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THE LINCOLN SATELLITE TECHNOLOGY PROGRAM THROUGH 1 JANUARY 1968

AN ANNOTATED BIBLIOGRAPHY

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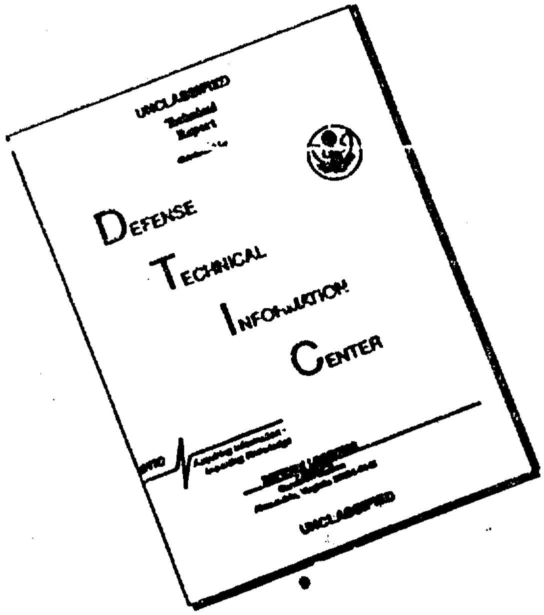

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ABSTRACT

This report comprises a bibliography of papers that pertain to Lincoln Laboratory's satellite communications program. More significantly, the purpose of this report is to provide a coherent program guide indicating the direction of this work and the accomplishments to date.

Accepted for the Air Force
Franklin C. Hudson
Chief, Lincoln Laboratory Office

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ACKNOWLEDGMENTS

A compendium such as is presented in this report only recognizes material that has been written for dissemination to the public. The unpublished material, the mechanical skills and techniques necessary for realizing a spacecraft, and the ideas, encouragement and consultations that are never recorded cannot be adequately acknowledged. Thus, we wish to extend credit to our co-workers in Division 7, Engineering, to our colleagues (past and present) in Division 6, Communications, and Group 63, Space Techniques and Equipment, and to the support teams who actually built the satellites and their components.

We would be remiss if we ignored the assistance of consultants and professional peers in other government, university, and commercial organizations with whom we freely exchanged knowledge. Their cooperation is gratefully acknowledged.

THE LINCOLN SATELLITE TECHNOLOGY PROGRAM THROUGH 1 JANUARY 1968

AN ANNOTATED BIBLIOGRAPHY

I. INTRODUCTION AND HISTORICAL BACKGROUND

The Space Techniques and Equipment Group of Lincoln Laboratory has been in existence approximately five years. During this period, seven satellites were launched: Lincoln Experimental Satellites LES-1, -2, -3, -4, and -5; and Lincoln Calibration Spheres LCS-1 and -2. Two more satellites are under construction or awaiting launching (LES-6 and LCS-3), and another satellite is in the active planning stage (LES-7). Seven space experiments were constructed and launched.*

During this same period, nearly 100 papers were prepared by members of the Group for general circulation, as well as a larger number of internal papers of limited distribution. The purpose of this report is not only to provide a bibliography of these papers, but, more significantly, to present a coherent program guide to indicate the direction of this work and the publicly available accomplishments to date.

Since its inception, Lincoln Laboratory has had a vigorous program in communication techniques (antijamming, optimum signaling, optimum receivers, coding, and decoding), in communication phenomenology (telephone circuits, tropospheric and ionospheric propagation, noise, orbital scatter, and channel characterization), and in communication systems (DEW line, SAGE, Mercury, and Apollo). Prior experience with the West Ford orbital scatter communications and a study of military needs indicated that the Laboratory should address its efforts to satellite communications. The DDRE Office agreed with this appraisal and Division 6 (Communications) was organized in 1963 to explore satellite communications for the military.

The civil communications satellite experience was limited to pioneering efforts of Score, Telstar, Relay, and Syncom. These satellites were spin-stabilized with low-gain omnidirectional antennas. Antenna pointing aboard satellites existed only on paper. Traveling-wave tubes were the only significant RF sources available. Civil programs were just getting under way with the organization of the Communication Satellite Corporation.

From the beginning, the Laboratory felt that the military program should be at near-synchronous attitudes, but boosters were limited. The Titan III Program had yet to launch its first vehicle.

* Plasma probe (EOGO-1, Mariner-4, Pioneer-6, EOGO-3, and Pioneer-7); gamma-ray telescopes (OSO-C and OSO-III).

