudes. For the satellites, ID number, epoch time, and orbital elements are required. The starting day of the simulation, the number of days to run, and the time interval between successive looks at the system are also inputs.

The computer simulates the motion of the earth and the satellites and computes the visibility data. Outputs, which vary with the program version and the user's choice, provide a schedule of the times at which satellites are visible, within the specified visibility constraints, to points or pairs of points on the earth's surface, and statistical data concerning average coverage times. Specific outputs may include the start and stop times and the duration of the visibility interval (visit), which satellite is visiting, the maximum elevation of the

satellite at the earth station during the visit, etc. Statistical data may include the average visit duration, the average interval (gap) between visits of specified satellites to specified ground stations, the maximum gap duration, the percentage of time each location could see at least one satellite which was simultaneously visible to one of the bases, the average and maximum outage duration, the average waiting time before communicating, and the probability distribution of outage durations.

The ground track for each satellite can be printed out, as can tables showing which satellites were visible to which bases and locations at each "look" (system snapshots). Data on maximum doppler shift and maximum rate of change of doppler can also be printed. For most purposes, time is quantized to an accuracy of one minute. The orbital model is capable of accuracies to a few seconds, with a more elaborate model available for applications requiring greater accuracy. Some output options provide a quick visual graph of the coverage times at various locations, others give a more detailed description of the visits, and still others give only summary statistics. Summary data are printed for each location, for each latitude, and for the total set of locations. One version allocates and schedules communication links, allowing for competition for use of satellite channels and earth station antennas, availability for tandem hops and alternate routing, and priorities, and prints out monthly availability figures.

The orbit model customarily used is based on a simple Keplerian ellipse, with first-order corrections for secular effects such as the regression of the ascending node and rotation of the line of apsides. A more complex model, including the effects of higher harmonics of the earth's gravitation field, is available. Drag effects are included in both models. (The drag coefficient is one of the required input quantities. It is routinely supplied by Navspasure in its one-line and five-line sets of orbital elements.) Orbital input data are in the Navspasure format. Any altitude, inclination, or eccentricity can be used, with the possible exception of synchronous equatorial. (In synchronous equatorial orbit small forces acting on the satellite have a cumulative effect that eventually causes large drifts in the satellite position.)

Most of the versions of the program do not calculate path loss, so frequency is not a consideration. One version of the program does calculate path loss. In this version, atmospheric losses for several specific frequencies, as a function of elevation angle and weather conditions, are included in the stored data.

Most of the versions of the program assume that the satellite has an earth coverage antenna, or one that covers a circular region of the earth, centered on the subsatellite point, possibly with a central hole in the pattern. The earth stations and other locations can be specified to cover certain ranges of elevation angle and azimuth. The version of the program that calculates path loss permits the satellites and/or the locations to have spinning, sharp-edged pencil beams, if desired. At present the path loss equation includes only free-space loss plus atmospheric attenuation, but the effects of the antenna pattern could easily be added to the calculation, since all the required angles are already being computed by the program.

The program is written in FORTRAN with various versions of the program ranging in size from about 1500 lines of source code to about 2500. Versions of the programs have been run on several computers, including the UNIVAC computers used by CSC's Infonet, HP-3000, and SEL-32 and SEL-85. The program is self-contained and the computer storage and memory requirements are flexible. With dimensioning to stay within about 32,000 words of data storage, runs can be made for several satellites and hundreds of earth locations. In versions of the program that accumulate a great deal of detailed information about the visits to each location, smaller numbers of locations can be accommodated on a given run, or additional storage space would be required.

Execution time varies depending on the number of satellites simultaneously being modeled, the number of earth stations and locations, and the duration of the simulated exercise. Typically, simulation of a day's operations with several satellites, several earth stations, and several other locations requires one or two minutes of computer time.

Size limitations are flexible, depending on the available memory and the amount of detail desired for each location. Runs have been made for up to 2000 locations at a time, for a year's operation with several satellites, while staying within 32,000 words of core. The program contains shortcuts that permit many locations at the same latitude to be handled almost as quickly as a single location. In most applications, however, it has been found that information is desired on only a small number of locations. The various versions of the programs have different dimensioning, generally for about 12 satellites, 10 earth stations, and about 500 other locations, but these numbers can easily be changed.

For further information on these three programs, please contact William L. Schummer, Systems Division, Computer Sciences Corporation, 6565 Arlington Boulevard, Falls Church, VA 22046. Information on ENEP must be coordinated with the DCEC. Specific requests on the Satellite Coverage Program should be directed to Robert Heppe at the CSC address.

B.6 ELECTROMAGNETIC VULNERABILITY ANALYSIS

The analytical procedures and computer codes presented to this point have all dealt with the susceptibility to interference of individual equipments placed in specified configurations, and fall into the general category of electromagnetic compatibility analysis. The behavior of communications networks, rather than individual equipments, constitutes the subject matter of electromagnetic vulnerability analysis. Networks are required to carry messages under a variety of stressing conditions, such as unintentional or intentional interference (jamming), storms, and nuclear blackout. Certain procedures and programs which have been developed to determine the capability of earth-satellite communications networks to survive and operate under stressed conditions are given in the three following subsections. These programs deal mainly with message traffic analysis, rather than equipment details, and the outputs are usually statistical.

B.6.a MILSATCOM VULNERABILITY ANALYSIS MODEL (MVAM)¹⁴

Introduction

The U.S. Air Force has the responsibility for the development, deployment, and operation of military satellite communications (MILSATCOM) systems. These systems are required to provide communications in the face of interference, disruption, deception, and potential destruction by opposing forces. Simulation of satellite communications provides an economical way to evaluate the performance of these stressed systems before large sums are expended on their development. The Air Force has had the computer program MVAM developed to assess the vulnerability of such systems. MVAM is a dynamic computer model which uses data bases prepared by the user to quantify the performance of various satellite communications systems in the presence of differing levels or types of stressing.

MVAM was developed by the MILSATCOM Project, Bell Technical Operations, Tucson, AZ, for the Air Force Electronic Warfare Center (AFEWC), Advanced Technologies Division, San Antonio, TX. It was developed between September 1980 and September 1982. Some enhancements are currently in development. The model is available for execution at either AFESC or Bell. The software is maintained by Bell Technical Operations. The program and services are available from AFEWC/SAX, San Antonio. MVAM has been used by Bell Technical Operations for the analysis of TACSATCOM II, the single channel transponder, and the AFSATCOM systems.

The Air Force is also responsible for laser communications, and AFESC is developing the LASERCOM Vulnerability Analysis Model (LVAM) to ascertain the vulnerability of LASERCOM links. This model is in the design stage at Bell Technical Operations, with the basic model to be completed by June 1983. LVAM will be discussed briefly at appropriate points in this subsection, which is primarily devoted to MVAM.

¹⁴Original material on MVAM was submitted by M. L. Popovich, R. J. Griebel, and C. L. Welch; on LVAM by W. O. Rasmussen. All are with Bell Technical Operations Corporation, Textron, 1050 East Valencia Road, Tucson, AZ 85706.

Code Description and Capabilities

MVAM is an event-driven traffic model designed to simulate MILSATCOM system characteristics and how key interfaces integrate with one another. The communications system is modeled by utilization of user-supplied data bases. These data bases include: technical description of the satellite segment and ground terminals; definition of communications types and data rates; definition of the system accesses and message rates; deployment and employment of the satellites and terrestrial (ground and air) terminals; technical definition of the threat, its deployment and method of employment; and any special features such as weather conditions, nuclear detonation activities, movement of platforms, terminals, storms, etc. Some of the special features are in the process of implementation. The detailed technical inputs are essentially the same as in other programs, such as number and location of satellites and ground terminals, powers, antenna patterns, and modulation types. The simulated equipments are assembled to form a communications system, and the behavior of this system under unstressed and stressed conditions is ascertained. The concept is capable of a full-scale dynamic simulation or a limited snapshot overview analysis. It was designed for user flexibility and ease of enhancement.

Two categories of events were defined in the traffic model. The first was classified as an external traffic event which represented a specific earth terminal's need to communicate via the satellite system, along with all the characteristics of the transmission (length, data rate, precedence, etc.). A second event type was categorized as an exogenous event which represented additional real-world dynamics to be modeled (storms, nuclear blasts, terminal equipment failure). Both categories of events are described.

To provide satellite transmission traffic for modeling, a means was required by which individual events could be generated. This need was met by the external event module, whose primary function is to expand generalized communication demand data, commonly called needlines, into a series of time-dependent distinct events. Since these events represent expected real-world use of a satellite system, they serve as the driving mechanism within the model. In addition to individual transmissions,

the module can create multiple destinations if a broadcast transmission is called by the given needline.

A needline usually consists of expected average communication demands in a fixed period of time (e.g., 24 hours) for a given pair of terminals. The specific demands include origin and destination of transmission, type or mode of transmission (data or voice), identification of a busy period and percent of transmission therein, average number of transmissions per period per precedence level (routine, priority, etc.), and the average length of transmission (bits for data, seconds for voice) per precedence. If the needline represents a broadcast message, the additional destinations must be specified.

The module applies queueing theory to provide statistically distributed events whose averages match the needline. The total number of transmissions per time frame is represented by a Poisson process whose mean is the average number of transmissions. After determining the total number of transmissions to be modeled in the time interval, a random time, representing the instant of occurrence, is attached to each event. The random time is based on a uniform arrival rate distribution in which the total traffic in the busy period represents the percent called for in the needline. Traffic in the remaining period of time is also uniformly distributed. Enhancement to the external event module to allow other traffic distributions (such as a normal distribution, which might correspond more closely to an unstressed environment, the uniform distribution representing the stressed environment) could be accomplished easily. The length of transmission is represented by a fixed portion, which includes the header and similar information, and a variable portion whose length is distributed exponentially. Accumulated statistics on the length will reflect the needline averages.

Exogenous events represent those real-world occurrences which are not communications related. If an MVAM user wishes to determine how well a satellite system will perform under these types of conditions, he merely creates a specific event. The events are specified by time and a set of parameters. Currently, MVAM allows for terminal movement events, which are intended for use with ground terminals and alter the location of a "stationary" terminal during the simulation run; stationary storms, for which the user simulates specific rain at a terminal; and nuclear

blasts, which are calculated off-line. Exogenous events now being added to MVAM as enhancements include temporary or permanent changes in terminal operational status, dynamic simulation of moving storms by specification of storm radius, path, and rain rate, retargeting and power variation of jammers, and on-line modeling of nuclear blasts.

The code can simulate and analyze a variety of military communications satellite features, including transmission attempts and processes when completion fails, queueing and preemption of traffic, evaluation of signal degradation due to atmospheric losses and to both intentional and unintentional interference, earth terminal movement (land, sea, and air), and nonsynchronous satellite orbits. Enhancements being added include dynamic system diagnosis and ECCM selection and implementation to include nulling, power increase, and transmission rate reduction.

The multipurpose philosophy of MVAM is embedded in the outputs. Currently, model outputs are geared toward satellite performance analyses and system design studies. Report formats are available for dynamic simulation results, snapshot runs, and presimulation system configuration. During the dynamic simulation, data relevant to the discrete events processed are retained in history files. This allows the analysis software to produce reports during or after simulation. All software was written to allow the generation of additional reports, as well as those existing, specific to various future MVAM uses.

Typical snapshot outputs include elevation reports, which determine for each synchronous satellite the elevation and azimuth angles to each earth terminal; orbital reports, which determine for nonsynchronous satellites their location versus time and the azimuth and elevation to a predefined earth location as a function of time; and ground reports, which provide geometries to each friendly terminal from the threat terminals in the scenario. Configuration reports, all in process of implementation, include routing reports that display the linkages established; antenna beam allocations, which are a detailed representation of the system beam coverages; and satellite net demand reports, which provide a detailed breakdown for each network of the satellite configuration, accesses, etc., as functions of grade of service, capacities, and demands.

There are several types of dynamic simulation outputs. Transmission history provides three levels of statistical summaries for the transmission events, including a detailed listing, a statistical summary by period, and a frequency plot of completions versus failures. Completion/failure reports provide a statistical summary, by mode and precedence, of transmission failures and their causes. Link history reports provide detailed engineering summaries of transmissions, including margins, losses, gains, geometries, and probabilities, for snapshot or full simulation runs. Report types being implemented include queue reports, providing summaries of data queueing (queue lengths, average delays), and ECCM reports, providing data specific to ECCM implementation (time, technique, and reason for implementation).

The snapshot and configuration presentations are most applicable to design studies and pre-MVAM analysis, whereas the dynamic simulations are appropriate to performance analysis and vulnerability studies.

The MVAM model accepts any orbital configuration. There are no frequency limitations. Antenna patterns are used by the model in the form of data bases entered by the user in discrete points which are interpolated by the model at run time.

MVAM applies different propagation models, depending on the transmission radio frequency and whether the link follows a satellite path or an earth path. Satellite paths include the uplink (earth terminal or jammer-to-satellite) and the downlink (satellite-to-earth terminal). Earth paths are from an earth-based (ground or airborne) transmitter to an earth-based receiver, and are included to allow modeling of downlink jamming.

For earth paths below 15 GHz, the MVAM utilizes the Longley-Rice Irregular Terrain Model with minor modifications. The loss value provided by the Longley-Rice model is actually a median value of a random variable and thus has an associated distribution. An operation provided by the Longley-Rice model is the calculation of the standard deviations to indicate the variability of this loss value. The MVAM provides two mechanisms to deal with this variability (user choice):

- (1) use of a certain probability point on the cumulative distribution or
- (2) use of a pseudorandom terrain model. In either case, the loss as a

distribution is replaced by a specific value from that distribution. In addition to this loss, the MVAM considers the effects of rain for frequencies above 4 GHz.

For earth paths above 15 GHz, the model determines whether line-of-sight (LOS) conditions hold between the transmitter and receiver. This test follows the Longley-Rice test for lower frequencies except that LOS distance over irregular terrain is used rather than smooth earth LOS distance. If LOS occurs, the loss is set to zero. Otherwise, the model assumes a loss of 3 dB per km beyond LOS distance. Loss statistics are then provided by the Longley-Rice model using a frequency value of 15 GHz. These statistics are processed as described above for frequencies below 15 GHz. Other considerations modeled include the effect of atmospheric absorption using data from CCIR Report 234, fog attenuation based on data provided by Lincoln Laboratories, and rain effects, based on the Crane/Feldman work. Nuclear and scintillation effects are modeled based on the Mission Research Corporation work done for the Air Force Weapons Laboratory.

The well-known algorithms utilized in the MVAM model are limited basically to the propagation algorithms discussed above. Some of the communications needlines are based on the Army's Communications Requirements Document (COMSR) sponsored by the Signal School at Ft. Gordon, GA.

In contrast to the complex networking of MVAM, the LASERCOM vulnerability analysis model (LVAM) is designed to analyze a single communications link. The basic model will allow the user to analyze an aircraft-space or space-space LASERCOM link and the effect thereon of a ground, air, or space based high energy laser jammer and/or a high altitude nuclear burst. Inputs to LVAM are those items that describe the LASERCOM transmitter, receiver, natural interference to the communications, and any man-made stressing of the link. LVAM then computes the effects on the communications fidelity as described by the signal to interference ratio, bit error rate, and similar expressions.

The outputs from the model are primarily numeric with some graphics. The model is structured so that many of the modules comprising the total LVAM may be operated in a stand-alone fashion. Therefore, there are two forms of output, one from the operation of an

individual module and the other from the operation of a collection of linked modules. As an example of single module operation, the receiver off-axis response module allows a user to specify the physical configuration of the receiving system including mirror size, location of baffles and shields, and so forth. The output from the module is a numeric table and a printer plot of the off-axis detector irradiation function. When several of the modules are linked, the output from LVAM is a composite of the outputs from the individual modules as well as values of quantities such as the S/I and BER which are calculated from the collection of modules.

LVAM is in the design and development stage, with certain modules now being constructed, and others to be implemented later.

Software Considerations

Except for the user interface to the Air Force AEWEDS system, the complete MVAM model is prepared in FORTRAN IV. The user interface is in TTDL language as implemented on AEWEDS. There are approximately 430 routines in MVAM, occupying some 60,000 lines of code including a generous number of comments. At present MVAM is installed on the CDC CYBER 172 located at Bell Technical Operations in Tucson, AZ, and the USAF PDP-11/70 (AEWEDS) at the USAF Electronic Security Command in San Antonio, TX. It is being installed on a PDP-11/70, also located at Bell in Tucson. It employs indexed sequential files, and therefore requires the IAS system offered by DEC on the PDP-11/70. Also, for user interface applications, the system is dependent on the Sperry Model 1655 display system and the TTDL display language installed on the AEWEDS system. Other support software is standard on the computers listed above.

Storage required for the running of MVAM include 8 to 10 tasks of 30K words each on the PDP-11/70 plus one disk drive. On the CDC CYBER 172, memory utilization is approximately 150K words of segmented random access memory and one disk drive. A typical snapshot run for the MVAM will take 1 to 5 minutes of CPU time. A full MVAM simulation involving a theater, corps, equivalent opposing forces, and thousands of messages has averaged about five times real time for CPU utilization. MVAM has been designed with completely flexible data bases so problem size is not

a factor. No limit is known for number of satellites, terminals, or messages, although when CPU run time becomes large, one might try to reduce the problem complexity.

The LASERCOM model LVAM will use FORTRAN IV, be self contained, will use very portable coding so that it may be operated on several computers, and will be limited to a single LASERCOM link. Other details and limits of the software of LVAM are not yet established.

References for Sec. B.6.a

1. *Generic Methodology Design Specification for MILSATCOM Vulnerability Analysis*, AFEWC/SAX, August 1982.
2. *User's Manual for MILSATCOM Vulnerability Analysis Model*, AFEWC/SAX, August 1982.
3. *Maintenance Manual for MILSATCOM Vulnerability Analysis Model*, AFEWC/SAX, February 1983.

For further information on MVAM or LVAM or any documentation, please contact Major Glenn R. Doughty or Captain James D. Ledbetter, USAF Electronic Warfare Center/SAX, Kelly Air Force Base, Building 2000, San Antonio, TX 78243.