The decision was made that if the Laboratory were to advance the state of the art, such advances must be made credible through demonstration. With the limited available resources, our goals had to be carefully chosen. For example, to avoid complex attitude control problems, emphasis was placed on a spin-stabilized arbitrarily oriented satellite with a switched antenna system.

From 1963 to 1968, communications satellite development by others was very rapid. The DoD IDCSP series of satellites was launched, the NASA ATS satellites made significant advances; the Comsat Corporation "Birds" were put into operation, and major new concepts such as the Hughes "Gyrostat" were put forward.

II. RF POWER GENERATION

The Group started with the general conviction that solid-state power sources must ultimately dominate satellite RF power generation because of their fundamental reliability. In 1963, solid-state sources suffered with respect to vacuum tubes in available power output and efficiency. Furthermore, little was known about radiation effects in the solid state, except for bulk parameter changes.

A. Amplifiers

1. Single Devices

One of the Group's earliest contributions to satellite technology was the efficient conversion of solar bus power to RF energy.

This was based on a new contribution to the old technology of narrow-band class-B amplifier design, the advance requires control of the out-of-band impedance seen by the amplifier, thus permitting shaping of the waveform at the collector (TR-428, MS-1685) for best efficiency at the maximum available power output. When this is combined with optimum choice of overdrive, careful measurement and matching of the input impedance of the amplifier, it has been demonstrated (MS-1221, MS-2055, and MS-2103) that one can achieve about 70-percent overall efficiency (DC input to RF output for a complete chain starting with a 1-mW oscillator output). The agreement, within measurement error, between circuit performance and the values predicted from device parameters, have changed RF amplifier design from an art to straightforward computation.

In addition to efficiency, these power amplifiers exhibit an insensitivity to driver output such that 10-db changes in driver output cause 1 db or less final power output changes. Furthermore, since the method is based on shaping of collector voltage waveforms, the amplifiers have demonstrated a remarkable reliability record due to the control of destructive high-harmonic collector waveform spikes.

The technique is insensitive to frequency, requiring only that f_T of the amplifier device equal or exceed about 3 times the operating frequency.

Finally, with only modest loss in efficiency, the DC resistance offered by the amplifier to a power source, like the solar panels, can be controlled to optimally match the expected changes in power source parameters during satellite lifetime (MS-2103). This can give as much as 3 db more effective radiated power than conventional designs at the start of satellite life.

These techniques have been demonstrated in the 250-MHz range for modules having 7-watts output (MS-1221), 11-watts output (JA-2767A), and 16-watts output (MS-2055) conservatively rated for space applications (e.g., operated at one-third of breakdown voltage and tested for space radiation resistance). The earlier models have demonstrated lifetimes of 2 years in space without significant change. These techniques apply anywhere that efficiency is significant, as in man-pack radios as well as satellites.

2. Multiple Devices

The low-frequency methods for employing multiple devices (e.g., paralleling, push-pull) have not offered space-acceptable freedom from unwanted oscillations and self-destruction through such mechanisms as "current hogging" (i.e., unequal current distribution among devices). To overcome this barrier, it has been demonstrated that multiple modules employing single devices can be combined with hybrids or hybrid-like techniques. This is possible only with construction techniques that control amplitude and phase differences between modules, over a range of operating temperatures and supply voltage variations. These developments have resulted in the combination of 4 modules for 46-watts output (TR-428) and 8 modules for 120-watts output (MS-2055, MS-2103).

B. Nonlinear Devices

1. Single Nonlinear Devices

Beginning with the work of Penfield and Rafuse, analytical techniques have been devised for computing the performance of abrupt-junction and other varactor multipliers (JA-2233, JA-2351, JA-2355, JA-2673). Equivalent circuits and measurement methods have been given for varactor parameters (JA-2313, JA-2775), including bias voltage effects on equivalent series resistance and their packages at frequencies up to X-band (JA-3133) giving matches to capacitance variation with bias voltage of better than 4 percent.

The introduction of the abrupt-junction varactor raised questions about performance, including bandwidth relative to the more gently graded doping distributions (JA-2233, JA-2355, JA-2673, JA-2688, JA-2531). In addition, it raised questions concerning more radical doping distributions, such as the negative gamma or hyper abrupt junction device whose performance has been computed (JA-2971), although it now appears that it cannot be realized in practice. The effects of overdrive on multiplier performance have been computed (JA-2688) and their apparent efficiency explained.