B.6.b SIMSTAR/DYNAMIC MULTI-MESSAGE SIMULATOR¹⁵

Introduction

The effectiveness of the Minimum Essential Emergency Communication Network (MEECN) in supporting the execution of the Triad forces under the strategic doctrine of "mutually assured destruction" was evaluated by a one-way type of C³ network analysis. This type of methodology only evaluated the ability of the MEECN to deliver a single message from the National Command Authority (NCA) to the Triad forces.

As strategic doctrine evolved from "mutually assured destruction" to "countervailing strategy," new requirements were placed on the MEECN. First, the C³ systems must endure beyond the initial states of a nuclear conflict by taking full advantage of survivability as well as durability through redundancy and replenishment. Second, it must be capable of routing more than one message and more than one type of

¹⁵Original material was submitted by Captain W. Kraus, USAF Studies and Analysis.

message. Finally, it must provide for two-way communications between the NCA, commanders, and the forces.

These same requirements must be embedded in the C^3 network analysis model that evaluates the effectiveness of the next-generation MEECN. It was these fundamental requirements that initiated the development of the SIMSTAR/Dynamic Multi-Message Simulator (DMMS) as the latest of the strategic C^3 analysis tools that have been sponsored by Headquarters USAF, Assistant Chief of Staff for Studies and Analyses (USAF/SA).

SIMSTAR/Dynamic Multi-Message Simulator is the end product of an evolutionary process that began in 1974 with the development of the first Network Status Model (NSM) and Dynamic Network Simulator (DNS) architectures. These original NSM/DNS models underwent a long series of enhancements and refinements during the 1976-1979 time period and finally resulted in the prototype Dynamic Multi-Message Simulator in 1979. In 1981, USAF/SA contracted with IRT Corporation, San Diego, to significantly improve the methodology and efficiency of the prototype DMMS and to test and document the software. The outcome of this effort was the SIMSTAR/Dynamic Multi-Message Simulator which was delivered to USAF/SA in August 1982. Additional enhancements will be completed in 1983.

The SIMSTAR/Dynamic Multi-Message Simulator is maintained by the Strategic Command, Control and Reconnaissance Division, Directorate for Strategic Force Analyses, Assistant Chief of Staff for Studies and Analyses (USAF/SASC). SASC maintains configuration control over SIMSTAR and reviews all requests for information pertaining to the model.

Because SIMSTAR has only recently been delivered, USAF/SASC is currently the only user. Until enhancements now being implemented are completed and USAF/SASC completes its validation of the methodology, SIMSTAR will not be released to other potential users. The validation process should be completed by the end of 1983.

Code Description and Capabilities

The original motivation behind the development of SIMSTAR was to develop a single C^3 network evaluation methodology that would allow the modeling of the Emergency Action Message (EAM) dissemination problem as well as two-way communications problems. Specific features that were deemed to be desirable include the ability to:

1. Simultaneously track multiple messages that may be injected at any node in the network. The message injection events may be caused either by prescheduled events or those that occur dynamically during the course of the simulation.
2. Accurately and efficiently compute RF propagation predictions on communications links that span the full spectrum, from extremely low frequency (ELF) through extremely high frequency (EHF), in ambient, electronic warfare (EW) jammed and nuclear-disturbed scenarios.
3. Destroy and dynamically restore nodes and jammers.
4. Realistically model equipment reliability (i.e., transmitters and receivers) in terms of probability of failure and of restoration after failure.
5. Dynamically allocate resources, including noncommunications-specific resources such as personnel.
6. Execute event-driven simulations that are based on the specifics of the data base used (e.g., the scenario and network element descriptions) for a truly dynamic modeling capability that efficiently uses computer resources.
7. Save link propagation prediction values, not only for later use within a given Monte Carlo history, but for use in subsequent Monte Carlo histories as well--thereby reducing overall computer run time to an absolute minimum.
8. Flexibly model background traffic so that the analyst need only input probability parameters, thereby eliminating needlessly large data bases and excessive run times.
9. Simulate fraudulent or altered messages that are caused by cognizant agents with a network.
10. Simulate perishability of messages in the network.
11. Model conditionally caused and multiple-caused events which may be tied to another event.
12. Employ satellite orbit models that simulate actual flight paths and calculate the location of space platforms for specific times.

SIMSTAR has been partitioned into three major programs: Preprocessor, Simulator, and Postprocessor. The interactive Preprocessor program operates in a query-response mode and allows the operator to specify the characteristics of the communications network to be analyzed, both in terms of the specifics of the nodes and interconnecting link parameters as well as the message traffic that is to travel throughout the network. The Preprocessor allows the analyst to specify the network using a "build approach" where a previously defined network or subnetwork may be merged into a new file and updated or modified as required, thus saving tremendous amounts of network definition and setup time.

The SIMSTAR Simulator accesses the data in the preprocessed input file and simulates the performance of the network under the specified environmental conditions of the scenario. The output of the computation module is the results of state calculations for the various Monte Carlo trials.

At the heart of the SIMSTAR Simulator is the RF propagation prediction module. This module contains submodules for the prediction of signal-to-noise (S/N) ratios, in ambient, EW jammed and nuclear-disturbed environments--at RF propagating frequencies that span ELF through EHF. The philosophy employed throughout the SIMSTAR architecture is that of a heuristic phenomenology modeling approach rather than a detailed deterministic approach. In other words, curve-fits and simplified phenomenology models (based on the results of more detailed longer running codes such as WESCOM, SIMBAL, WRECS, NUCOM, WEPH, etc.) have been developed and incorporated into SIMSTAR.

The propagation prediction module generates the signal-to-noise ratio at a receiver site based on system level transmitter and receiver parameters (ERP, bandwidth, frequency) and then, depending on the modulation, modem, and receiver characteristics, determines a most probable character error rate which is translated into Correct Message Receipt Probability (CMRP) or Probability of Acceptable Message (PAM). In the presence of EW jamming, RF propagation predictions are based on the jammer's location and transmitter characteristics, and the jammer signal-to-noise ratio is determined. The jammer signal-to-noise ratio

is combined with the desired signal-to-noise ratio to calculate a signal-to-interference ratio which is used to determine the CMRP.

Perhaps even more important than the RF propagation techniques themselves is SIMSTAR's ability to save the results of previous link performance computations for subsequent use--not only within the same Monte Carlo history but for later histories as well. The key to this link performance reuse capability is a technique for allowing the analyst to specify (via the Preprocessor) the acceptability windows, in terms of time since the performance of the last computation as compared to the current scenario time (for ambient and nuclear-disturbed environments), as well as node motion/distance acceptability windows for moving nodes. Tremendous savings in computer run times are made possible because of this link performance reuse capability.

Upon completion of the specified number of histories, the analyst may use the Postprocessor to reduce the data from the history file. There are currently eight alternative options available for displaying the results of the simulation. These are reports of Correct Message Receipt Probability, Node/Jammer Survivability, Equipment Availability, Resource Utilization Statistics, Path Usage Statistics, Queue Statistics, Event-History Summary, and Surviving and Connected Warheads.

Software Considerations

SIMSTAR is a self-contained simulation model which has been written in FORTRAN IV under the 1966 ANSI standards and conventions. The vastly expanded coding features allowed by the 1977 ANSI standards have been avoided to make the software as machine independent as possible. In addition, the strict software standards as imposed by USAF/SA have been followed, thereby making the source code very structured, readable, and maintainable.

The computer memory required to load and execute the SIMSTAR Simulator is dependent on the size of the problem being considered. Currently SIMSTAR is dimensioned to handle 300 nodes which may be moving, stationary, or satellites (each node may have up to 15 transmitters, 15 receivers, and 9 processors). The problem may involve up to 99 receiver classes, 99 transmitter classes, 50 jammers, 50 nuclear bursts, 15 messages, and 500 exogenous events. Based on these

dimensions, the memory required for SIMSTAR is: Preprocessor (145 subroutines)--1.0 Mbyte, Simulator (267 subroutines)--5.4 Mbytes, and Postprocessor (56 subroutines)--1.0 Mbyte.

SIMSTAR has been installed on a VAX 11/780, IBM 3032, and CRAY-1. The CPU time required for the SIMSTAR Simulator execution is very machine dependent. An example of required CPU time for the SIMSTAR simulator as a function of the number of Monte Carlo replications performed is shown in Fig. 14. These times were based on a test case consisting of: 70 nodes (48 moving, 10 fixed, and 12 satellites), 26 receiver classes, 33 transmitter classes, 10 jammers, 40 nuclear bursts, 14 messages, and 15 exogenous events. For this test case, there were a total of 77 transmitters, 390 receivers, and one message which was extensively routed, similar to a force execution message.

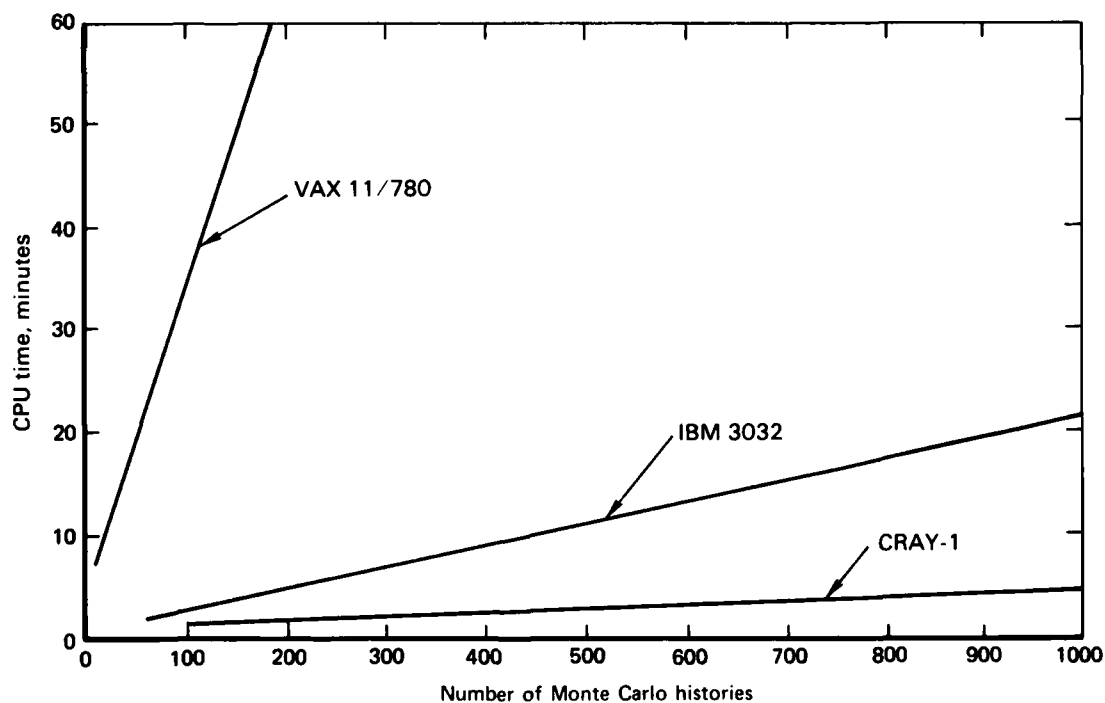


Fig. 14 - CPU time required for Monte Carlo histories run

The CPU time required for the Preprocessor and Postprocessor is minimal. However, these programs do require a significant amount of terminal connect time for development of the data bases in the Preprocessor (input file for the simulator) and analysis of the output data file (created by the Simulator) in the Postprocessor.

Documentation

The SIMSTAR documentation is divided into eight volumes:

- Volume I - *SIMSTAR Executive Summary*
- Volume II - *SIMSTAR Pre-processor User's Manual*
- Volume III - *SIMSTAR Simulator User's Manual*
- Volume IV - *SIMSTAR Post-processor User's Manual*
- Volume V - *SIMSTAR Pre-processor Programmer's Manual*
- Volume VI - *SIMSTAR Simulator Programmer's Manual*
- Volume VII - *SIMSTAR Post-processor Programmer's Manual*
- Volume VIII - *SIMSTAR Analyst's Manual*

The purpose of the *SIMSTAR Executive Summary* is to present a top-level description of SIMSTAR potential applications, capabilities, and limitations at a level of detail that would be useful to management-level decisionmakers. The purpose of the *SIMSTAR User's Manual* is to provide a documentation source that will enable a nonprogramming SIMSTAR user to understand the SIMSTAR logical structure, the input data requirements, the results produced by SIMSTAR, and the use of SIMSTAR results. The *SIMSTAR Programmer's Manuals* provide all the details necessary for a programmer to understand the operation of the Preprocessor, Simulator and Postprocessor; and to trace through SIMSTAR for debugging, modifying, and/or converting SIMSTAR for use on computing systems other than those for which it was originally designed (the IBM 3032 or 3033, the VAX 11/780 or 11/750). The *SIMSTAR Analyst's Manual* provides detailed information that will enable an analyst to understand SIMSTAR's functional structure and the algorithms and computational techniques employed.

For further information on SIMSTAR, please contact Headquarters United States Air Force, Assistant Chief of Staff for Studies and Analysis (USAF/SASC), Washington, DC 20330.

B.6.c PROPAGATION NETWORK ANALYSIS CODE (PNAC)¹⁶

Introduction

The Propagation Network Analysis Code (PNAC) is the result of an effort sponsored by the Air Force Weapons Laboratory (AFWL) to assess the performance of satellite communication systems in critical strategic C³ and warning networks. The threats of particular concern to these networks are electronic countermeasures (ECM) and disturbances in the radio-frequency propagation medium caused by high-altitude nuclear detonations. PNAC is designed to predict the performance of specific, individual links as well as entire C³ networks when subjected to these kinds of attacks. Main objectives during the development of PNAC were that the code be modular, flexible, and economical to operate, particularly in nuclear environment descriptions where first principles codes are too lengthy and cumbersome for operational analyses and more engineering-oriented codes are required. These objectives have been achieved and PNAC can produce useful analyses of a wide variety of satellite communication systems and networks of interest to the Department of Defense.

The PNAC was developed by Computer Sciences Corporation, Albuquerque Operations, with important contributions by Mission Research Corporation of Santa Barbara, and Berkeley Research Associates, Berkeley. The PNAC has evolved over a period of more than five years as understanding of high-altitude nuclear effects on RF propagation has increased. The basic code became operational in 1980 and was able to predict high-altitude nuclear effects on selected satellite links of interest to the DoD. Since that time, the code has been improved with the addition of more modulation types, coding schemes, nuclear laydown scenarios, and ECM effects. Atmospheric effects such as attenuation due to rain, water, vapor, and oxygen were also added.

¹⁶Original material was supplied by Wesley G. Nichols, Computer Sciences Corporation, Albuquerque, NM.

The PNAC is maintained by Computer Sciences Corporation, Albuquerque Operations, under the supervision and direction of the Air Force Weapons Laboratory. Equipment performance data bases and SCENARIO nuclear environment code developments are provided by Mission Research Corporation and Berkeley Research Associates under subcontract to CSC. PNAC programs and services are available from 1st Lt. Eddie Preston, Air Force Weapons Laboratory, NTYC, Kirtland Air Force Base, NM, 87117. Programs and analyses have been used by AFWL, Sandia National Laboratories, and the Federal Emergency Management Agency, as well as in-house by CSC.

Code Description and Capabilities

The PNAC was designed to simulate the propagation of multiple messages in C^3 networks under nuclear and ECM attack. Such systems have a multiplicity of communication link types, including satellite airborne and ground line-of-sight links. The communication nodes could correspond to aircraft, satellites, or ground stations.

Link and node reliabilities and availabilities change rapidly according to the nuclear and jamming scenario. High-altitude nuclear bursts in particular affect the RF propagation paths of satellite-to-ground and satellite-to-aircraft links. Critical messages must be carried over the degraded system to deliver warning and status information and orders to the strategic forces, and to receive status reports from the forces. The PNAC calculates the link and network error rates and expresses the results as a probability of receipt of an acceptable message.

The dynamic features of network topology and link reliability in PNAC are uniquely applicable to the modeling of strategic C^3 networks--namely, the time-dependent link reliabilities and node failure probabilities. Since message propagation is simulated on a link-by-link basis, the dynamics are properly modeled, as described in more detail below.

The link capacities are specified on a per link basis to model the various link speeds present in such a system. Since links are not perfectly reliable and are subject to interruption, messages will

sometimes be erroneously received or blocked entirely, and must be sent again. This function is accurately modeled in PNAC.

The specification of three classes of messages reflects the existence of critical broadcast messages (e.g., EAMs) as well as less critical or less widely disseminated messages. Multiple levels of precedence (up to 100) of transmission are also simulated in PNAC. In practice, the sender of an important message usually will wish to have its receipt acknowledged by the final destination. This report-back capability is simulated by an answer message in which the final receipt triggers a reply.

Appropriate to the stochastic performance of C^3 networks, several of the outputs are statistical measures. The model thus determines the network effectiveness in expeditiously delivering critical traffic. Also provided are relevant performance measures such as the expected number of nodes receiving a message versus time and the probability that a directed message is received, along with important link engineering parameters such as link or message error rate, bit energy to noise density ratio, scintillation index, and fading decorrelation time.

PNAC can also predict the performance of space-based radars in a nuclear-disturbed environment. Although not directly related to the communication use of PNAC and funded under a different contract, this capability is mentioned so the user can be aware of the full capabilities of the code. The PNAC has been designed to permit the user to specify a wide variety of analysis scenarios, almost any type of network, a range of equipment types involving satellite communication links, and a broad range of high altitude nuclear and jamming threats as input data.

The analysis scenario describes the network to be analyzed and lists the messages to be transmitted, their origins and destinations, and times of transmission. The analysis scenario will also describe the nuclear and jamming attacks to be applied against the network, although these data are actually incorporated in the propagation environment data base. Network parameters include node locations, connectivity, and processing rate(s); link types and data rate(s); queue characteristics, routing and alternative routing plan, community of interest restrictions, and priority/precedence plan. Pertinent transmission

parameters are frequency assignments, frequency hopping/spread spectrum bandwidths, modem types, antenna gain, beamwidth and sidelobe characteristics, transmitter power or EIRP, receiver noise temperature or gain/temperature, and rain environment. The message parameters are message type and length, addressees, times of transmission, and acknowledge or answer-back requirements. Threat parameters for nuclear attacks include weapon location, type and yield, and time of detonation. ECM threats involve jammer location, type, target, antenna characteristics, power or EIRP, and times of transmission. This is a long list of input data but it is all required for a meaningful analysis and is almost always available.