Efficiency bounds (JA-2737B) and power-frequency limitations (JA-2885) on nonlinear multipliers at all orders have been established.

The bandwidth of doublers has been analyzed (JA-2355) as well as comments on intermodulation distortion in varactors (JA-2784) and in p-i-n switches (JA-3051). Varactor multiplying chains and nonlinear resistors have special problems in the enhancement of low-level spurious signals; these have been analyzed (MS-1781).

It has also been demonstrated that the varactor can be used as a binary phase modulator up to X-band (MS-1370) at 1-watt CW power input with 40-db carrier suppression and 2.0 db of insertion loss.

Varactors have also been used for high-efficiency (50-percent) up-conversion from 915 to 7750 MHz (JA-2498) and for a broadbanded 60- to 914-MHz up-conversion (MS-1217A). In addition to demonstration, the performance of such up-converters has been computed for overdriven abrupt-junction varactors (JA-2693, MS-1718).

In the design of high-power nonlinear devices, one of the limiting parameters has been the ability to conduct away dissipated heat. Present package design was standardized in World War II for low-level detector applications. A new package design has been proposed that has the theoretical possibility of 0.5°C temperature rise per watt dissipated (MS-2115).

2. Multiple Devices and Bulk Power Generation

With the limitations of single devices it was clear quite early that means were essential for generating power in the bulk material or in multiple devices. The first effort in this direction pre-dating Gunn effect, LSA, and IMPATT modes was a microwave equivalent of the traveling-wave amplifier (MS-1786). Investigation showed that this was a surface wave rather than a bulk wave phenomenon, so the technology was not pursued further.

An extension of this concept involved the discrete equivalent of two coupled transmission lines propagating coupled waves at different frequencies (JA-2959, MS-1888). This proposal has the advantage of distributing the heat sources over larger areas. It can be conceptually simplified by considering the separate diodes as being paralleled through $\lambda/2$ lines (MS-1981), although there are some advantages in using lengths other than $\lambda/2$ (JA-3041A). The disadvantage of this proposal is that parasitic oscillations can be set up unless active steps are taken to suppress such oscillations (JA-2959, MS-2002, JA-3027, MS-2105). Arrays have now been built with four devices capable of accepting 60 watts at 1 GHz and doubling with efficiencies of about 60 to 70 percent (MS-2043) as well as triplers.

III. ANTENNA POINTING AND ORBITAL DYNAMICS

The first satellite despun antenna system ever launched was used in LES-1 and -2 (JA-2908A, GR-1964-55). It led directly to an automatic on-board orbit determination and stationkeeping system in a rather interesting way. The program had the guiding principle that a minimum of ground command should be used to avoid relying on a weak link that could be jammed or spoofed by the enemy.

On a spinning satellite, the simplest form of antenna pointing requires that the satellite rotation rate be established and that the antenna be despun at that rate, in such a phase as to point toward the earth. The satellite rotation rate can be established from sensors that operate on visible light from the sun to create 128 or 256 pseudo pickets around the satellite (MS-2109) to clock the phase of satellite rotation. The longitudinal location of the earth on the satellite is established also by visible earth sensors. A number of variants were employed in LES-1, -2, and -4 for establishing the proper position of the antenna. The techniques for electronic antenna switching at X-band are given in detail in the publications of Group 61 and are described generally in JA-2908A and GR-1964-55.

A more subtle method of earth-directed antenna pointing involves the measurement of orbital period (by the time taken to pass between two points of known sun-earth angular position in orbit). From these measurements, instructions can be given to switch the antenna with appropriate angular increments from one of the sun-earth angle positions. This technique was used in LES-4, and the results indicated operation of the system consistent with the highly elliptic orbit into which LES-4 was placed by Transtage failure (JA-2908A).

While making an error analysis of the LES-4 orbital period determination system, we discovered that the system was sensitive to noncircularity of the orbit. This suggested that the period could be corrected to terms of the second order in eccentricity by making time measurements at points separated by 180° in orbit (MS-1930A, MS-2102, MS- . 23). This, in turn, suggested that orbital parameters could be determined rather simply aboard the satellite by use of time measurement alone taken between points in orbit that had known sun-earth angle relationships.

An existence theorem for the number of observations needed to establish an orbit from satellite observations and linearized control equations was determined (MS-1970). In particular, by returning to ancient navigation techniques of clock and sextant, a conceptually simple stationkeeping system was devised requiring that a known sun-earth angular relationship be maintained (e.g., high noon) at a time determined on board the satellite by a comparison clock.