The link (equipment) performance data base describes the performance of the equipment used in each link in the presence of propagation disturbances. It consists of a table of important equipment performance parameters at various levels of disturbance from a benign environment to a level of disturbance sufficient to cause total link failure. The parameters used are: E_b/N_o (bit energy to noise density ratio), S_4 (scintillation index), τ_o (decorrelation time), and f_s (frequency selective bandwidth).

Link performance data bases are constructed by extensive computer simulation of the performance of each modem type in the presence of various levels of high-altitude nuclear-induced propagation disturbances, and then validation of these results with existing equipment or prototypes where possible. Jamming degradation is handled by introducing an additional noise level proportional to the effectiveness of each jammer type against the particular modem type used in each satellite link.

To date, four link performance bases have been constructed for the FSK and PSK satellite modems of most interest to DoD programs, and others are in preparation. The available data bases are all for frequency-hopped systems with convolutional coding. The frequency selective bandwidth characteristic has not yet been included in all data bases but is included in those most susceptible to this mode of degradation. Users desiring to employ PNAC should contact the AFWL project officer or the contractor code custodian, Computer Sciences Corporation, Albuquerque Operations, to determine which data bases are available and appropriate for the user's need.

A major problem in the simulation of RF propagation through nuclear-disturbed regions has been an accurate description of the striated, high-altitude environment over the time periods of hours which are of interest to communications analysts. This problem has been solved by the environment description used in PNAC, called SCENARIO, which was developed under AFWL direction by Mission Research Corporation of Santa Barbara, California. SCENARIO provides a striation phenomenology for multiburst scenarios covering CONUS-sized areas extending to altitudes greater than 10,000 km and lasting for time scales of hours. SCENARIO provides these environment descriptions efficiently, relatively inexpensively, and in a format directly usable in evaluations of satellite network performance.

The major components of SCENARIO are: fireball, neutral, and plasma grids, and the striation model. The parameters used in calculating propagation effects are: electron density, neutral mass density, plasma velocity, ion temperature, electron density fluctuation variance, magnetic field components, and the inner and outer scale size.

These parameters are derived from much previous research and experimentation in nuclear weapons effects and only require the input of nuclear weapon type, yield, and detonation location (including altitude) for their determination. The late-time grids are 32 x 32 x 11 cells in size and all eight values in each cell are computed at intervals ranging from 1 or 2 minutes to 15 minutes or more. If the values of these quantities are needed at other times (the usual case) or at other spatial locations (also the usual case), linear temporal and spatial interpolations are performed. Thus, the environment can be obtained for any point, or along any line, through the disturbed region.

The PNAC consists of a preprocessor, link performance calculator, network assessment module, and a postprocessor. There are six major subprograms. Major inputs are obtained from the link performance data base, propagation environment data base, and analysis scenario, and the preprocessor constructs a routing table and lists the node and link parameters.

The propagation environment is created off-line by the SCENARIO program from nuclear weapon data and detonation times supplied by the analysis scenario. The overall simulation is time-stepped and event-driven by events (mainly message transmissions) supplied by the analysis scenario. The performance of each RF link is calculated as needed by the link calculator using data obtained by space and time interpolation among the data points supplied by link performance and propagation data bases in conjunction with a line integral routine. The link performance data are then supplied to the network assessment module where overall performance measures such as message error rate, probability of acceptable message receipt, and time of receipt are calculated.

A fairly complex message processing algorithm of the minimum-path type which was adapted from the STRAT COMMAND code developed by System Technology Corporation is used in the network assessment module. An explanation of its operation will not be attempted in this short description.

A broad range of link, message, and network outputs are available from PNAC. The outputs of most interest will usually include some of the input data, such as node locations, input message list, times of nuclear events, and so forth. For some analyses, only the message receipt time at each destination or the probability of its successful receipt is needed.

In such cases much of the data accumulated during PNAC processing can be suppressed, reducing the output which must be examined by an analyst. In other analyses, the cause of high error rates or nonreceipt of messages are of primary interest, so more PNAC statistics are desired. These quantities, such as E_b/N_o , S_4 , τ_o , electron density, queue length, path followed, repetitions required for delivery, and other data of this type can be printed out for each message on each link to each addressee. Formats for quantities likely to be of use have been prepared. Any quantity or parameter accumulated in the PNAC dynamic mass storage system for any time during the simulation can be retrieved and printed in a format tailored to the user's requirements if an existing format is not suitable.

There are a variety of plots, both line and contour, available for displaying graphically the output from PNAC.

The PNAC is also applicable to communication networks other than strategic C³ networks. It can calculate message transmission statistics for a great variety of networks under stressed conditions, provided that the node, link, and message model accurately depict the particular features of the communications systems in the network. Networks and scenarios whose parameters change during the run cannot be handled.

PNAC imposes no particular orbit limitations on satellite systems to be analyzed. Geostationary and nongeostationary orbits are accepted. A wide variety of orbital data sets are accepted, including classical element sets, orbit injection conditions, two-card NORAD SPADATS element sets, inertial cartesian position and velocity, geographical spherical position and velocity, and two-position vectors with times. The propagation equations employed in PNAC are perfectly general and apply to all frequencies, however, the frequencies most used in satellite analyses to date have been 200 MHz and higher. Antenna patterns can be specified by the user in the detail desired up to 100 points in any single plane.

The propagation model used in PNAC was specially developed to account for amplitude and phase scintillation, absorption, refraction, and frequency-selective effects when RF energy traverses the upper atmosphere, ionosphere, and higher altitudes that have been affected by the detonation of nuclear weapons. Rain, water vapor, and oxygen attenuation are treated in PNAC as described in Recommendations and Reports of the CCIR, 1978, Kyoto, Volume V, Reports 719, 721, and 564-1.

A number of changes and improvements to PNAC are planned and some are being implemented. Among these are:

1. Addition of a model to calculate the effects of nuclear-caused dust;
2. Addition of a model to calculate the effects of low-altitude nuclear detonations;

3. Validation of the propagation model at near-optical and optical frequencies;
4. Addition of a model to calculate navigation errors resulting from disturbed propagation on the GPS system;
5. Addition of a number of equipment performance data bases for satellite links of interest to the DoD;
6. Refinement of computational routines to facilitate the calculation of certain radar parameters.

Software Considerations

PNAC is written in FORTRAN-77, with operational versions in FORTRAN-IV. The six combined subprograms include about 40,000 lines of code. PNAC is operational on the VAX 11/70 and PRIME-750. It is self-contained for operation. If graphics are required a special subprogram must be added. Executable subroutines require a total of about 2700 PRIME storage blocks. Scenario data dumps produce about 170,000 binary words or 34,000 coded form card images.

The SCENARIO portion of the program is performed approximately in real time, using the VAX, after the early fireball portion of the calculation is concluded. The network simulator takes about four CPU hours (VAX) for 30 nodes, 24 messages plus answers, directed broadcast or broadcast. There are no physical limitations on problem size, but all problems examined to date have been encompassed by 60 nodes (including satellites), 300 links, and 50 messages.

References for Sec. B.6.c

1. Nichols, W. G., G. D. Cable, and J. F. Ehrhart, *Propagation Network, Analysis Code (PNAC) User's Manual*, Computer Sciences Corporation, AFWL-TR-81-7, CSC-4489-C-004 (Rev.), 1 November 1980.
2. Nichols, W. G., G. D. Cable, and D. L. Kellum, *Propagation Environment Data Bases for Use with the Propagation Network Assessment Code*, Computer Sciences Corporation, CSC-4489-C-007, 6 April 1981.
3. Nichols, W. G., et al., *Satellite Communications System Performance Assessment, Final Report*, Computer Sciences Corporation, CSC-4489-C-009, 19 June 1982.

Reference 1 provides information for the use of PNAC. Reference 2 describes the data bases required to perform a calculation, and Ref. 3 gives the results of a particular application.

For additional technical information on PNAC please contact Wesley G. Nichols, Computer Sciences Corporation, Systems Division, 1400 San Mateo Boulevard SE, Albuquerque, NM 87108. For programs and services please contact Lieutenant Eddie Preston, Air Force Weapons Laboratory, NTYC, Kirtland Air Force Base, NM 87117.

B.7 MULTIPURPOSE TREATMENTS

The analytical procedures and computer programs that have been presented in the preceding sections have mostly been quite specific. An intrasystem program involving wire bundles cannot be used to treat a communications link from a satellite to the ground. In this section, we present a program (B.7.a) that can be used to analyze intrasystem, cosite, and intersystem interference, and programs developed at ECAC (B.7.b) that contain among them treatments of all the indicated interference types.

B.7.a ELECTROMAGNETIC COMPATIBILITY FREQUENCY ANALYSIS (EMCFA)¹⁷

Introduction

The electromagnetic compatibility frequency analysis (EMCFA) computer program analyzes possible interference between transmitters and receivers. It differs substantially from the other programs described in this report in that it includes nonlinear mixing actions. The program was developed by Martin Marietta Aerospace Denver, Johnson and Marshall Space Centers, and IBM Huntsville. The original program was developed for the Apollo project in 1967. It was completely rewritten and improved by Martin Marietta for Viking in 1972, and has been expanded and updated continually since then. It is maintained by R. O. Lewis, Martin Marietta Corporation Aerospace Division, Denver, who also provides program services. The program has been used by the Johnson Space Flight Center for all shuttle flights to determine compatibility

¹⁷Original material was supplied by R. O. Lewis and G. S. Pettit, Martin Marietta Aerospace, Denver Division.

between payload transmitters and receivers and orbiter transmitters and receivers; by Jet Propulsion Laboratory for spacecraft compatibility; and by Martin Marietta Corporation for commercial spacecraft, launch vehicle, and launch vehicle payload RF compatibility analysis.

This program provides the designer with a tool to predict direct and intermodulation product interference to system receivers from transmitters in the environment, and to determine corrective action to minimize or eliminate these interferences. The program's purpose is to analyze the many intermodulation product combinations possible with multiple transmitters and to determine which of these are nonproblems. The program performs a worst-case analysis so those combinations that do not appear in the output are not problems. The combinations that do appear in the output may or may not be problems. They indicate situations that should be analyzed in more detail. The program provides a great deal of information to assist in this evaluation, but it does not provide an absolute criterion since in fact it provides a worst-case analysis. The interferers may be located anywhere, from the immediate vicinity of the receiver to distant sites. Interferences are computed at receiver antennas and as a result of receiver mixer action. Since nonlinear elements are present in the receiver inputs, the frequencies of the interfering signals may be vastly different from the frequency of the desired signal.

The nonlinear element, which may represent a corroded joint or a tunneling effect in a metal, is characterized by a nonlinear diode equation which involves several exponentials relating input voltage and output current. The equation represents a circuit formed by a dipole antenna connected to a series resistor, which is then in series with a circuit of oppositely directed parallel diodes. The radiation resistance of the dipole is proportional to the square of the frequency for frequencies below 9 GHz, and is constant at 73 ohms for higher frequencies. The combination of exponentials is expanded in a Taylor series, so the output current is an Nth-order polynomial in the input voltage. (N can be anything from 1 to 9 and is the order of the intermodulation product. $N = 1$ is direct interference and $N = 9$ is 9th order. The order is the sum of the harmonic numbers of the contributors that form the interference.) Although there may be a very large number

of transmitters and receivers present, it is assumed that no more than N or an assigned input value are active at any one time. Hence, the output of the nonlinear devices can contain mixtures of the fundamentals from each of the N interferers, and the details are obviously very complicated. Experience has shown that an N value of 5 is adequate in most cases and 7 in practically all cases.

All defined combinations of transmitter frequencies are calculated and compared with the receiver passband. The RF energy from each transmitter selected for operation with the subject receiver is calculated at the location of the nonlinear element, which is normally the first structure that can be seen as one looks in the boresight direction from each of the receiving antennas. The mixing of the various signals then occurs in the elements. The resultant signal is radiated back to the receiving antenna, if it is in the frequency range of the receiving system. Near field equations, off axis gain, and off frequency gain are used in the calculations. A rectangular modulation spectrum is currently assumed, with a constant peak amplitude and a width equal to twice the deviation. This transmitter spectrum model will be revised in a future update of the program to reflect various transmitter modulation types more accurately.

Interference also occurs in the mixer of each receiver, and can involve harmonics of the local oscillator frequency. All defined combinations of transmitter frequencies are determined and mixed with all defined harmonics of the receiver local oscillator, and the results are compared with the passband of the first intermediate frequency amplifier. If this comparison is successful, the amplitude is calculated by first determining the isolation between the input port of each transmit antenna and the receiver antenna, then calculating the voltage in the mixer incorporating the attenuation of the receiver preselector at each transmit frequency. Finally, each transmitter signal and the receiver local oscillator is mixed and the amplitude into the first intermediate frequency amplifier is compared with the receiver sensitivity.

The program output provides a record of the input data, the isolation between antennas, and tables and graphs of the predicted interferences. These outputs show the designer which areas require more

rigorous attention to prevent incompatibilities between transmitters and receivers in a system.

Code Description and Capabilities

This program involves a very detailed analysis of the intermodulation characteristics of the systems. Consequently, it requires more information about the equipments than do the other programs described in this report. The program has three levels of analysis. It will automatically run at the level possible with the detail of the input data. The three levels are (1) an intermodulation product (IMP) frequency analysis, (2) an IMP frequency analysis and amplitude calculation using nonlinear elements as the coupling path, and (3) the level 2 analysis and an IMP analysis in all receiver mixers. The input requirements described below represent what is required for level 3. In general, leaving out the data required for lower level analyses will cause the program to run at the lower level or, if only minor omissions are made, to make assumptions for missing data, and then run at the higher level. The number of receivers, transmitters, and antennas are required. For each receiver, one needs the name and number, center frequency, 3 dB, 60 dB, and automatic tracking bandwidth, and maximum sensitivity. The number and identification of the transmitters involved in the mixing process, the number acting simultaneously (N or fewer), the number of antennas connected to the receiver, and the cable loss between the receiver input port and the output terminal of each antenna are required. In the mixing action, the constants representing the diodes (default values are supplied) and the number of terms retained in the power series are needed inputs. The receiver preselector is to be selected as one of eight types (Bessel, Butterworth, Chebyshev, Gaussian, Legendre, M-Derived, Synchronously Tuned, and Transitional). The preselector filter's number of poles, its maximum attenuation and/or its 3 dB and 60 dB bandwidths are required. The RF gain to the first mixer, the first local oscillator frequency, and the amplitude into the first mixer are needed. For the first and second intermediate frequency amplifiers the 3 dB bandwidth and 60 dB bandwidth may be input if desired (default values are supplied). If the unit is a transponder, the attenuation between the receiver and transmitter is needed.

For each transmitter one requires a name, identification number, and modulation type (continuous wave, pulse, phase, frequency, or amplitude modulation). The transmitter center frequency, output spectrum (frequency deviation) and typical modulation frequency for cw modulated transmitters; pulse width, rise and fall time, and pulse repetition frequency for pulsed transmitters; and the output power are to be specified, plus the number of antennas and the corresponding cable loss associated with each transmitter.

The intersystem codes specify antenna locations geographically (latitude and longitude). This code specifies them physically. For each antenna system, one needs the name and number of each antenna and the number of antennas in the system. The standard application of the code is to RF interference on a vehicle (the space shuttle is an example), so the position of each antenna associated with the vehicle is specified as a height above a reference, a distance out from an axis, and an angle about that axis (cylindrical coordinates), with corresponding data for the location of the nonlinear elements in receiving antennas. The antenna pointing direction (elevation and azimuth) and on-axis gain are required. Optional inputs are efficiency, circumscribing diameter, sidelobe and backlobe ratio to on-axis gain, and polarization (type and orientation). Finally, the source region of each antenna and the attenuation between RF independent regions may be specified, if desired.

The program begins by listing the inputs. As discussed, the number of receivers and transmitters may be very large. An example worked out at Martin-Marietta, which we will describe but not list, involved the RF compatibility of the space shuttle while located on Pad 39A at the Kennedy Space Center. This example is a 5th order IMP analysis. There are 17 receivers and 27 transmitters associated with the shuttle and its environment when so located, 21 of the transmitters being on or near the vehicle, the other 6 remotely located (5.5 to 25.6 st mi away). Twelve of the transmitters are pulsed, three are AM communications, five are FM, and seven are PM. Any receiver will be exposed to 15 to 20 transmitters, any five on simultaneously, with the sum of the harmonics of the transmitters (totaling order 5 or less) being retained in the

mixing calculations. Note that the program will handle up to 30 receivers, 50 transmitters, and 50 receivers.

The program first selects a particular receiver antenna. The gain of each transmitter in the direction of the nonlinear element associated with that receiver is calculated, and then the peak power incident on that element from that transmitter. Next, the isolation between that transmitter and the receiver is determined. The frequencies of the Nth order intermodulation products are found for all combinations of transmitter frequencies and their harmonics, plus any local oscillator frequencies or their harmonics which may be radiated or mixed, plus any harmonics of the local oscillator of the specified receiver. There may be as many as about 10^6 frequencies to be calculated per receiver. Each intermodulation frequency is compared with both the receiver RF passband and/or the IF passband. If any frequency lies in the indicated passband, the amplitude of the corresponding waveform is calculated and compared with the receiver sensitivity at the appropriate level. The program is then cycled over all receivers.