The techniques for instructing the satellite to move to a new station, to circularize its orbit, and the control law for these followed (MS-1930A, MS-2102). General rules for controllability of satellite orbits were also elucidated (MS-1970). The satellite can only observe solar time, and corrections must be made for the eccentricity of the earth's orbit about the sun (MS-1930A, MS-2102). This correction is complicated by attitude errors (TN-1966-21).

Finally, a momentum source must be employed to provide the impulse for stationkeeping. One interesting possibility is solar radiation pressure (JA-3113).

Use of visible earth and sun sensors has been particularly helpful since their signal-to-noise ratio is high, components are readily available, and testing is easy relative to infrared sensors (MS-2109). They have the disadvantage of requiring discrimination between sun, moon, and earth that proves to be relatively simple using angular or amplitude constraints. Earth-center detection is relatively complicated since the visible portion may be crescent shaped, rather than circular, making for some logical additions to establish the location of earth center from a spinning satellite.

IV. ATTITUDE CONTROL

Early in the LES program, we decided to develop an experimental magnetic attitude control system. The first rudimentary version was exercised on LES-1 and -2 (JA-2908A, GR-1964-55). This system was extended to act as a commutated magnetic motor in order to maintain the satellite spin axis normal to the orbit plane (TN-1965-48, MS-2098). The system (MS-1555) used less than 500 mW and weighed less than 700 grams (TN-1965-45) when used on LES-4 (MS-1562). It was designed to operate near synchronous attitude where the earth's field is low.

The sensors that recognize the apparent latitude of the earth as seen from the satellite were devised using simple photodetectors (MS-2109). Visible light is also used to establish the sun-earth angular relationships that control the commutation phase of the magnetic motor.

V. RADIATION CAUSES AND EFFECTS

Following the main direction of the Group toward the extensive use of solid-state devices for satellites, it seemed appropriate to investigate the effects of high-energy electron damage, a major mechanism for limiting the life of solid-state devices. In 1964, the data necessary for calculating such damage to synchronous satellites were very sparse. Available scientific data were directly concerned with electron flux well within the magnetopause (e.g., Van Allen belts) or with the solar "wind" in interplanetary space (TN-1966-26). The little data available at synchronous attitudes were samples taken by lunar or interplanetary probes on their way out. We proposed an experiment to measure the number of electrons arriving per second above four energy thresholds located at 150 keV, 850 keV, 2.75 MeV, and 4.0 MeV (TN-1965-5, MS-1716). The experiment was to have a narrow acceptance angle of 0.01 steradian to establish the direction of electron arrival in a coordinate system rotating with the satellite. The experiment was launched on LES-4 into a highly elliptical orbit (far from that planned) and data were obtained from 100 to 18,000 nm (MS-1716). The experimenters were able to correlate their results closely with other lower altitude measurements and to extend these results to near-synchronous altitudes. Unfortunately, the low perigee caused air drag to change spin-axis orientation violently, making interpretation of angle-of-arrival data nearly impossible. Scientifically, the data were also productive in showing delayed correlations with earth magnetic activity indices at different altitudes.

Even before a measure of the electron environment was on hand, a simulation facility was designed for research and test, first using commercial facilities and later using a Lincoln-designed facility. This facility had interchangeable electron-proton sources with energies up to 4 MeV at high fluxes. The unique features include a magnetic lensing facility to spread the electron beam over an area 5 feet in diameter with full thermal, solar, and vacuum environment (JA-3003, TN-1966-12). This facility permits testing of complete satellites, as well as testing of instruments and components. Among its novel features is a spectrum-spreading capability that permits the electron flux-energy distribution to be matched with the measured orbital environment.

The Lincoln-designed facility has been used to obtain the energy distribution internal to a cylindrical satellite in generalized parameters (MS-1923) suitable for general-purpose design.

In addition to the damage to materials used in satellite construction (e.g., plastics, lenses), the machine has been used principally to measure surface effects in transistors and diodes (see the specialized bibliography included in this report) up to 10^{15} electrons/cm^2. Governmental contractors have access to electron damage evaluations of specific components measured in this facility, as well as for use in instrument calibration. Research in this facility has focused on modeling the radiation effects in MOS and MNS interfaces. Special attention has been given to leakage and voltage shifts that are particularly destructive to logic systems and micropower circuits.

VI. POWER SYSTEMS

The use of solar power systems in satellites is so widespread, one might consider that very little could be contributed in design technique to this field, however, a number of problems have been solved that are of general interest.

The problem of solar-cell shadowing affects many satellite power systems. In addition to gross shadows, a frequent concern is the shadowing by wires of thin antennas, like dipoles. Equivalent circuits have been formulated and experimentally verified for silicon cells (JA-2814) so that system design, including shadow effects, can be done.

The overall system design is frequently faced with priority considerations. In a degrading power situation, one would like to be sure that power is made available in ascending priority order such that, say, a telemetry system is the first on and last off. The technique for achieving a priority turn-on, without electronic logic and other power system design considerations, has been described (MS-1828); the technique was employed on all LES launches. A silicon solar cell degrades with time due to radiation damage, and its output varies with temperature and solar flux. Some systems, particularly the radiating part of a communication satellite, can effectively use all of the available power at all times. This is possible by (1) operating the RF power amplifiers directly off the solar bus – eliminating the weight and inefficiency of a special converter, and (2) matching the DC resistance of the power amplifier to the time-varying source impedance of the solar array. A system has been designed to do both, and appears to allow a 3-db increase in effective radiated power at the start of life without significant penalty at the end of life (MS-2103).

Finally, the solar power plant is dependent on the behavior of the silicon cell in orbit. Measurements have been made in LES-4 and -5 on a variety of cells and cover slips (MS-2108).

VII. SATELLITE SYSTEMS

The design of a satellite is a highly interrelated affair, not all of which is readily reducible to writing. Some of the parameters and experiences are recorded for LES-1, -2, -3, and -4 (GR-1964-55, JA-2908A, MS-1725); LES-3 has also been described (JA-2767A).

VIII. MISCELLANEOUS

A number of miscellaneous topics of significant utility have arisen in satellite design that have warranted recording.

Extensive use of digital logic has been made possible only through the use of micropower circuits. Typically, a flip-flop might consume 60 to 100 μW through use of complementary logic and high impedances (MS-1151, JA-2906, GR-1965-6). When the number of discrete components in a satellite are numbered in the tens of thousands, some thoughts are necessarily given to reliability improvement through redundancy. Several techniques have been evolved. One proposes the equivalent of the binary erasure communications channel coding through the use of parametric elements (TN-1965-3, JA-2806). This proposal has not yet been actively pursued, since it requires the development of a new logic component line. The second technique proposes a triplicated pulse-powered logical element with a majority voting element consisting of 3 capacitors (JA-2961). The unit allows stage-by-stage voting and could use as little as 100 pW per logical element in the low-speed logic usually employed.

The extensive use of logic has required packaging development in which the logic mounting and connectors are integrated into a single unit with integral radiation shielding and external test provisions (JA-2839). Among the useful circuits that have been discovered, the "diamond" circuit (TN-1966-39) has proved valuable for storage, for operational amplifiers, and for a variety of other situations for which design parameters are given.

IX. BIBLIOGRAPHY OF GROUP 63 EXTERNAL PUBLICATIONS

The following list is a bibliography of Group 63 publications for the period 1 January 1964 to 1 January 1968 that are generally available. The list is ordered by manuscript number. An entry to the list by subject is available through the text at the beginning of this report. This list does not include Radar Astronomy, Antenna Pointing Satellite Systems, and other papers published by other Groups in Division 6.*

Since meeting speeches are not generally available, even though released for publication, some are included here in abstract form; in some cases, complete texts are available from the author(s).

* Reports on Radiation Effects are listed on p. 12

Abstracts for the following meeting speeches are not included in this report since the material has been published previously and is available in most libraries: MS-1151, MS-1217A, MS-1555, MS-1718, MS-1923, MS-1981, MS-2043, and MS-2055.

An index to meeting speeches by author appears at the end of this report (Sec. XI).

Technical Report

TR No.				DDC No.
436	A Theoretical Analysis and Experimental Confirmation of the Optimally Loaded and Overdriven RF Power Amplifier	D. M. Snider	7 Nov. 1966	647799

Group Reports

No.				
1964-53	The Lincoln Experimental Satellite	H. Sherman P. Waldron D. [illegible]. MacLellan	14 Oct. 1964	449485
1965-5	Design Aspects of Minimal-Power Digital Circuitry	W. G. Schmidt D. E. Chace	9 Feb. 1965	612669