The program output is both tabular and graphical. Those signals whose frequencies and amplitudes meet the conditions are listed, accompanied by an identification of which harmonics of which transmitters and/or local oscillators produced the signals. A sample of the output is given in Tables 15 and 16 and Fig. 15. Receiver No. 10, of the indicated ensemble of 17 receivers, has a center frequency of 2041.9 MHz, a local oscillator frequency of 1810.9561 MHz, a first IF center frequency of 230.992 MHz, 3 dB and 60 dB bandwidths of 24 and 84

Table 15

TRANSMITTER CHARACTERISTICS

No.	Type	Center Frequency (MHz)	Deviation (MHz)	Power (W)
6	PU	1093.0	0.8	1,000
19	PM	2060.3645	0.3	8.5
20	PU	5690.0	2.0	2,800,000 (range 13.3 mi)
22	PM	2041.95	1.8	2,000 (range 9.2 mi)

Table 16
INTERFERENCE PRODUCTS IN IF BANDWIDTH

Identi- fication Number	Center Frequency (MHz)	+ or - Deviation (MHz)	Amplitude (dBm)	Combination of Transmitter Frequency (by No.) and Local Oscillator Frequency Used to Form Interference
1	249.41	0.3	-77.0	F(19) - LO(10)
2	230.99	1.8	-59.7	F(22) - LO(10)
3	212.58	3.9	-66.0	-F(19) + 2F(22) - LO(10)
4	204.85	5.6	-85.8	-F(20) + 2F(22) + LO(10)
5	223.27	4.1	-97.1	F(19) - F(20) + F(22) + LO(10)

MHz, and a minimum sensitivity of -115.0 dBm. It receives interference from 15 transmitters. Suppose the transmitters numbered 6, 19, 20, and 22 are operating simultaneously. Their relevant characteristics are given in Table 15. Transmitter 20 is the Kennedy Space Center AN/FPQ-14, the others are all on or close to the vehicle. These transmitters produce at least five significant intermodulation products (there may be more), in the IF bandwidth of Receiver No. 10. Transmitter No. 6 did not contribute to any of these. The characteristics of these potentially interfering signals are listed in Table 16 and depicted graphically in Fig. 15.

The IF passband sensitivity and the several signals are graphed in Fig. 15. The sensitivity, minimum at -115 dBm at 231 MHz, reduces to 56 dBm at 188 and 273 MHz. This sensitivity, shown as curve R of Fig. 15, rises along the skirts, since a stronger signal is required to produce the same output. Each signal is represented by a constant amplitude from the center frequency minus the deviation to the center frequency plus the deviation.

It may be seen from Fig. 15 that all five signals exceed the sensitivity curve, and hence can produce interference. These potential interferences are all with respect to the receiver sensitivity, and hence represent a carrier/noise ratio. They should be compared with the desired signal amplitude in Receiver No. 10 to determine the

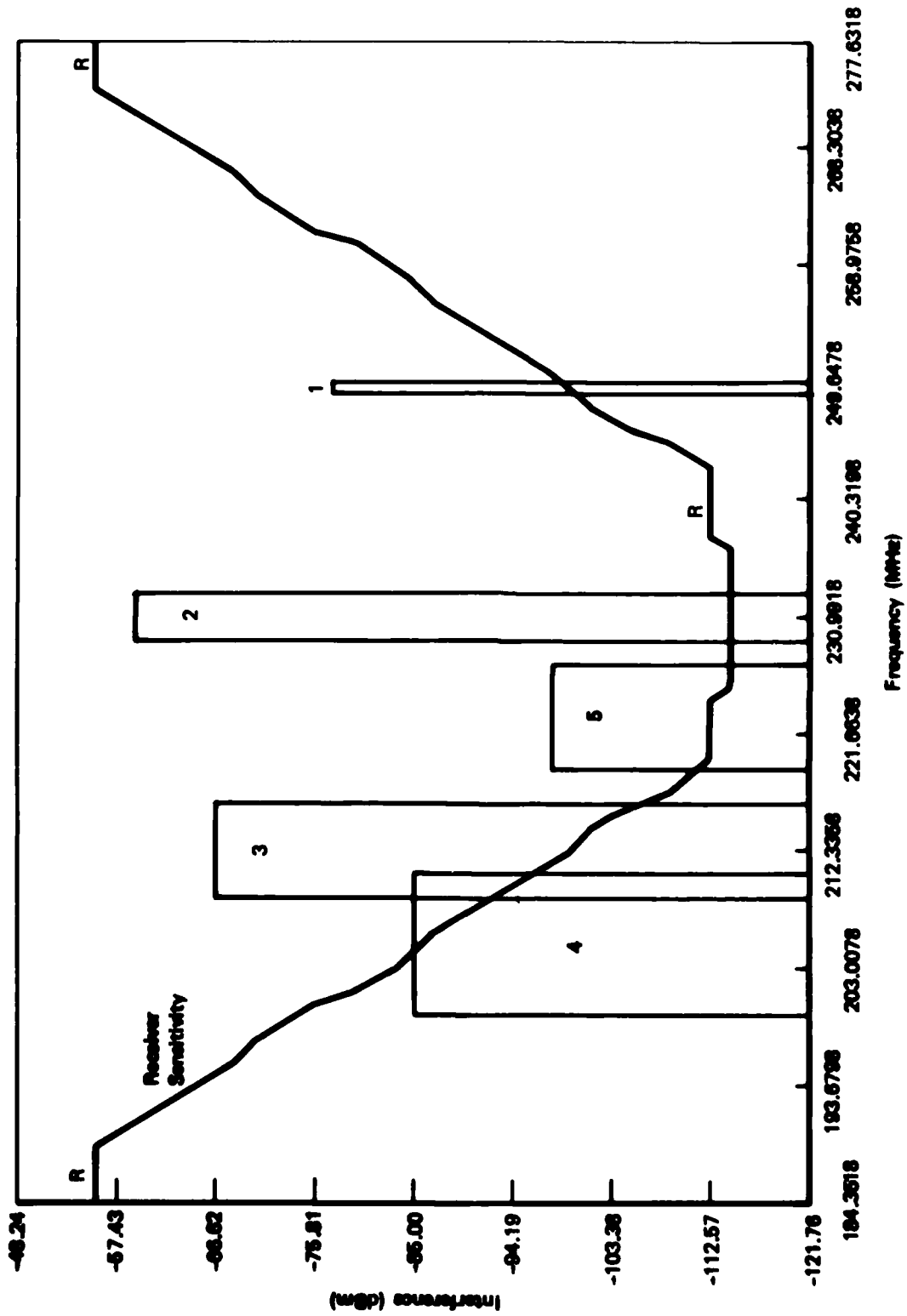


Fig. 15 - Sample output

signal/interference ratio. This information can be determined from the antenna-to-antenna coupling table produced by the program. Normally, interference is not allowed above the receiver threshold.

Besides the specific data on interferences, the program tabulates the number of times each transmitter is involved in an interference, both on a frequency and an amplitude basis. For the example, this would be a 17 x 27 matrix, with two items per entry. The total number of interferences produced by each transmitter, or experienced by each receiver, is also presented. These totals may run into many thousands. For the example, the grand total of interferences on a frequency basis was 33,168, on an amplitude basis 521. The total number of combinations of transmitter frequencies which were investigated but did not result in an interference was 15,778,979, showing the very large scale of the problem.

This output has been discussed at considerably greater length than the corresponding data for other programs considered in this report, because it is so very different.

The program has no orbit limitations, although in the example the interferers were at fixed locations on the ground. An orbital calculation would require specification of the location of the interfering antenna for geostationary satellites, or an ephemeris calculator for nongeostationary satellites. Any frequency range may be employed. Antenna patterns are calculated from the input data, and may be adjusted for near-field, off-axis, and off-frequency operation. Free-space propagation is used at present, but surface-wave calculations, which affect the isolation between nearby antennas on the same vehicle, will be added at a later date. There are no special algorithms. Since this program will analyze any configuration, it can treat cosite, intrasystem, and intersystem compatibility.

Software Considerations

The program is written in ANSI Standard FORTRAN-77. It contains approximately 4350 lines of code, and is installed on the CDC-6600 and the DEC VAX 11/780. It is expected that in the future it will be installed on the IBM 370 and a large memory microcomputer. The ANSI Standard FORTRAN Library is required as support software, and operation

the VAX 11/780 requires a memory of 366K bytes. Execution time on the VAX 11/780 averages 25 minutes for a problem of the scope given here. The program is limited to 50 transmitters, 50 antennas, and 30 receivers, but can be easily increased if computer memory size permits.

Documentation and References

No documentation has been released. For further information on this program, please contact R. O. Lewis, Martin Marietta Corporation, Aerospace Division, P.O. Box 179, Mail Stop S-8013, Denver, CO 80201.

B.7.b ANALYSIS CAPABILITIES AT ECAC

The DoD Electromagnetic Compatibility Research Center (ECAC) was established in Annapolis, MD in 1961 to analyze the electromagnetic compatibility (EMC) aspects of developing communications-electronics systems and to build a data base for support of analysis efforts. The data base has been described in Section III.A.2 of this report. The analysis capabilities will be discussed here.

The EMC analysis tools developed by ECAC can be applied to a large variety of EMC problems. In recent years, the number of electronic systems has grown exponentially. The usable portion of the frequency spectrum has become overcrowded, and the potential for interference among systems has increased dramatically. In these circumstances, it is necessary to ensure that newly developed systems are compatible with their intended operational environments. The EMC process involves careful consideration of frequency allocation and management, design, procurement, production, site selection, installation, operation, modification, and maintenance. Analytical tools have been developed to treat subsystem models (antennas, receivers, and transmitters), propagation models, degradation analysis, environmental synthesis, cosite analysis, and satellite systems. The models and codes will be described briefly.

Subsystem Models

Antenna models have been developed to predict radiation from and reception by antennas at frequencies from a few Hertz through the submillimeter band. The capabilities encompass the near field, far

field, backlobes, sidelobes, and main beam, and cover frequencies both inside and outside the design band. Approximately 20 computer models are available to predict the performance of linear antennas, parabolic and nonparabolic reflectors, and phased arrays. These computer models include such types as thin-wire method of moments codes (see Section B.4.b) capable of predicting antenna performance at frequencies from a few kHz to hundreds of MHz, and a geometrical theory of diffraction code that predicts both near and far fields from all aspects of a focal-fed parabolic reflector. The antenna models are enhanced by adding preprocessor, postprocessor, and special graphics capabilities. The graphics can display such phenomena as the generally complicated input geometry of an antenna and any surrounding metallic objects. For those situations where no computer models are available, manual procedures have been established.

A large number of receiver EMI models have been developed to predict receiver performance degradation as a result of interfering signals. The complexity of the analysis may range from simple techniques involving comparison of predicted signal levels with established thresholds to analyses of interference effects on receiver synchronization systems. Many of the models are detailed manual techniques that supplement generalized automated models and cover both linear and nonlinear effects. Available analysis models facilitate linear processing calculations such as the gains and losses of various types of filters, frequency-dependent rejection as a function of detuning, synchronization acquisition times, and time and range gating. Receiver simulation methods have been developed to model time- and frequency-domain receiver processing by using time sampling, digital filtering, and fast-Fourier-transform techniques. These simulation techniques have been applied to the analysis of wideband, narrowband, analog, and digital receivers. Automated and manual techniques for investigation of nonlinear effects evaluate adjacent-signal interference, spurious responses, and intermodulation for narrowband communications equipments. Specialized models of receiver terminal devices (multiplexers and digital decoders), automatic gain control loops, spread-spectrum receivers, millimeter wave receivers, and electro-optic receivers have also been developed.

Transmitters are the major source of electromagnetic interference. EMI may be caused by either transmitter in-band emissions (the spectrum intentionally generated to create the desired signal) or out-of-band emissions (noise, spurious radiations, and intermodulation products). Manual and automated mathematical models are available for emission spectrum synthesis for radar and communications systems. Data concerning the out-of-band emissions are obtained from measurements and are less well known and less readily available than is in-band information. ECAC represents the total emission spectrum by synthesizing bounds on the in-band signal spectrum and adding empirical data on the transmitter noise level and spurious emissions, including harmonics. Out-of-band emissions from a powerful transmitter can seriously affect sensitive receivers in adjacent portions of the frequency spectrum. The information on the normal and out-of-band emission spectra is used as an input to the receiver and antenna models.

Propagation Models

Several general-use tropospheric, ionospheric, and special-purpose propagation models are available. The tropospheric models include smooth-earth and irregular terrain surfaces (10 kHz to 20 GHz). The smooth-earth models can predict basic transmission loss over a smooth, spherical, and imperfectly conducting earth. They consider ground wave, diffraction, and tropospheric scatter modes of propagation and treat the effects of refraction in an exponential atmosphere. The Terrain Integrated Rough Earth Model (TIREM) is an ECAC-developed point-to-point model that can predict path loss over specific terrain profiles (40 MHz to 20 GHz).

The ionospheric propagation model can predict path loss in the 10 to 100 kHz band where the undisturbed ionospheric D-region acts as a waveguide. Ground-wave and sky-wave modes are used. Other available models can predict HF propagation parameters on maximum usable frequency, lowest usable frequency, frequency of optimum traffic, signal-to-noise ratio, path reliability, and service probability.

Special-purpose propagation models can be used to calculate earth-space link performance, millimeter-wave and electro-optic propagation effects, rain scatter coupling between terrestrial and earth-space

microwave links, coupling between antennas on aircraft, tropospheric ducting, and foliage attenuation.

Degradation Analysis Models

The analysis capabilities discussed above provide the means for predicting the occurrence of interference and calculating the ratio of desired and interference power levels being processed by a victim receiver. Degradation models are employed to determine the impact of interference and power ratios on receiver or systems operations. Automated degradation models include time waveform simulation techniques for analyzing digital and analog receivers, and time-domain and frequency-domain characteristics. Manual degradation models provide a means to relate power ratios to degradation or bit-error probability for digital systems, scope condition number or pulse-per-scan for radar systems, articulation score or articulation index for voice systems, or probability that a predetermined degradation threshold will be exceeded over a given average.

Environmental Synthesis

EMC analysis generally concerns the determination of potential performance degradation effects produced when deploying one or more new systems into a previously established environment. Examples of EMC analysis include: identification of potential interference victims and sources, estimation of performance degradation, identification of interference-free operational frequencies, and determination of optimal equipment location to avoid interference.

ECAC has developed techniques for modeling electromagnetic environments as they currently exist, hypothetical environments as they would exist during tactical engagements, and combinations of the two. By extracting information from frequency assignment and location data files, an appropriate environment, including terrain, can be prepared to support an externally generated tactical scenario. The environment can be complex and dynamic, including rapidly rotating search radars, missile seekers, frequency hopping communications equipment, and similar time-dependent phenomena, and may require a combination of correlated computer simulation techniques and limited military exercises. The

analysis models use appropriate subsystem investigations to determine the parameters for evaluating interference potential, and then translate these parameters into estimates of performance degradation.

Cosite Analysis

This group of analyses and computer programs has been discussed in Section B.3. Phenomena considered include a variety of nonlinear interactions, such as receiver or transmitter intermodulation, spurious emissions and responses, receiver desensitization, saturation, and cross-modulation. High power effects and cable and antenna couplings are also treated. Procedures are both manual and automated.

Satellite Systems Analysis

Analysis capabilities are maintained for satellites, earth stations, and space-to-earth propagation. Automated space-system analyses are available for calculating subsatellite points on the earth's surface, predicting RF and optical propagation losses over the earth/space path, and predicting when satellites are in the field of view from an earth station. Automated coordination procedures (see Section B.2) have been developed to perform the detailed area interference analysis necessary to site a mobile or transportable earth terminal.

The space-system analysis capabilities have been applied primarily to the interaction of space/earth RF links with other systems in the operating environment. Examples include extensive analysis of the coexistence of sensitive DoD satellite communications terminals with other electronic equipment on board the same terrestrial platform, and potential interference between a proposed international AEROSAT system and other in-band users such as MARISAT and VHF air traffic control systems.

Reference for Sec. B.7.b

Guide to Capabilities and Services, Department of Defense
Electromagnetic Compatibility Analysis Center (ECAC), Annapolis,
August 1982.

IV. ANALYSIS FOR SPADOC AND WARC

Several projects with support from ECAC were initiated to cover the objectives of the overall project. The space environment data base and the analysis codes and computer programs were considered essential components for predicting and analyzing intentional and unintentional interference on space systems being monitored by the Space Defense Operations Center (SPADOC), and to assist the Air Force in preparation for space services World Administrative Radio Conference (WARC).

A. INTENTIONAL/UNINTENTIONAL EMI ANALYSIS FOR SPADOC

During the formulation phase of the project we were asked, as one of the principal objectives, to design a capability for identifying and analyzing intentional and unintentional EMI for space systems. If EMI were to occur in practice, the investigation should provide identification of possible sources. The purpose of this capability was to support SPADOC. Since SPADOC is a fairly new DoD aerospace agency, we shall first briefly describe its history and mission.

SPADOC Mission and History¹

Space defense mission policy and authority are contained in directives developed at national, Department of Defense (DoD), Joint Chiefs of Staff (JCS), and Air Force levels.[1] These directives are:

National Security Decision
Directive 42;
National Security Defense
Memorandum 333

DoD Space Policy, 22 Jun 82;
Directive 5160.32, 8 Sep 70:
Assistant Secretary of Defense for
Command, Control, Communications
and Intelligence (C³I) Letter;
Various Policy Letters

¹The material on the SPADOC Mission and History was provided by the Air Force Space Division (YNCC), Space Defense Program Office, Surveillance Command and Control Directorate, Command and Control Division, Los Angeles Air Force Station, P.O. Box 92960, Los Angeles, CA 90009.

JCS, Unified Command Plan; Joint
Strategic Capabilities Plan

AF, AFM 1-1 and 1-6, AFR 23-9;
Space Defense Systems Program
(SDSP) Program Management
Directive (PMD)

The Joint Chiefs of Staff have tasked the Commander in Chief, Air Defense (CINCAD) with the warning and verification of hostile space events, protection of U.S. space assets, and negation of enemy space assets under crisis conditions or during hostile events. To accomplish these space tasks CINCAD will, through SPADOC, combine emerging space defense activities and forces under a single operational authority and an integrated C³ center. SPADOC will make tactical assessments, using all source information, of a potential threat against U.S. space assets so that information can be provided to the National Command Authorities, National Military Command System, Unified and Specified Commands, space system owners and operators, and other space defense decisionmakers.