Technical Notes

TN No.				
1965-3 (JA-2806)	Failure Erasure Circuitry: A Duplicate Technique for Failure-Masking Systems	J. B. Connolly W. G. Schmidt	14 Oct. 1965	477218
1965-5	Proposed Electronic Systems for the LES Radiation Experiment (September 1964)	J. H. Binsack	20 July 1965	619977
1965-11	Signals Distortion in a Frequency Divider	J. Max	12 Mar. 1965	614425
1965-45	Design of Electromagnetic Torque Rods	W. L. Black	21 Dec. 1965	627600
1965-48	LES-4 Spin Axis Orientation System	E. A. Vrablik W. L. Black L. J. Travis	1 Oct. 1965	624358
1966-12	Lincoln Accelerator Laboratory	C. L. Mack, Jr.	2 Sept. 1966	639962
1966-21	Position Error in Station-Keeping Satellite	B. J. Moriarty	1 Apr. 1966	633034
1966-26	Solar Plasma Measurements	J. D. McCarron	21 July 1966	637998
1966-39	Diamond Circuit Considerations	J. D. McCarron	21 July 1966	637166
1966-64 (MS-1716)	Observations of Inner and Outer Zone Electrons Since December 1965	J. L. Ryan V. J. Sferrino	28 Dec. 1966	649139

Journal Articles

JA No.			
2204	Band-Pass Filters with Linear Phase	R.M. Lerner	Proc. IEEE 52, 249 (1964)
2233	The Analysis of the Abrupt Junction Varactor Doubler as a Function of Frequency	A.I. Grayzel	Unpublished
2313	A Simplified Technique for Measuring High Quality Varactor Parameters	D.E. Crook	Solid State Des. 6, No. 8, 31 (1965)
2351	The Frequency Dependence of the Powers and Impedances of Varactor Frequency Multipliers	A.I. Grayzel	Proc. IEEE (Correspondence) 52, 1056 (1964)
2355	The Bandwidth of the Abrupt-Junction Varactor-Frequency Doubler	A.I. Grayzel	IEEE Trans. Circuit Theory CT-13, No. 1, 52 (1966), DDC 641001
2498	High Efficiency Varactor Upper-Sideband Upconverter	H.J. Pratt W.J. Ince R.C. Sicotte	Proc. IEEE (Correspondence) 53, 305 (1965), DDC 616132
2524	A Bandwidth-Insertion-Loss Tradeoff	W.L. Black	IEEE Trans. Circuit Theory CT-12, No. 4, 615 (1965), DDC 633174
2531	Greater Doubler Efficiency Using Varactor Diodes with Small Values of Gamma	A.I. Grayzel	Proc. IEEE (Correspondence) 53, 505 (1965), DDC 620981
2545	Experiment in Solar Orientation of Spin Stabilized Satellite	M.C. Crocker E.A. Vrablik	AIAA J. 3, 1350 (1965), DDC 620979
2673	Computation of the Performance of the Abrupt Junction Varactor Doubler	A.I. Grayzel	IEEE Trans. Microwave Theory Tech. MTT-14, No. 5, 239 (1966), DDC 642197
2682A	Exact Design of Multiplexers Having Contiguous Channels	A.I. Grayzel	Unpublished
2688	A Note on Overdriven Abrupt Junction Varactor Doublers and Frequency Converters	A.I. Grayzel	Proc. IEEE (Correspondence) 53, 2140 (1965)
2693	A Note on the Abrupt Junction Large Signal Upconverter	A.I. Grayzel	Proc. IEEE (Correspondence) 54, 78 (1966), DDC 634856
2737B	An Efficiency Bound for Varactor Frequency Multipliers	W.L. Black	Unpublished
2767A	The Lincoln Experimental Satellite No. 3 (LES-3)	D.M. Snider	Unpublished
2775	The Cutoff Frequency of a Varactor Diode with Variable Series Resistance	A.I. Grayzel	Proc. IEEE (Correspondence) 54, 875 (1966), DDC 642168
2784	Comments on "A Large Signal Analysis Leading to Intermodulation Distortion Prediction in Abrupt Junction Varactor Up-Converters"	A.I. Grayzel	IEEE Trans. Microwave Theory Tech. MTT-15, No. 3, 183 (1967)
2808	Failure-Erasure Circuitry: A Duplicative Technique of Failure-Masking Systems	J.B. Connolly W.G. Schmidt	IEEE Trans. Electron. Computers EC-16, 82 (1967), DDC 653674
2814	Shadows and Available Power in Satellite Solar Panels	A. Braga-Illa	Unpublished

JA No.			
2839	Digital Electronics Packaging Techniques for the Lincoln Experimental Satellites	W.G. Schmidt D.H. Galvin	Unpublished
2885	Some New Power-Frequency Inequalities for Nonlinear Capacitative Harmonic Multipliers	W.L. Black	Proc. IEEE 54, 1995 (1966), DDC 651524
2906	A High-Speed, Low Power Complementary Flip-Flop	D.E. Chace	Electron. Communicator 1, 5 (1966)
2908A	Lincoln Experimental Satellite Program (LES-1, -2, -3, -4)	H. Sherman D.C. MacLellan R.M. Lerner P. Waldron	J. Spacecraft Rockets 4, 1448 (1967), DDC 663685
2922A	A Theoretical Analysis and Experimental Confirmation of the Optimally Loaded and Overdriven RF Power Amplifier	D.M. Snider	IEEE Trans. Electron Devices ED-14, 851 (1967)
2959	Varactor Multiplier Arrays for Increased Power Handling Capability	D. Parker A.I. Grayzel	Proc. IEEE (Correspondence) 55, 437 (1967), DDC 654863
2961	Micropower Redundant Circuits Correct Errors Automatically	R.E. McMahon N.B. Childs	Electronics 40, No. 3, 66 (1967), DDC 655313
2971	The Negative Gamma Varactor	A.I. Grayzel	Proc. IEEE (Correspondence) 55, 469 (1967), DDC 655317
3003	Van Allen Belt Simulation	C.L. Mack	J. Spacecraft Rockets 4, 819 (1967), DDC 658780
3027	Experimental Results of a Frequency Doubler Using a Varactor Array	D. Parker A.I. Grayzel	Proc. IEEE (Correspondence) 55, 715 (1967), DDC 658769
3041A	Design of Mutually Matching Multiple-Varactor Array for Power	D.D. Tang	Proc. IEEE (Correspondence) 55, 1756 (1967), DDC 663686
3051	Intermodulation Products Generated by a p-i-n Diode Switch	R.L. Sicotte R.N. Assaly	Proc. IEEE (Letters) 56, 74 (1968), DDC 668721
3113	Stationkeeping a 24-Hour Satellite Using Solar Radiation Pressure	W.L. Black M.C. Crocker E.H. Swenson	J. Spacecraft Rockets 5, 335 (1968)
3133	Circuit Characterization of Varactor Junction and Package Parasitic Paremeters by Microwave Measurements	D. Tang	Unpublished

Meeting Speeches

MS No.			
1040	A New Fourier Technique for Frequency-Domain Synthesis on Delay-Line Filters	J. Max	Seventh Midwest Symposium on Circuit Theory, Univ. of Michigan, 4-5 May 1964
1151	Low Power Fast Pulse Circuit Techniques in the MIT Gamma-Ray Telescope	F.W. Sarles J.K. Roberge	IEEE Trans. Nucl. Sci. NS-12, No. 1, 46 (1965)
1217A	Design of a Broadband 60 to 914 mc Stripline Upconverter	A.I. Grayzel R.S. Berg	First IEEE Annual Communications Convention, Globecom VII, Univ. of Colorado, 7-9 June 1965