SPADOC is a component of the Space Defense Command and Control System (SPADCCS). SPADCCS is the command, control, and communications element of the Space Defense Systems Program (SDSP) that will integrate the facilities, hardware, software, communications, procedures, and personnel required to conduct space defense operations. Specifically, SPADCCS will consist of the centralized command and control facility (SPADOC), those centers within the NORAD Cheyenne Mountain Complex (NMC) that direct or support SPADOC, the command and control centers outside the NMC that are either in their entirety elements of SPADCCS or contain SPADCCS functional areas (National Military Command Systems (NMCS), Unified and Specified Commands, Joint Electronic Warfare Center (JEWEC), Electromagnetic Compatibility Analyses Center (ECAC), Consolidated Space Operations Center (CSOC), Air-Launched Anti-Satellite (ALASAT) Mission Control Center, the NORAD/ADCOM Test Development and Training Center, directed energy facilities, space system operations center, and the communications links integrating these and other space-related systems and centers).

The main objective of SPADCCS and its associated SPADOC is to provide the National Command Authorities an efficient and responsive space defense command and control system for use during space crisis and conflict situations. To accomplish this broad objective, the SPADOC must be capable of meeting the following detailed objectives:

- a. Provide collection, reporting, storage, and retrieval for new and existing data that are required to support space threat detection and identification, situation evaluation, contingency planning, response selection and response execution.
- b. Provide an efficient, timely, and responsive operational system for monitoring, evaluating, verifying, and reporting routine, anomalous, and hostile space events.
- c. Provide a centralized operational system to work with DoD and interagency activity for rapidly planning, coordinating, evaluating, and recommending responses to anomalous and hostile space events directed at any segment of space systems.
- d. Provide a centralized, interactive, and responsive system to monitor, direct, and coordinate the overall execution of space defense options.
- e. Provide a fast and secure responsive system to evaluate, portray, and disseminate damage and attack information; to provide operations evaluation to update plans; to facilitate space system reconstitution and to support negotiation and termination of hostilities.
- f. Provide a centralized agency to achieve the best potential utilization of space defense assets.
- g. Provide a centralized capability to interface and coordinate DoD and interagency activity for training and exercising all aspects of space defense operations.

SPADOC's ability to support CINCAD's space defense mission requires interfacing with the NCA/NMCS, Unified and Specified Commands, space surveillance systems, space system owners and operators, NASA, shuttle control, space weapon systems, and other space-related agencies, such as

JEWC and ECAC. All reporting to outside agencies will be through the Command Post or with the approval of the CINC/Command Director. SPADOC will also interface with other operations centers within the NCMC.

SPADOC is being implemented in four phases to provide appropriate C³I capability at planned milestones to support space defense missions such as weapon and countermeasure testing and operations. The first three phases, begun October 1979, are developing an early capability by tying together non-NCMC and NCMC systems. The existing NCMC systems are being augmented by additional personnel and operational procedures and a limited change in Automatic Data Processing Equipment (ADPE), communications, and facility resources. Phase 4 will provide a total display capability that will be used by operations and command personnel to ensure a complete and accurate understanding of the current situation and its implications. The displays will also be used for a "quick look" assimilation of information to support critical decisions under stress conditions. Existing and new communication capabilities, both internal and external to the NCMC and SPADCCS elements, will be used to get the information and provide a flow of information to all users.

EMI Analysis

Rand and ECAC have been constructing a capability for identifying and analyzing intentional and unintentional EMI for space systems. Intentional interference (jamming) would be considered a hostile event, so the establishment of the capability to distinguish intentional EMI from unintentional is a critical requirement. The treatment is a complex process requiring a detailed data base of possible EM sources and computer-based analysis models. The ECAC has proposed a methodology to support SPADOC's requirements.

The satellite systems, both space and earth segments, scheduled for monitoring by SPADOC are listed in Table 17. Each system has multiple satellites, earth stations, sensors, radio frequency links, and/or electro-optical links. The data required for EMI analysis of these systems are not available in any one agency and must be compiled and continually updated from several sources. The short time interval available for identification of an incident report compounds the difficulty of the analysis process.

Table 17

U.S. AND ALLIED SPACE SYSTEMS MONITORED BY SPADOC

Military	Other U.S. Systems	Commercial	Allied
AFSATCOM	GSFC STDN/NOCC	COMSTAR	ANIK
AFTAC	NASA STS (JSC)	MARISAT	NATOSAT
DMSP	NESS/SOCC	RCA DCSS	
DSCS		SBS	
DSP		WESTAR	
ESC			
FLTSATCOM			
GPS			
HQ SAC/CP			
SD/AFSCF			
SD/DO			
SDS			
TRANSIT			
VELA			

The required technical and operational data items have been included in the design of the Space Systems Data Base (Appendix A) and the other EM emissions that may cause interference are in supplemental data bases maintained by ECAC. Interference and jamming sources can be identified by applying the proposed ECAC methodology.

Information on space system operational conditions monitored by SPADOC will also be needed on a continual updated basis. Information should include health and status information on RF transmission and reception links of TT&C, transponders, satellite payloads, associated earth terminals, operational control centers, and relay network interconnect systems. SPADOC is establishing Memorandum of Agreements (MOA) and Interface Control Drawings (ICD) with the user/operators of satellite systems to provide this information, which in turn should be made available for the data base maintained at ECAC. Three levels of operational status information are maintained by SPADOC for space systems: fully operable (green), partially degraded (yellow), and inoperable (red).

The analysis codes and computer programs compiled in this report and those proposed by ECAC will make it possible to identify and analyze intentional and unintentional interference. The ECAC methodology requires the development of new software to perform this function. The Electromagnetic Vulnerability Analysis Codes described in this report (Section III.B.6) will allow analysis of the susceptibility to and impact of jamming of satellite systems.

In addition, an extensive preliminary analysis process, designed and proposed by ECAC, of each system would be required to minimize the real-time analysis following an incident report. The preliminary (pre-incident) analysis would consist of three steps: space system susceptibility analysis, identification of equipment types, and identification of equipment locations/platforms. Each step would require the assembly of data from various sources, automated or manual analysis of the data, and organization of the results for use in the next step. Each step would be documented for later use, and interim outputs would be made available as backup information in case of real-time computer failure. The real-time (post-incident) analysis would consist of automated short comparisons and selects from small data bases, resulting in prioritized lists that could then be used by SPADOC as concise technical inputs to the decision concerning the issuance of an alert message.

Continual technical coordination with ADCOM has been conducted during the research phase of the project and the design of the Space Systems Data Base and the Analysis Codes and Computer Programs. Negotiations are in progress among ADCOM, JEWG, and ECAC for developing a continuing analysis capability in this critical area. A feasibility study to provide analysis support to SPADOC has been prepared by ECAC.[2] The Space Systems Data Base and the other data bases and analysis programs maintained by ECAC would be made available to the analysis support project.

B. SUPPORTING PREPARATIONS FOR SPACE SERVICES WARC

The International Telecommunication Union (ITU) is a special agency of the United Nations (see Section II). The purpose of the ITU is to facilitate improved efficiency and understanding in worldwide use of telecommunications. Administrative conferences are convened by the ITU to consider specific telecommunication matters. The International Radio Regulations stem from decisions of World Administrative Radio Conferences (WARC).

The results of the 1979 WARC included adopting Resolution No. 3 on the use of the geostationary satellite orbit and on the planning of space services utilizing it. The ITU Administrative Council has scheduled future conferences for 1985 and 1988 for Space Services WARC to address Resolution No. 3. Preparations for the U.S. position for the 1985 WARC will be led by the Department of State, supported by NTIA, FCC, DoD, and NASA. The Office of the Secretary of Defense will provide the DoD interface with the State Department. The military departments will prepare their requirements as part of the overall U.S. position.

The USAF Space Division will have responsibility for preparing the Air Force requirements. The space environment data base being developed by ECAC and the analysis programs developed in the Rand project on the geostationary orbit will be available to support this effort. A series of tasks were prepared by Air Force Space Division, Rand, Aerospace Corporation, and ECAC. A Project Plan for FY83, *1985 Space WARC Technical Support*, was submitted by ECAC, and has been funded by the Directorate of Advanced Space Communications. The Project Plan calls for ECAC efforts that will be based on the ECAC data base and analysis capabilities as well as ECAC experience in providing technical support to the military departments for past World Administrative Radio Conferences.

Preparatory tasks for the Space Services WARC are discussed below.

Identification of Air Force space services requirements for use of the geostationary satellite orbit and use of frequency bands allocated to the geostationary and global space services. ECAC will provide information concerning the spectral usage of DoD and allied space systems that use or plan to use the fixed-satellite frequency bands,

with emphasis on the 7/8 and 20/30/40 GHz ranges. The technical detail required in describing these systems is determined by the analysis requirements and by the data format requirements of the Space Division. As a minimum, data must be made available to describe satellite frequency bands, bandwidths, antenna patterns, EIRP values, geostationary longitudes, and associated earth station parameters and locations. The data will be assembled from ECAC space- and earth-station data and inputs from appropriate program offices.

Analysis of the ability of existing international radio regulations to satisfy Air Force space systems requirements for the geostationary orbit (Task 1). In addition to the identification of frequency bands allocated to the various space services, the entire body of international radio regulations will be reviewed by ECAC. Emphasis will be on technical constraints such as power limitations and the pointing accuracy of antennas, and definitions and coordination procedures for satellite systems including orbital replenishment and satellite station-keeping. The identification and interpretation of the international radio regulations will proceed concurrently with the compilation of Air Force requirements to permit the timely review of specific issues and the early formulation of specific Air Force proposals.

After compiling the international rules and regulations, the current and future Air Force space system requirements should be analyzed and compared to these regulations. If any Air Force requirements are not provided for, preliminary proposals for modifications will be prepared.

Monitoring the on-going WARC preparatory activities and analysis of technical issues affecting Air Force space systems. Preparation for the Space WARC will be a dynamic process characterized by the solidification of proposals and positions over several years. Activity will be conducted within CCIR Study Groups, the committees of the IRAC, and the FCC Advisory Committee on Space Services WARC. Proposals and ideas will be put forth on both government and civil telecommunications requirements. These proposals may conflict with Air Force requirements, so it is necessary to constantly monitor the proposals of other telecommunications interests to ensure that there will be no adverse impact on Air Force requirements. Also, technical proposals often

require detailed technical analysis to permit assessment. ECAC's approach to this requirement is to attend all relevant preparatory meetings to gather and analyze written proposals and obtain a sense of the Space WARC preparation.

Consultative support to and coordination with USAF Space Division concerning Space Services WARC issues. Based on expertise developed in conducting the tasks outlined above, ECAC envisions that presentations and documentation will be necessary to support USAF SD requirements within the Air Force. Attendance by ECAC will be required at the Air Force Space Working Group meetings to assist preparations and maintain a perspective of Air Force requirements.

REFERENCES FOR SEC. IV

1. National Security Decision Directive 42; National Security Defense Memorandum 333; DoD Space Policy, June 22, 1982; Directive 5160.32, September 8, 1970; Assistant Secretary of Defense for Command, Control, Communications, and Intelligence letter; various policy letters; JCS Unified Command Plan; Joint Strategic Capabilities Plan; Air Force Manuals AFM 1-1 and 1-6; Air Force Regulation AFR 23-9; and Space Defense Systems Program (SDSP) Program Management Directive (PMD).
2. Preis, J., *Feasibility Study Regarding the Assessment of EM Effects on Space Systems*, Project Plan FY83/84 (Draft), P.O. Box 499, DoD/ECAC, IIT Research Institute, Annapolis, MD, September 13, 1982.

V. CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Increased space traffic and debris, spectral demands, and requirements for orbital slots and position control indicate possible problems of orbital and spectral congestion in space systems at present and in the foreseeable future. The very large geographic areas visible to satellites imply potential electromagnetic signal interference, which will require analysis and control. We have drawn the following conclusions from the studies of this report:

1. The extensive data base on space and earth electromagnetic environments being established at ECAC, Annapolis, and the computer-based analysis programs documented in this report, provide the required capability for analysis and control.
2. The process provides the ability to analyze potential electromagnetic interference produced by orbital repositioning of satellites to avoid collisions with debris or other satellites.
3. The procedures, processes and analytical models reported in this project comply with the technical criteria, rules and regulations, and coordination requirements established by the national and international frequency management agencies.
4. Capabilities developed through this project could provide an essential national resource for management decisionmaking and architectural planning on space-related programs.

RECOMMENDATIONS

In the transition of this project to Air Force management and implementation, we recommend that:¹

¹These recommendations are being implemented; see the Preface.

1. An Air Force organization should be established as the Office of Primary Responsibility (OPR) to manage and maintain a continuing program for analysis of orbital and spectral congestion problems, providing access to and employing the data base and analysis techniques described in this report.
2. The Space Systems Program Offices of the Air Force Product Divisions, supported by the appropriate contractors, should be responsible for analysis of specific space systems. In the initial implementation phase, choice among particular analysis models and computer programs should be the responsibility of the analyst who is investigating a specific problem. As the process develops, preferences among models should emerge. Participation could be voluntary during the implementation phase.
3. The following Air Force documents should be revised to include references and instructions for the use of this project:
 - SDR 55-1, Satellite Position Management, 15 September 1983 (OPR: SD/YO).
 - AFR 55-XY, Spacecraft Orbital Position Management (Draft), 10 March 1982 (OPR: AF/XOSO).
 - AFR 100-31, Frequency Management and Electromagnetic Compatibility, 23 July 1980, and AFSC Supplement, Communications-Electronics, 22 June 1981 (OPR: AF/SITI).
 - MIL-STD-1541 (USAF), Military Standard Electromagnetic Compatibility Requirements for Space Systems, 15 October 1973, and Proposed MIL-STD-1541 (USAF) (Draft), 15 August 1982 (OPR: SD/ALTI).
 - AFR 80-23, Research and Development, the U.S. Air Force Electromagnetic Compatibility Program, 29 March 1982 (OPR: AF/RDPT) and Space Division (AFSC) Supplement 1, AFR 80-23 (Draft), 19 April 1983 (OPR: SD/ALTI).

4. The project capabilities should support identification and analysis of intentional and unintentional electromagnetic interference for the Space Defense Operations Center (SPADOC).
5. The data base and analysis capabilities should be used in preparation of Air Force requirements for the geostationary Space Services World Administrative Radio Conference (WARC), 1985.

Furthermore, we recommend that the analytical capabilities documented in this report be employed for management decisionmaking and architectural planning by all national space-related agencies.

PART 3

APPENDIXES

Appendix A¹

SPACE SYSTEMS DATA FORMAT

DESCRIPTION

A space system is defined as a group of cooperating space and earth stations. Space stations are satellites. Earth stations include fixed and mobile (including airborne and shipborne) terminals in all space-related service classes.

The space systems data base consists of system data (I), space segment data (II), and earth segment data (III). The *system* data are general and consist of such items as ownership, mission function, TT&C network (telemetry, tracking and command), and frequency bands used. The *space segment* data are composed of satellite-type records, technical descriptions, modulation descriptions, and satellite environmental information. Satellite types are groups of identical satellites within systems. Technical descriptions are given for each on-board equipment such as space transponders, receivers, antennas, etc. Modulation descriptions are given for transmitters and receivers. Satellite environmental information includes orbital descriptions and assignment information and is required for each satellite. Orbital descriptions for current objects in space are obtained from NORAD (North American Aerospace Defense Command) and are entered automatically into the data base. The *earth segment* data follow the same organizational pattern as the space segment. Information is collected for earth station types (nomenclatures), technical descriptions (for each equipment), modulation descriptions (for transmitters), and earth station environmental information.

The technical characteristics required to describe space systems were derived from:

¹The Space Systems Data listings in Appendix A incorporate items suggested by Rand [Ref. 2, Sec. I], invited additions submitted by attendees at the Conference on Space Systems Data Bases and Analysis Capabilities held at ECAC, November 17-19, 1981, and a major expansion contributed by ECAC [Ref. 1, Sec. III.A.1].

1. An investigation of ECAC interference analysis requirements, other than cosite analysis;
2. The requirements of non-ECAC-developed intersystem interference analysis models;
3. The requirements of international frequency coordination procedures; and
4. Data now maintained in J/F-12s, NCF records, and other automated files.

Administrative data are being collected to identify:

1. Space systems, satellites, and earth stations;
2. The country, consortium, agency, or organization developing, owning, controlling, and operating the system;
3. Security classification, releasability, and sources for each data element.

DATA FIELD DESCRIPTION

The fields which are included in the data base are described in the ECAC report.[Ref. 1, Sec. III.A] The field descriptions are not necessarily rigorous definitions, but are intended as guidance for data gathering. For technical fields, units are specified and guidance and/or definitions given. Nontechnical fields are discussed and clarified by examples.

Classification, Source, and Remarks

Each element in the data base can be individually classified and original source identified. The classification is either unclassified (U), confidential (C), or secret (S), and can be modified with releasability information as, for example, C-NoForeign or S-NATO only. The sources are itemized in the list of references and for each data element the source is identified by its itemization number.

ECAC will compile the data listed in the format from comparable technical items included in DoD Form 1494, "Application for Frequency Allocation," the USAF Standard Message Format (SMF), "Application for

Frequency Assignment," and FCC Form 130 series B, C, D, E being revised for use in IFRB notification for space systems (see Section II). Supplemental information, if required, will be requested from developing and operating agencies. This data format is intended for use in the EMC analysis process described in the report and is not proposed as a new or substitute format for the forms established by the frequency management agencies. The extensive detail indicated in the proposed format is required to cover the numerous inputs derived from the analyses and included in the computer programs.

This data collection format was designed to accommodate current and future systems. The format will accommodate space systems which operate in the normal radio frequency bands as well as electro-optical (EO) systems. Although the latter have not been discussed in the body of the report, it is expected that computer codes will be developed to evaluate interference for EO systems, and it is advantageous to provide a standard format for data entry.

The format published in Ref. 1, Sec. III.A.1, includes single columns per page, lines for data entry, and an extensive list of definitions and guidelines. The format has been compressed for publication in this Appendix, but it contains all the items listed in the ECAC report.

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I. SYSTEM

1. System Name

2. Alternative System Names

- a. IFRB
- b. Other

3. Responsible Country/Consortium

- a. Responsible Agency

4. Active and Future Satellite List

Satellite Name, Mission
Identifier, Object Number

5. TT&C Data

- a. Responsible Agency
- b. Uplink Frequency Bands
- c. Downlink Frequency Bands
- d. Sensor Wavelength Bands
- e. Network
- f. Ground Sites

6. Mission Data

- a. User Agency
- b. Satellite Type
Nomenclatures
- c. Earth Station Type
Nomenclatures
- d. Mission Function
 - 1) Service class
 - 2) Functional use
- e. Technical Information
 - 1) Implementation
 - 2) Uplink frequency bands
(or wavelengths)
 - 3) Downlink frequency
bands (or wavelengths)
 - 4) Sensor wavelengths
bands (or frequencies)
 - 5) Beacon frequencies
 - 6) Crosslink frequency
bands (or wavelengths)
- f. Geographic Area of Use

7. Description

II. SPACE SEGMENT

Satellite Type

1. Satellite Type Nomenclature (or Other Identifier)
2. Manufacturer
3. On Board Equipment Overview
4. On Board Equipment Nomenclature List
5. Associated J/F 12 Numbers
Equipment and J/F 12 Numbers
6. Research and Development Agency

Technical Description: Transmitter (Basic or Operating Mode Record)

1. Equipment Nomenclature
2. Manufacturer
3. Operating Mode(s)
4. Description
5. Frequency and Frequency Range
6. Modulation Type(s)
CCIR Emissions Designator(s),
Old and New
7. Transmitter Power or Power Density
8. Power Type
9. Harmonic Attenuation: 2nd, 3rd, Rest
10. Spurious Attenuation

11. RF Filter Type

- a. Center Frequency
- b. 3 dB Bandwidth and Number of Poles or Bandwidths and Relative Levels

12. Emissions Descriptions

- 3 dB Bandwidth and Roll-Off or Bandwidths and Relative Levels

13. Access Mode

14. Output Device

15. EIRP, Antenna

Technical Description: Receiver (Basic or Operating Mode Record)

1. Equipment Nomenclature
2. Manufacturer
3. Operating Mode(s)
4. Description
5. Frequency and Frequency Range(s)
6. Modulation Type(s)
DDIR Emissions Designator(s),
Old and New
7. RF Filter Type
 - a. Center Frequency
 - b. 3 dB Bandwidth and Number of Poles or Bandwidths and Relative Levels
8. RF Preamp Gain
9. Limiting Technique

10. Saturation Level or Third Order Intercept Point

11. For Each IF Stage:

- a. IF Stage Number
- b. IF Frequency
- c. LO Frequency
- d. LO Injection Level
- e. IF Filter Type
- f. 3 dB Bandwidth and Number of Poles or Bandwidths and Relative Levels

12. Spurious Rejection

13. Image Rejection

14. Required Signal-to-Noise Ratio or Required E_b/N_0 or Sensitivity and Criterion

15. Access Mode

16. Effective Receiver Noise Temperature or Noise Figure

17. G/T, Antenna Type

Technical Description: Space Transponder (Basic or Operating Mode Record)

1. Equipment Nomenclature

2. Manufacturer

3. Operating Mode(s)

4. G/T, Antenna Type

5. Uplink Center Frequency

6. Uplink Filter Type

- a. Uplink Filter Center Frequency
- b. 3 dB Bandwidth and Number of Poles or Bandwidths and Relative Levels

7. Limiting Technique

8. Saturation Level or Third Order Intercept Point

9. Usable Channel Bandwidth

10. Channel Filter Type

- a. Center Frequency
- b. 3 dB Bandwidth and Number of Poles or Bandwidth and Relative Levels
- c. LO Frequency

11. For Each IF Stage:

- a. IF Stage Number
- b. IF Frequency
- c. LO Frequency
- d. LO Injection Level
- e. IF Filter Type
- f. 3 dB Bandwidth and Number of Poles or Bandwidth and Relative Level

12. Spurious Rejection

13. Output Power or Power Density

- a. Power Type
- b. EIRP, Antenna Type

14. Output Device

15. Downlink Center Frequency

16. Downlink Filter Type

- a. Downlink Filter Center Frequency
- b. 3 dB Bandwidth and Number of Poles or Bandwidths and Relative Levels

17. Harmonic Attenuation: 2nd, 3rd, Rest

18. Spurious Attenuation

19. Transponder Noise Figure or Noise Temperature

20. Transponder Gain

Technical Description: EO Emitter
(Basic or Operating Mode Record)

1. Equipment Nomenclature
2. Manufacturer

Coherent:

3. Operating Mode(s)
4. Laser Type
5. Wavelength Range and Frequency Range
6. Primary Line Width and Line Shape
7. Power and Power Type
8. Energy
9. Radiant Emittance Pattern
10. Modulation Type(s)

CCIR Emissions Designator(s),
Old and New

Noncoherent:

3. Operating Mode(s)
4. Source Type, Shape, and Area
5. Radiator Type
 - a. Equivalent Blackbody Temperature
 - b. Emissivity
6. Wavelength Range and Frequency Range
7. Power and Power Type
8. Spectral Emissions Pattern:

Radiant Intensity (or Radiance)
and Wavelength

9. Spatial Emission Pattern:

Radiant Intensity (or Radiance)
and Angle

10. Modulation Type(s)

CCIR Emissions Designator(s),
Old and New

Technical Description: EO Detector
(Basic or Operating Mode Record)

1. Equipment Nomenclature
2. Manufacturer
3. Operating Mode(s)
4. Detector Type
5. Function
6. Wavelength Range and Frequency Range
7. Detector Responsivity and Wavelength
8. Detector Geometry
 - a. Single Unit or Array Element
 - 1) Shape
 - 2) Dimensions
 - 3) Area
 - b. Array
 - 1) Type (circular, linear, etc.)
 - 2) Dimensions
 - 3) Spacing between elements
 - 4) Number of elements
9. Detector Temperature
10. Detector Noise Current (or Voltage)
11. Sensitivity
12. Noise Figure

- 13. Noise Bandwidth
- 14. Detector Material

Technical Description: Antenna
(Basic or Operating Mode Record)

- 1. Equipment Nomenclature
- 2. Manufacturer
- 3. Operation Modes
- 4. Antenna Type
- 5. Antenna Dimensions
- 6. Phased Array Description
 - a. Number of Elements
 - b. Type of Elements
 - c. Spacing Between Elements
- 7. Number of Beams and Beam Types
- 8. Antenna Feed Lead Type
- 9. Transmit Gain
- 10. Receive Gain
- 11. Transmit Gain Pattern: Use
Figure if Available or Off-Axis
Angles and Relative Levels
- 12. Receive Gain Pattern: or
Off-Axis Angles and Relative
Levels
- 13. Transmit Polarization
- 14. Receive Polarization
- 15. Type of Illumination
- 16. Efficiency
- 17. Antenna Noise Temperature Range
- 18. Horizontal Beamwidth (Transmit)
- 19. Horizontal Beamwidth (Receive)
- 20. Vertical Beamwidth (Transmit)

- 21. Vertical Beamwidth (Receive)
- 22. Description

Technical Description: EO Emitter
Optics (Basic or Operating Mode
Record)

- 1. Equipment Nomenclature
- 2. Manufacturer
- 3. Operating Mode(s)
- 4. Effective Aperture Area
- 5. Beam Divergence
- 6. Polarization
- 7. Transmittance
- 8. Emissions Pattern: Radiant
Emittance and Angle
- 9. Motion Type
- 10. Scan Rate:
 - a. Circular
 - b. Horizontal
 - c. Vertical

Technical Description: EO Receiver
Optics (Basic or Operating Mode
Record)

- 1. Equipment Nomenclature
- 2. Manufacturer
- 3. Operating Mode(s)
- 4. Effective Aperture Area
- 5. Effective Focal Length
- 6. Effective Focal Number
- 7. Polarization
- 8. Field of View: Instantaneous
and Total

9. Transmittance Pattern: Transmittance and Angle	8. Assigned Frequencies and Assignment Number
10. Transmittance Spectrum: Transmittance, Wavelength	9. Coverage Area (Specify for Each Antenna)
11. Motion Type	10. Status
12. Scan Rate:	11. NORAD Space Object Number
a. Circular	12. Future Satellite:
b. Horizontal	a. Object Number
c. Vertical	b. Country of Origin
13. Shutter Speed	c. Projected Launch Date
a. Shutter Type	d. Inclination
14. Reticle Rotation Rate or Reticle Nutation Rate	e. Apogee
	f. Perigee
	g. Period

Satellite Environmental Information

Network

1. Satellite Name	a. International Designator
2. Satellite Alternative Names	b. Object Number
a. IFRB	c. Country of Origin
b. Other	d. Agency Responsible for Maintenance
3. System Name	e. Launch Date
4. Satellite Type: Nomenclature	f. Launch Site
5. Interrange Operations: Number	g. Period (min)
6. FCC Call Sign	h. Apogee (km)
7. Orbit Type	i. Perigee (km)
a. Nominal Subsatellite Longitude*	j. Epoch Time (yr, day, fraction of day)
b. Station Keeping Limits* (N-S and E-W)	k. Inclination (deg)
	l. Right Ascension (deg)
	m. Argument of Perigee (deg)
	n. Mean Anomaly (deg)
	o. Mean Motion (rev/day)
	p. First Time Derivative of Mean Motion Rate (rev/day ²)
	q. Second Time Derivative of Mean Motion Rate (rev/day ³)
	r. Drag Coefficient (1/earth radii)
	s. Eccentricity
	t. Epoch Revolutions

*Geostationary Only.

NOTE: Provisions are being made in the file design to store internationally published information concerning each network, and to record administrative data (dates, document numbers, etc.) for each advanced publication, coordination, notification, and agreement concerning that network.

III. EARTH SEGMENT

Earth Station Type

1. Earth Station Type Nomenclature
2. Manufacturer
3. Description
4. Equipment Nomenclature List
(Transmitters, Receivers,
Modems, Antennas, etc.)
5. Associated J/F 12 Numbers:
Equipment, J/F 12 Numbers
6. Platform Type
7. Research and Development Agency

Technical Description: Transmitter
(Basic or Operating Mode Record)

Data items same as Space Segment
(page 268).

Technical Description: Receiver
(Basic or Operating Mode Record)

Data items same as Space Segment
(page 268).

Technical Description: EO Emitter
(Basic or Operating Mode Record)

Data items same as Space Segment
(page 270).

Technical Description: EO Detector
(Basic or Operating Mode Record)

Data items same as Space Segment
(page 270).

Technical Description: Antenna
(Basic or Operating Mode Record)

Data items same as Space Segment
(page 271).

Technical Description: EO Emitter
Optics (Basic or Operating Mode
Record)

Data items same as Space Segment
(page 271).

Technical Description: EO Receiver
Optics (Basic or Operating Mode
Record)

Data items same as Space Segment
(page 271).

Earth Station Environment Information

Site Description

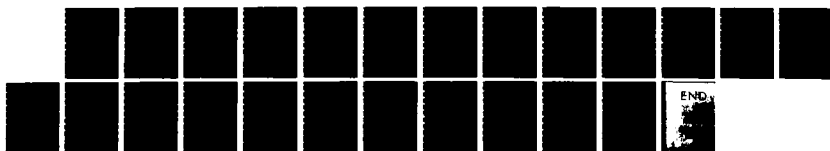
1. Station Type Nomenclature
2. Location
 - a. Site Name
 - b. Latitude
 - c. Longitude or UTM Grid
Reference, Northing,
Easting, Grid Zone,
Spheroid
 - d. Site Altitude
 - e. City, State, Country
3. Fixed/Mobile
4. Platform Type
5. Radius of Movement
6.
 - a. Rain-Climatic Zone
 - b. Radio-Climatic Zone
(A, B, C)
 - c. Horizon Elevation Profile
(Attach Figure)

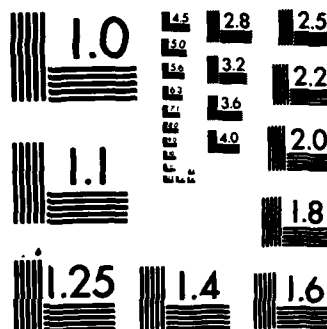
7. Operating Agency/Organization
8. Call Sign
9. Operating Mode(s)
10. Satellite(s) Communicated With
11. Space System(s)
12. Assigned Frequencies
13. Frequency Assignment Numbers
 - a. FRRS
 - b. FCC

Antenna Type

14. Antenna Nomenclature
15. Horizontal Arc Scanned Rate
16. Vertical Arc Scanned Rate
17. Feedpoint Height
18. Azimuth Pointing Angle
19. Elevation Point Angle

AD-A140 841 TECHNIQUES FOR THE ANALYSIS OF SPECTRAL AND ORBITAL 4/4
CONGESTION IN SPACE SYSTEMS(U) RAND CORP SANTA MONICA
CA A L HIEBERT ET AL. MAR 84 RAND/R-3046-AF
UNCLASSIFIED F49620-82-C-0018 F/G 22/3 NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

II. or III. MODULATION DESCRIPTION:

SINGLE CHANNEL FM

1. Modulation Type
 - a. CCIR Emissions Designator(s), Old and New
2. Peak Deviation
3. Frequency Limits of Modulating Signal
4. RMS Modulation Index
5. Preemphasis
6. Applicable Equipments

3. Audio Frequency (Relative to Video Carrier)
4. Peak Deviation
 - a. Video
 - b. Audio on Subcarrier
 - c. Subcarrier on Carrier
5. Energy Dispersal on Carrier
 - a. With Video Signal
 - b. Without Video Signal
6. Preemphasis and Noise Weighting
 - a. Video
 - b. Audio

FDM/FM

1. Modulation Type
 - a. CCIR Emission Designator(s), Old and New
2. Number of Voice Channels
3. RMS Test Tone Deviation
4. Baseband Peak-To-Average Power Ratio
5. Preemphasis
6. RMS Multichannel Deviation
7. RMS Modulation Index of the Carrier
8. Applicable Equipments

7. System Type (M, etc.)
8. Applicable Equipments

AM

1. Modulation Type
 - a. CCIR Emission Designator(s), Old and New
2. Baseband Signal Description
3. Modulation Index
4. Carrier Suppression
5. Undesired Sideband Suppression
6. Applicable Equipments

FM TV

1. Modulation Type
 - a. CCIR Emission Designator(s), Old and New
2.
 - a. Video Frequency Limits
 - b. Video Carrier Frequency

DIGITAL

1. Modulation Type
 - a. CCIR Emissions Designator(s), Old and New
2. Baseband Signal Description, Information Rate

3. Applied Coding Type, Code Rate and Code Block Length
4. Symbol Rate
5. Performance Criteria
6. Applicable Equipments

SPREAD SPECTRUM

1. Modulation Type
 - CCIR Emissions Designator(s), Old and New
2. Baseband Signal Description, Information Rate
3. Applied Coding Type, Code Rate
4. Symbol Rate
5. Performance Criteria

Spread Spectrum

6. Type
 - a. Direct Sequence
 - 1) Code block length
 - 2) Code type
 - 3) PN code rate
 - 4) DS bandwidth
 - or b. Frequency Hopping
 - 1) Number of channels
 - 2) Channel bandwidth
 - 3) Channel spacing
 - 4) Hop rate, dwell time
 - 5) Hopping bandwidth, dead time
 - or c. Chirp (Pulsed FM)
 - 1) Frequency sweep
 - 2) Sweep time
 - or d. Time Hopping
 - 1) Gate length
 - 2) Period
 - or e. Hybrid Systems (Describe)
7. Processing Gain
8. Synchronization Type
9. Applicable Equipments

PULSED SYSTEMS

1. Modulation Type
 - a. CCIR Emission Designator(s), Old and New
2. Pulse Width
3. Pulse Rise Time
4. Pulse Fall Time
5. Pulse Repetition Rate
6. Frequency Deviation on Rise
7. Frequency Deviation on Fall
8. Pulse Compression Ratio
9. Pulse Grouping
10. Maximum Duty Cycle, Chirped Frequency Shift, Code Rate, Other
11. Applicable Equipments

II. or III. ACCESS MODES

TDMA

1. Type
2. Frame Rate
3. Frame Preamble Length, Preamble Rate
4. Burst Preamble Length
5. Slot Length
6. Number of Slots
7. Guardband

FDMA*

1. Number of Channels
2. Channel Bandwidth
3. Channel Spacing

CDMA or SSMA

1. Code Length
2. Number of Users (Nets)
3. Symbol Rate
4. Code Type

Other Type (Describe)

*If channel bandwidths and spacing are not uniform, attach description.

GLOSSARY

CCIR	International Radio Consultative Committee
DCA	Defense Communications Agency
DoD	Department of Defense
DSCS	Defense Satellite Communications System
E_b/N_o	Bit Energy to Noise Density Ratio
ECAC	Electromagnetic Compatibility Analysis Center
EIRP	Effective Isotropic Radiated Power
EO	Electro-Optical
ER	Earth Radius
ESA	European Space Agency
FCC	Federal Communications Commission
FET	Field Effect Transistor
G/T	Receive Antenna Gain to System Noise Temperature Ratio
IFRB	International Frequency Registration Board
INMARSAT	International Maritime Satellite Organization
INTELSAT	International Telecommunications Satellite Consortium
ITU	International Telecommunication Union
NORAD	North American Aerospace Defense Command
OUSD	Office of the Under Secretary of Defense
SGLS	Space Ground Link System
STDN	Space Tracking and Data Network
S/N	Signal-to-Noise Power Ratio
TDRSS	Tracking and Data Relay Satellite System
TT&C	Tracking, Telemetry and Command
TWT	Travelling Wave Tube
UTM	Universal Transverse Mercator
J/F 12	Joint Chiefs of Staff, Military Communications Electronics Board, Frequency Panel J-12 form
RF	Radio Frequency
IF	Intermediate Frequency
LO	Local Oscillator
FRRS	Frequency Resource Record System (ECAC)
RMS	Root Mean Square

PN	Pseudo-Noise
DS	Direct Sequence
TDMA	Time Division Multiple Access
FDMA	Frequency Division Multiple Access
CDMA	Code Division Multiple Access
SSMA	Spread Spectrum Multiple Access

Appendix B

PROBABILITY CALCULATIONS FOR NONGEOSTATIONARY SATELLITES

This appendix gives the detailed calculations for the probability of interference involving nongeostationary satellites, the mean and maximum duration of interference, and the mean interval between episodes. The descriptive material and the results of the analysis are given in Section III.B.5.f.

The configuration to be considered is depicted in Fig. B.1. The spacecraft is at A, orbital radius r_A ; the interferer at B, orbital radius r_B ; and the ground station is at G. The line of sight from G to A

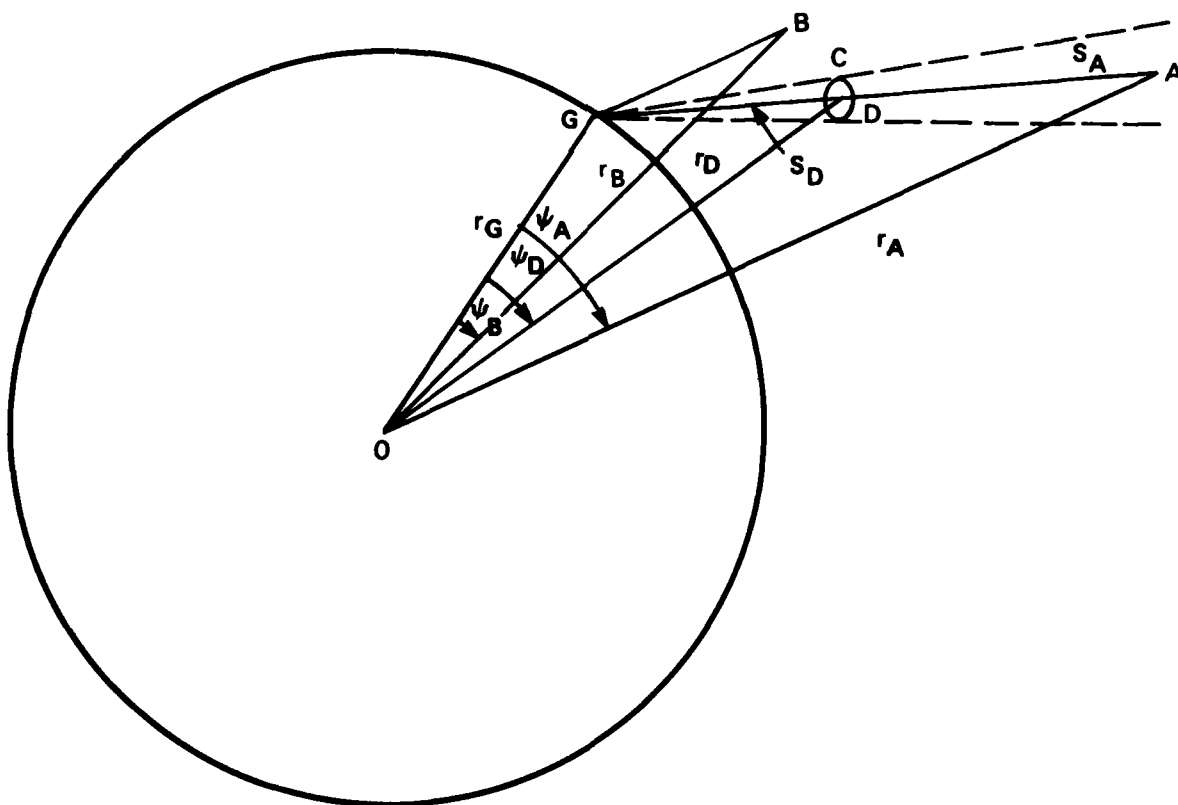


Fig. B.1 – Interference geometry

cuts the sphere of radius r_B at the point D. The antenna beam, pointed at A, intersects the sphere of radius r_B in a curve for which C is a typical point. For narrow beams (neglect terms higher than the second degree in the beam width, θ), this curve, which is given by a complicated transcendental equation, reduces to an ellipse. The receivers and interference conditions, determined for practical cases by the DSIP-2 or MILESTONE 4 programs, have generally led to threshold cone angles near 5 deg, which satisfy the beam width condition above ($\theta^2 = .0076$ kept, $\theta^4 = .000058$ neglected). If B, the position of the interferer, lies within the ellipse, interference will occur. As discussed earlier, the use of earth-coverage antennas on most satellites implies that the signal level does not depend strongly on range, and the use of the cone angle to mark interference situations is reasonable.

We shall first calculate the position of the point D and the curve C as functions of the coordinates of A, which are of course functions of time. The coordinates of B, also functions of time, will be compared to C. If the nodal crossing position of B is so placed that the orbit passes through the ellipse C, then we investigate the time range during which B must pass through its node so that B actually lies in C. This gives the time interval of interference. Since we are dealing with probabilities, this time interval must be suitably averaged.

Let the vector from the center of the earth O to the point A be denoted by $\vec{X}_A$, and similarly for B, C, D, G. The vector from the ground station G to A is $\vec{X}_{AG}$, and similarly. Define K as the quotient of the slant range S_D from G to D and the slant range S_A from G to A. Since the vectors $\vec{X}_{AG}$ and $\vec{X}_{DG}$ are parallel, we have the relations:

$$\vec{X}_{DG} = K\vec{X}_{AG} \quad (B.1a)$$

$$\vec{X}_D - \vec{X}_G = K(\vec{X}_A - \vec{X}_G) \quad (B.1b)$$

$$\vec{X}_D = K\vec{X}_A + (1 - K)\vec{X}_G \quad (B.1c)$$

Since the vectors $\vec{X}_A$ and $\vec{X}_G$ are known, the determination of D reduces to evaluating the ratio K. Take the square of the magnitude of equation (B.1c), and we obtain:

$$r_B^2 = K^2 r_A^2 + 2K(1 - K)r_A r_G \cos \psi_A + (1 - K)^2 r_G^2 \quad (B.2)$$

where we used the fact that D is on the sphere of radius r_B , and the angle ψ_A is the central angle between A and G, as shown in Fig. B.1. Solve Eq. (B.2) for K, and we find:

$$K = [(r_B^2 S_A^2 - r_A^2 r_G^2 \sin^2 \psi_A)^{1/2} - r_G(r_A \cos \psi_A - r_G)] / S_A^2 \quad (B.3a)$$

$$S_A^2 = r_A^2 + r_G^2 - 2r_A r_G \cos \psi_A \quad (B.3b)$$

Equation (B.3b) is the law of cosines applied to the triangle OAG. Two very convenient auxiliary quantities P and Q are defined by:

$$P = Kr_A / r_B \quad (B.4a)$$

$$Q = (1 - K)r_G / r_B \quad (B.4b)$$

For most practical cases Q is small and P is near unity.

Equation (B.1c) gives the coordinates of P in terms of those of A and G and the ratio K calculated by (B.3). As shown, Eq. (B.1c) contains no reference to the earth-centered coordinate system which must be used to relate theory to practice. Let the latitude be denoted by L, the longitude by ϕ . It is very convenient to reference all longitudes to the longitude of the ground station G, so we take $\phi_G = 0$. The latitude and longitude of D are then given by:

$$\sin L_D = P \sin L_A + Q \sin L_G \quad (B.5a)$$

$$\tan \phi_D = P \cos L_A \sin \psi_A / (P \cos L_A \cos \phi_A + Q \cos L_G) \quad (B.5b)$$

The spacecraft and interferer are assumed to be moving in circular orbits. The great majority of earth satellites, other than the Molniya satellites and a few scientific satellites in highly eccentric orbits, have eccentricities less than .01, so the assumption is reasonable. The inclination of the spacecraft orbit to the equator will be denoted by I,

the longitude of the northbound nodal crossing by Ω , and the time of the nodal crossing by τ . The spacecraft orbital rate will be $n = 2\pi/T$, where T is the period, and the earth's spin rate by n_E . As a result of the perturbation in the gravity field caused by the earth's equatorial bulge, the orbit plane will precess around the polar axis. This effect will be included in the spin rate. Then the coordinates of the spacecraft over the rotating earth are given by:

$$\sin L = \sin I \sin M \quad (B.6a)$$

$$\phi = \Omega + \tan^{-1}(\cos I \tan M) - n_E M / n \quad (B.6b)$$

$$M = n(t - \tau) \quad (B.6c)$$

The last term in (B.6b) represents the effect of the rotation of the coordinate system. For synchronous equatorial satellites this term cancels the second term, leaving the longitude over the rotating earth constant, as is of course proper. For satellites with apogee below 1500 km, which includes the great majority of nonsynchronous satellites, the rotation term will affect the time at which interference may occur, but will have little effect on the duration.

The elevation angle to the satellite must exceed a prescribed minimum angle, ϵ , if the satellite is to be visible. Apply the law of sines to triangle OGA of Fig. B.1, and we obtain the maximum permissible value of ψ_A , ψ_{AX} , as:

$$\psi_A \leq \cos^{-1}(r_G \cos \epsilon / r_A) - \epsilon = \psi_{AX} \quad (B.7)$$

There is a corresponding expression for ψ_B .

The angle ψ_A can be expressed in terms of the inclination I_A , nodal crossing Ω_A , and orbital phase M_A . Equation (B.7) then provides a limitation on the nodal crossing so that the satellite actually comes into the field of view from the ground station G, and determines the range of values of the orbital phase which corresponds to visibility. There are four situations to consider, corresponding to direct and retrograde orbits, and to northbound or southbound passes, as depicted in Figs. B.2a to B.2d. We see that for the northbound passes,

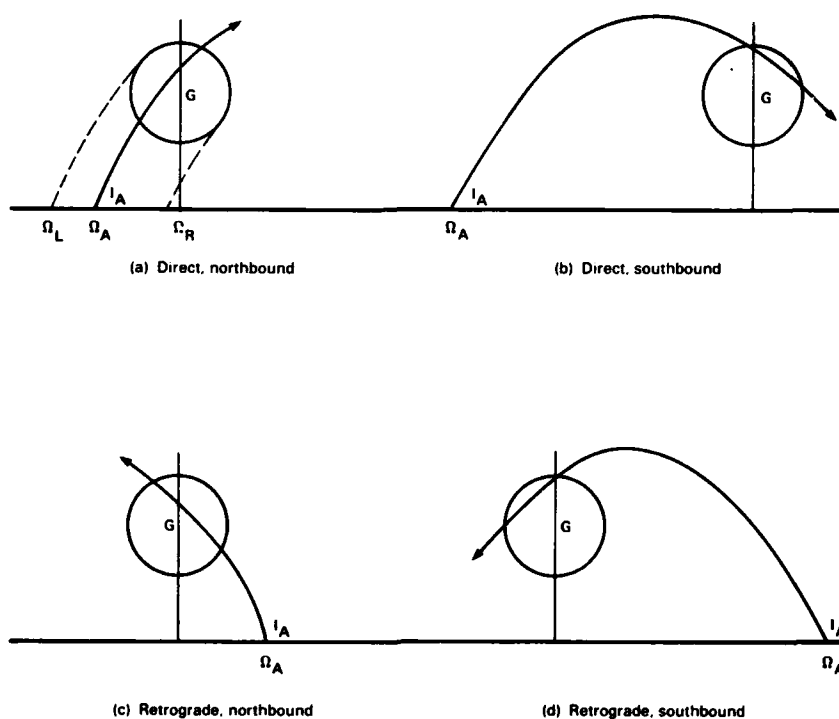


Fig. B.2 — Satellite passes

$-\pi/2 \leq \Omega_A < \pi/2$, for the direct, southbound pass $\Omega_A < -\pi/2$, and for the retrograde southbound pass $\Omega_A > \pi/2$. The limiting values Ω_L and Ω_R are shown in Fig. B.2a. Their position for the other cases is clear, but indicating them would make the figure very cluttered.

It is convenient to introduce three auxiliary angles, γ_A , δ_A , ζ_A , by the relations:

$$\cos \gamma_A \cos \delta_A = \cos L_G \cos \Omega_A \quad (\text{B.8a})$$

$$\cos \gamma_A \sin \delta_A = \sin L_G \sin I_A - \cos L_G \cos I_A \sin \Omega_A \quad (\text{B.8b})$$

$$\cos \gamma_A = \cos \gamma_{AX} / \cos \gamma_A \quad (\text{B.8c})$$

The angle γ_A is specified to lie between $-\pi/2$ and $\pi/2$, so $\cos \gamma_A$ is

positive. The condition of visibility (B.7) then corresponds to the reality of the angle ζ_A defined in (B.8c), that is, $\gamma_A < \psi_{AX}$. The angle γ_A may be represented directly by:

$$\sin \gamma_A = \sin L_G \cos I_A + \cos L_G \sin I_A \sin \Omega_A \quad (\text{B.9})$$

from which the limiting values of Ω_A may be derived by setting $\gamma_A = \pm \psi_{AX}$. The orbital phase M_A lies in the range:

$$\delta_A - \zeta_A \leq M_A \leq \delta_A + \zeta_A \quad (\text{B.10})$$

where the quadrants of δ_A and M_A match. Since M_A is proportional to time, Eq. (B.10) gives the time of visibility of satellite A at ground station G. In this analysis, the rotation term has been lumped with the node.

As a test case, consider a Defense Meteorological Support Program (DMSP) satellite (1978-42). This satellite is in a retrograde orbit ($I = 98.65$ deg) at an altitude of 825 km. Take a minimum elevation angle of 5 deg and a ground station at a latitude of 35 deg (Vandenberg AFB). The limiting angle ψ_{AX} is found from Eq. (B.7) as 23.1 deg, and the limiting values of Ω_A are found from Eq. (B.9) as $-22.2 < \Omega_A < 36.2$ deg for northbound passes, $157.8 < \Omega_A < 216.2$ deg for southbound passes. The period of this satellite is 101.3 minutes and the maximum duration of visibility, which occurs when the satellite passes directly over the ground station, is 13 minutes.

Equations (B.5) and (B.6) give the course of the point D on the sphere $r = r_B$ as a function of time. Suppose the orbit of B and the course of D intersect at the point E. Then, unless the orbits are of nearly equal inclination, interference will only be possible when B and D are near E. Let the values of M_A and M_B which correspond to the point E be denoted by M_{AE} and M_{BE} . Define the phase departure P_A by:

$$P_A = M_A - M_{AE} \quad (\text{B.11})$$

with a corresponding expression P_B . We shall expand the coordinates in powers of P_A and P_B , and keep only second-order terms. The angle between the line of sight to B and to D is given by:

$$\cos\theta_{BD} = (\vec{X}_B - \vec{X}_G) \cdot (\vec{X}_D - \vec{X}_G) / S_B S_D \quad (B.12a)$$

$$= [r_B^2 \cos\psi_{BD} - r_B r_G (\cos\psi_B + \cos\psi_D) + r_G^2] / S_B S_D \quad (B.12b)$$

and the condition that the points are both in the beam is $\theta_{BD} \leq \theta$.

It is convenient to first introduce the latitude and longitude differences of B and D from E by:

$$L_B = L_E + u_B \quad (B.13a)$$

$$\phi_B = \phi_E + w_B \quad (B.13b)$$

with corresponding expressions for D, and the coefficients C_1 and C_2 by:

$$C_1 = \cos L_G \sin L_E \cos \phi_E - \sin L_G \cos L_E \quad (B.14a)$$

$$C_2 = \cos L_G \cos L_E \sin \phi_E \quad (B.14b)$$

Then the expansion to second order becomes:

$$\begin{aligned} S_E^2 \theta^2 / r_B^2 \geq & (u_B - u_D)^2 + \cos^2 L_E (w_B - w_D)^2 \\ & - r_G^2 [C_1 (u_B - u_D) + C_2 (w_B - w_D)]^2 / S_E^2 \end{aligned} \quad (B.15)$$

This may be immediately recognized as the equation of an ellipse.

We use (B.5), (B.6), and (B.11) to express the latitude and longitude departures u_D and w_D in terms of P_A , and use (B.6) and (B.11) to express u_B and w_B in terms of P_B . The rotation terms will be dropped. The results are:

$$u_B = (\sin^2 I_B - \sin^2 L_E)^{1/2} P_B / \cos L_E = d_B P_B \quad (B.16a)$$

$$w_B = \cos I_B P_B / \cos^2 L_E = e_B P_B \quad (B.16b)$$

$$u_D = \frac{\partial}{\partial M} [P(M) \sin I_A \sin M + Q(M) \sin L_G] \Big|_{M_{AE}} P_A / \cos L_E = d_A P_A \quad (B.16c)$$

$$\begin{aligned} w_D &= P_A [\cos I_A P^2(M) + P(M) Q(M) \cos L_G (\cos I_A \cos \Omega_A \cos M - \sin \Omega_A \sin M) \\ &\quad + (Q \partial P / \partial M - P \partial Q / \partial M) (\cos I_A \cos \Omega_A \sin M + \sin \Omega_A \cos M)] \Big|_{M_{AE}} / \cos^2 L_E \\ &= e_A P_A \end{aligned} \quad (B.16d)$$

The time at which the projected point D goes through E will be called t_{AE} , and similarly for B. We introduce coefficients f_1, f_2 by:

$$f_1 = n_B d_B - n_A d_A \quad (B.17a)$$

$$f_2 = n_B d_B t_{BE} - n_A d_A t_{AE} \quad (B.17b)$$

and corresponding coefficients g_1, g_2 , in which e replaces d . We further define coefficients a_2, a_1, a_0 by:

$$a_2 = 1 - r_G^2 C_1^2 / S_E^2 \quad (B.18a)$$

$$a_1 = r_G^2 C_1 C_2 / S_E^2 \quad (B.18b)$$

$$a_0 = \cos^2 L_E - r_G^2 C_2^2 / S_E^2 \quad (B.18c)$$

and another set of coefficients A_2, A_1, A_0 by:

$$A_2 = a_2 f_1^2 - 2a_1 f_1 g_1 + a_0 g_1^2 \quad (B.19a)$$

$$A_1 = a_2 f_1 f_2 - a_1 (f_1 g_2 + f_2 g_1) + a_0 g_1 g_2 \quad (B.19b)$$

$$A_0 = a_2 f_2^2 - 2a_1 f_2 g_2 + a_0 g_2^2 \quad (B.19c)$$

Then the time at which the interfering satellite enters or leaves the beam directed toward the desired satellite is given by the quadratic equation:

$$A_2 t^2 - 2A_1 t + A_0 = S_E^2 \theta^2 / r_B^2 \quad (B.20)$$

whose roots are:

$$t_{1,2} = \{A_1 \pm [A_2 S_E^2 \theta^2 / r_B^2 - (A_0 A_2 - A_1^2)]\} / A_2 \quad (B.21)$$

The second term under the square root may be greatly simplified, and finally expressed in the form:

$$A_0 A_2 - A_1^2 = Z^2 (t_{BE} - t_{AE})^2 \quad (B.22a)$$

$$Z^2 = n_A^2 n_B^2 (d_{BE}^2 - d_{AE}^2) \cos^2 L_E (r_B^2 S_A^2 - r_A^2 r_G^2 \sin^2 \psi_A) / r_B^2 S_A^2 \quad (B.22b)$$

It is readily shown that A_2 is positive. The duration of interference is accordingly given by:

$$\Delta t = 2[A_2 S_E^2 \theta^2 / r_B^2 - Z^2 (t_{BE} - t_{AE})^2]^{1/2} / A_2 \quad (B.23)$$

This expression involves many quantities evaluated at the point E. The coordinates of E may be expressed as functions of the nodal crossing positions Ω_A , Ω_B , and so may the orbital phases M_{AE} , M_{BE} . It may be seen from (B.17a), (B.18), (B.19a), and (B.22b) that A_2 and Z are independent of the nodal crossing times τ_A , τ_B , which only appear in t_{AE} , t_{BE} through the relations:

$$t_{AE} = \tau_A + M_{AE} / n_A \quad (B.24a)$$

$$t_{BE} = \tau_B + M_{BE} / n_B \quad (B.24b)$$

We wish to average the duration of interference Δt over all possible parameters, which will yield the long-term probability of interference.

Before calculating these averages, let us consider the situation where one of the satellites, say A, is synchronous equatorial. In this case, the point D is fixed. The coordinates of B are expanded around D, with the nodal crossing Ω_B left undetermined. The result for the duration of interference becomes:

$$\Delta t = 2[A_2 S_D^2 \theta^2 / r_B^2 - (a_0 a_2 - a_1^2) f_1^2 (\Omega_B - \Omega_D)^2]^{1/2} / A_2 \quad (B.25)$$

where the quantities d_A , e_A are to be set equal to zero.

The maximum duration of interference is derived immediately from (B.23) or (B.25) as:

$$(\Delta t)_x = 2 S_D \theta / r_B A_2^{1/2} \quad (B.26)$$

The coefficients d and e , defined in Eq. (B.16), have the property that for southbound passes which go through the same intersection point E (D for synchronous) as the northbound passes, d changes sign, while e remains the same. We define an expression F_B by the relation:

$$F_B = (\sin^2 I_B - \sin^2 L_D)^{1/2} \quad (B.27)$$

Then, in the synchronous case, we determine the northbound and southbound values of A_2 by:

$$C_{3N} = (C_1 F_B + C_2 \cos I_B / \cos L_D) / \cos L_D \quad (B.28a)$$

$$A_{2N} = n_B^2 (1 - r_G^2 C_{3N}^2 / S_D^2) = n_B^2 B_N^2 \quad (B.28b)$$

$$C_{3S} = (-C_1 F_B + C_2 \cos I_B / \cos L_D) / \cos L_D \quad (B.28c)$$

$$A_{2S} = n_B^2 (1 - r_G^2 C_{3S}^2 / S_D^2) = n_B^2 B_S^2 \quad (B.28d)$$

The maximum duration of interference is:

$$(\Delta t)_x = T_B S_D \theta / \pi r_B (B_N, B_S) \quad (B.29)$$

where T_B is the period of the satellite B .

If the orbital period of the interfering satellite B is not rationally related to the spin period of the earth, all values of Ω_B will occur if the satellite is observed for a long time. Hence, we shall average the duration of interference Δt , given by Eq. (B.25), over the

values of Ω_B , and obtain the mean duration of interference. The northbound and southbound passes make equal contributions to the mean duration. Evaluating the average, denoted by angular brackets, yields:

$$\langle \Delta t \rangle = \int_0^{2\pi} \Delta t d\Omega_B / 2\pi \quad (\text{B.30a})$$

$$= S_E^2 \theta^2 / r_B^2 n_B d_B (a_o a_2 - a_1^2)^{1/2} \quad (\text{B.30b})$$

Substituting from Eqs. (B.16) and (B.18) and simplifying reduces this to:

$$\langle \Delta t \rangle = T_B S_A S_D^2 \theta^2 / 2\pi r_B (r_B^2 S_A^2 - r_A^2 r_G^2 \sin^2 \psi_A)^{1/2} F_B \quad (\text{B.31})$$

The area of the ellipse defined by Eq. (B.15) may be evaluated, and proves to be π times the geometrical expression in Eq. (B.31). The probability of interference is thereby deduced to be:

$$\text{Prob} = 2(\text{Area}) / (2\pi)^2 F_B \quad (\text{B.32})$$

The fraction of the sky covered by the ellipse is $(\text{Area})/2\pi$. A factor of 2 arises from the combination of northbound and southbound passes, and the remaining factor $1/2\pi F_B$ converts from position along the axis to time within the ellipse. We see from Eq. (B.31) that the probability of interference is proportional to the square of the beam width θ , whereas Eq. (B.29) shows that the maximum duration of interference is proportional to the first power of θ . It may be easily shown that these calculations, which involve a nonsynchronous satellite interfering with a synchronous satellite, are identical with the calculations for the reverse situation.

The expected time between interferences of nonsynchronous satellites with synchronous satellites may be calculated. At the altitudes in question (below 1500 km), a satellite will make one northbound and one southbound pass per day through the field of view of the ground station. We see from Eq. (B.6b) that each pass will occur within a section of the axis of angular width $2\pi n_E / n_B$. The angular width along the axis such that there will be some interference will be the difference between the roots of Eq. (B.25), regarded as an equation in $\Omega_B - \Omega_E$. This width may be simplified to:

$$\Delta\Omega = 2S_A S_D \theta B_N(B_S) / (r_B^2 S_A^2 - r_A^2 r_G^2 \sin^2 \psi_A)^{1/2} F_B \quad (B.33)$$

where B_N or B_S , defined in Eq. (B.28b) or Eq. (B.28d), refer to the northbound or southbound passes, respectively. The expected time between occurrences of interferences is therefore:

$$\text{Interval} = 2\pi n_E / n_B \Delta\Omega \quad (B.34)$$

The probability of interference, mean and maximum duration, and interval between occurrences are given in Eqs. (B.32), (B.31), (B.29), and (B.34), all of which apply to interference between synchronous and nonsynchronous satellites. Let us return to Eq. (B.23) and calculate the several quantities for interference between pairs of nonsynchronous satellites. We shall first consider the case where the satellite orbits are unrelated. The nodal crossing positions and times will be random variables, and we will average over them to obtain the desired results.

Let satellite A cross the axis at position Ω_A , located arbitrarily within the visibility strip defined by Eq. (B.9), at time $t = \tau_A = 0$, since we may select the time reference. For interference to occur, satellite B must also cross within the strip, and the crossing time τ_B must be such that Eq. (B.23) has positive values. We first specify Ω_A and Ω_B , and average over τ_B . We then average over the values of Ω_B such that B crosses the track D, and finally average over Ω_A .

The average over τ_B is elementary, and yields:

$$\langle \Delta t \rangle_{\tau_B} = \int_0^{T_B} \Delta t d\tau_B / T_B \quad (B.35a)$$

$$= T_A S_A S_E^2 / 4\pi r_B (r_B^2 S_A^2 - r_A^2 r_G^2 \sin^2 \psi_A)^{1/2} \cos L_E |d_B e_A - d_A e_B| \quad (B.35b)$$

If Ω_A is held constant, and Ω_B is allowed to vary, the path of B will intersect D at a point E, and M_{AE} and M_{BE} can be found. There is a one-

to-one correspondence between Ω_B and M_{AE} , so M_{AE} can be introduced as the integration variable in the average over Ω_B . It is straightforward to derive the relation:

$$d\Omega_B/dM_{AE} = (d_B e_A - d_A e_B)/d_B \quad (B.36)$$

from which we obtain:

$$\langle \Delta t \rangle_{\tau_B, \Omega_B} = \frac{T_A \theta^2}{8\pi^2 r_B} \int_{M_1}^{M_2} \frac{dM_{AE} S_A S_E^2}{(r_B^2 S_A^2 - r_A^2 r_G^2 \sin^2 \psi_A)^{1/2} (\sin^2 I_B - \sin^2 L_E)^{1/2}} \quad (B.37)$$

Here M_1 and M_2 are the values of M_{AE} for which the curves B and D intersect at the limits of the field of view. The expressions under the integral sign are to be treated as functions of M_{AE} and Ω_A , so the integral is a function of Ω_A , which also appears implicitly in the limits. Expression (B.37) must be averaged over Ω_A . The analysis becomes quite complicated. The integrand is expressed in terms of new variables, one of which is ψ_A , which measures the distance of the point E from the point directly above the ground station. The second variable measures the azimuth of the point E relative to G. We expanded the integrand in powers of ψ_{AX} , defined in Eq. (B.7), and kept fourth-order terms. A typical value of ψ_{AX} is 23 deg, and the fourth-order terms, when calculated explicitly, were about 5 percent of the contribution from the second-order terms. The probability of interference is itself small, so calculation to an accuracy of 5 percent seems unnecessary, and we shall present only the second-order portion. To second order, the integrand is independent of the azimuthal variable. After extensive simplification, there results:

$$\langle \Delta t \rangle = \frac{T_A \theta^2}{2\pi^2 r_B} \int_0^\psi \frac{\sin \psi d\psi S_A(\cos \psi) S_E^2(\cos \psi)}{(r_B^2 S_A^2 - r_A^2 r_G^2 \sin^2 \psi)^{1/2} F_A F_B} \quad (\text{B.38a})$$

$$F_A = (\sin^2 I_A - \sin^2 L_G)^{1/2} \quad (\text{B.38b})$$

$$F_B = (\sin^2 I_B - \sin^2 L_G)^{1/2} \quad (\text{B.38c})$$

It has been assumed that both inclinations sufficiently exceed the latitude of the ground station that the field of view does not reach the northernmost position of either satellite. The integral which remains in Eq. (B.38a) is proportional to the area of the ellipse, averaged over the field of view. Since the size and shape of the ellipse can vary considerably over the field, this integral cannot be further approximated. A program for the HP-34C calculator, which has a built-in integration routine, has been written to evaluate the integral numerically. On the other hand, the factors F_A and F_B , which should be evaluated over the field of view, vary only slightly with position, and have been approximated by their values at the center. This is the cited 5 percent approximation. A factor of 4 has been included in Eq. (B.38) to take account of northbound and southbound passes, which contribute equally to the mean interference time. Again, the mean interference time is proportional to the square of the beam width. To the indicated accuracy, the probability of interference is:

$$\text{Prob} = 4 \langle \text{Area} \rangle / (2\pi)^3 F_A F_B \quad (\text{B.39})$$

where the bracket around the area denotes the average. The analogy with Eq. (B.32) is evident, and has the same interpretation.

The maximum duration of interference occurs when the time difference $t_{BE} - t_{AE}$ of Eq. (B.23) is zero, and is given by Eq. (B.26). The quantity S_E is maximum, and A_2 is minimum, when the interference occurs near the edge of the field of view. The expression is quite complicated, and the simplest procedure is to substitute numerical values.

The interval between interference episodes may be estimated by the same procedure as was used for synchronous satellites. The synodic period of satellite B with respect to satellite A is the time for B to

gain or lose one orbit compared to A. If there is an interference at a given time, then the satellites should be in the proper time phase a synodic period later. The probability that they are in the proper space phase is $4(\Delta\Omega_A/2\pi)(\Delta\Omega_B/2\pi)$, where $\Delta\Omega_A$ is the width along the axis such that A enters the field of view, similarly for B, and the factor 4 accounts for north and south passes. Hence, we estimate the interval between occurrences of interference as:

$$\text{Interval} = \pi^2 \sqrt{T_A T_B} / \Delta\Omega_A \Delta\Omega_B T_B - T_A \quad (\text{B.40})$$

Most nonsynchronous satellites are randomly related, and it suffices to use the formulas (B.39) and (B.40) for probability and interval, plus the discussion for maximum duration. However, there is a class of satellites, the sun-synchronous satellites, which are mutually synchronized and require a special investigation. These satellites include the meteorological and earth-resources satellites, so the class is very important. They are in orbits such that the local time of the nodal crossing is fixed, which permits them to photograph specified regions of the earth under constant solar illumination. Thus, only the longitudes of the nodes are available for averaging.

We will clarify the situation by considering a particular case. The DMSP satellite, described before, is sun-synchronous. It crosses the equator northbound at 11:30 am local time. The Landsat-3 (L-3) earth resources satellite, also sun-synchronous, crosses the equator southbound at 9:30 am local time. They will be in proper time phase near 10:30 a.m. local time, which occurs when both satellites are near 60°N latitude (there is a corresponding location in the southern hemisphere which we shall ignore). For them to be in proper space phase, the nodal crossings must be so arranged that L-3's southbound crossing is about 38 deg west of DMSP's northbound crossing. Thus, we take as a parameter the nodal crossing of one satellite, require the nodal crossing of the second satellite to be in the vicinity of the value where the space phase is proper, average over the permissible range of the second crossing such that there is an interference, then average over the range of the first nodal crossing such that both satellites are in the field of view during the interference.

The times t_{AE} and t_{BE} of Eq. (B.23) are defined with respect to a universal time reference. Since the nodal crossing times are fixed in the local time frame, the form we shall use for t_{AE} is:

$$t_{AE} = \tau_{AL} - \frac{\Omega_A}{n_E} + \frac{M_{AE}}{n_A} \quad (B.41)$$

and a similar equation for t_{BE} . Here τ_{AL} is the nodal crossing time in the local reference frame and n_E is the earth spin rate corrected for orbital precession.

If we examine the orbits of the various sun-synchronous satellites, we find there is very little variation of the parameters. There have been 13 sun-synchronous satellites launched by the United States since 1975. The inclinations lie between 98.6 deg and 99.8 deg, the mean altitudes between 808 and 1106 km. If we exclude the satellites Nimbus 6 and P-76, the range of inclination for the remaining 11 satellites is 98.6 deg to 99.3 deg, the range of altitude between 808 and 950 km. We shall make at worst only a few percent error in the probability if we calculate the intersections for orbits of equal altitude, and the results are greatly simplified.

We introduce an angle ξ , defined by:

$$\cos \xi = \cos I_A \cos I_B + \sin I_A \sin I_B \cos(\Omega_A - \Omega_B) \quad (B.42)$$

Then the values of M_{AE} and M_{DE} are given by:

$$\sin M_{AE} = \sin I_B \sin(\Omega_A - \Omega_B) / \sin \xi \quad (B.43a)$$

$$\sin M_{BE} = \sin I_A \sin(\Omega_A - \Omega_B) / \sin \xi \quad (B.43b)$$

under the assumption of equal altitude. The quadrants of Ω_A , Ω_B , and ξ must be selected so M_{AE} and M_{BE} are in their proper quadrants. Thus, for the intersection of DMSP traveling north as A, and Landsat-3 traveling south as B, $\Omega_A - \Omega_B$ must be near -142 deg, ξ near -42 deg, M_{AE} near 60 deg, and M_{BE} near 120 deg, where the rotation of the earth during the passage from node to intersection has been included.

The separation of the nodal crossings such that the time difference $t_{BE} - t_{AE}$ is zero defines a value of Ω_B , which we call Ω_{BO} . From Eq. (B.41), we deduce the variation of the time difference $t_{BE} - t_{AE}$ to first order as:

$$t_{BE} - t_{AE} = - \left(T_E - T_B \frac{\partial M_{BE}}{\partial \Omega_{BO}} + T_A \frac{\partial M_A}{\partial \Omega_{BO}} \right) (\Omega_B - \Omega_{BO}) / 2\pi \quad (B.44a)$$

$$= -y(\Omega_B - \Omega_{BO}) \quad (B.44b)$$

Average the duration of interference Δt given by Eq. (B.23) over the variable Ω_B , and we obtain:

$$\langle \Delta t \rangle_B = S_E^2 \theta^2 / 2r_B^2 yz \quad (B.45)$$

where the quantities S_E , y , and z are evaluated at $\Omega_B = \Omega_{BO}$, which is a function of Ω_A . For equal altitude satellites, the quantities y and z can be greatly simplified, and yield:

$$y = \left(T_E - \frac{(|\cos I_A| + |\cos I_B|)}{1 + \cos \xi} T_A \right) / 2\pi \quad (B.46a)$$

$$z = 4\pi^2 \sin \xi (r_B^2 S_A^2 - r_A^2 r_G^2 \sin^2 \psi_A)^{1/2} / T_A^2 r_B r_A \quad (B.46b)$$

We observe that as Ω_A varies the interference takes place approximately along a line of constant latitude. The second term in Eq. (B.46a) is only about 1 percent of the first, so it can be neglected, consistent with previous assumption. The result for the probability is:

$$\text{Prob} = T_A [\int d\Omega_A A(\cos \psi)] / (2\pi)^3 T_E \sin \xi \quad (B.47)$$

where the integral denotes the area of the ellipse, integrated over the values of Ω_A such that the point of intersection is within the field of view. This integral was evaluated using the HP-34C, as before.

The maximum duration of interference is found by setting $t_{BE} = t_{AE}$ in Eq. (B.23), then evaluating at the boundary of the field of view, where the ellipse is largest. The time between episodes is found from the synodic period, analogous to Eqs. (B.34) and (B.40), but lacking the factor of 2 in Eq. (B.34) or 4 in Eq. (B.40) that takes care of northbound and southbound passes.

This completes the calculation of the various quantities. The key results for probability are in Eqs. (B.32), (B.39), and (B.47), and for maximum duration in Eq. (B.29) for the synchronous case (the other cases are very complicated). The interval between episodes is given in Eqs. (B.34) and (B.40).

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