MS No.			
1221	Design of a High Efficiency 213 mcs Power Source	D.M. Snider	Unpublished
1370	X-Band 0° – 180° Binary Phase Modulator Using Step Recovery Diode	D.D. Tang	Unpublished
1381	Some Simple Reliability-Improving Redundancy Techniques	W. L. Black	Unpublished
1555	Magnetic Torquing of Spinning Satellites	R.W. Brockett B.J. Moriarty	Joint Automatic Control Conference, AIAA, August 1966
1562	A Magnetic Satellite Spin Axis Orientation System for Use at Near Synchronous Altitudes	W.L. Black B. Howland L.J. Travis E.A. Vrablik	AIAA Guidance and Control Spec. Conference, Seattle, 15-17 August 1966
1685	Design of a High Efficiency UHF Power Source	D.M. Snider	Summer Course Lecture, Univ. of Michigan, 8 June 1966
1716 (TN 1966-64)	LES-4 Observations of Inner and Outer Zone Electrons Since 21 December 1965	J.L. Ryan V.J. Sferrino	Unpublished
1718	The Design and Performance of "Punch Through" Varactor Upper Sideband Up-Converters	A.I. Grayzel	NEREM Record (1966), DDC 651521
1725	Flight Experience with LES 1-4	D.C. MacLellan H. Sherman P. Waldron	NEREM, Boston, 2-4 November 1966
1781	Enhancement of Spurious Signals in Frequency Multipliers	A.I. Grayzel	Conference on Frequency Generation and Control of Radio Systems, London, 22-24 May 1967
1786	Field Theory of a Solid State Traveling Wave Amplifier	D. Parker	Unpublished
1828	Solar Energy Conversion Techniques for Communication Satellites	A. Braga-Illa	Milano Chapter Italian Association of Electricity and Electronics, Milano, 12 January 1967
1888	Traveling Wave Varactor Frequency Multipliers for Increased Power Handling Capability	D. Parker A.I. Grayzel	Unpublished
1923	The Internal Radiation Environment of Cylindrical Spacecraft	C.L. Mack	IEEE Trans. Nucl. Sci. NS-14, 204 (1967), DDC 668199
1930A	Automatic Geosynchronization of Artificial Satellites	A. Braga-Illa	Seventh Int'l Technical Scientific Meeting on Space, Rome, Italy, 21-23 June 1967
1970	The Controllability and Observability of Satellites in Near Circular Orbits	R.W. Brockett	Symposium on Application of Modern Control Theory, M.I.T., 17 May 1967
1981	Increased Power Handling Capability and Improved Efficiency of Frequency Multipliers Using Varactor Arrays	D. Parker A.I. Grayzel	Engineering Applications of Electronic Phenomena, Cornell Univ., 29-31 August 1967
2002	Experimental Performance of Varactor Arrays	D. Parker A.I. Grayzel	IEEE Int'l Microwave Symposium, Boston, 8 May 1967

MS No.			
2043	Varactor Arrays	D. Parker A.I. Grayzel	
2055	High Power High Efficiency Transistor RF Amplifiers	D.M. Snider	NEREM Record (1967)
2098	An Electromagnetic Attitude Control System for a Synchronous Satellite	W.L. Black B. Howland E.A. Vrablik	
2102	Orbit Determination From the Satellite	A. Braga-Illa	
2103	Transmitted Power Maximization in Communication Satellites	A. Braga-Illa D.M. Snider	
2105	The Generation of High Microwave Power Using Arrays of Varactor Diodes	D. Parker A.I. Grayzel	Second AIAA COMSAT Symposium, San Francisco, 8-10 April 1968
2108	Solar Cell Calibration Experiments on the Lincoln Experimental Satellites	F.W. Sarles L.P. Cox E.A. Vrablik	
2109	The Design of Visible Light Sensors for Use at Quasi-Synchronous Altitudes	N.R. Trudeau F.W. Sarles G.H. Ashley B. Howland	
2115	Proposal for High Power Varactor Package	D.D. Tang	IEEE Int'l Solid State Circuit Conference, Philadelphia, February 1968
2123	Automatic Orbital Guidance of Satellites	A. Braga-Illa	Rome Chapter AEI, Rome, Italy, 9 January 1968
2128	High Power Frequency Multipliers Using Varactor Arrays	D. Parker A.I. Grayzel	IEEE Int'l Solid-State Circuits Conference, Univ. of Pennsylvania, 14-16 February 1968

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Technical Notes

TN No.				DDC No.
1965-20	Analysis of Radiation Effects in Telemetry Circuits	A.G. Stanley	21 July 1965	619389
1967-20	Electron Irradiation of P-Channel Junction FETs	A.G. Stanley	13 Apr. 1967	651760

Journal Articles

JA No.			
2532	Effects of Electron Irradiation on Metal-Oxide Semiconductor Transistors	A.G. Stanley	Proc. IEEE (Correspondence) 53, 627 (1965). DDC 621206
2683	Effect of Electron Irradiation on N-Channel MOS Transistors	A.G. Stanley	Proc. IEEE (Correspondence) 53, 2150 (1965), DDC 632152

JA No.			
2696	Electron Threshold Energy for Surface Ionization Effects in Silicon Planar and MOS Transistors	A.G. Stanley	Unpublished
2761	Effects of Electron Irradiation of Metal-Nitride-Semiconductor Insulated Gate Field-Effect Transistors	A.G. Stanley H.A.R. Wegener*	Proc. IEEE (Correspondence) 54, 784 (1966), DDC 640529
2798	A Model for Shifts in the Gate Turn-On Voltage of Insulated-Gate Field-Effect Devices Induced by Ionizing Radiation	A.G. Stanley	IEEE Trans. Electron Devices ED-14, 134 (1967), DDC 654856
2849 (MS-1651)	Comparison of MOS and Metal-Nitride-Semiconductor Insulated Gate Field-Effect Transistors Under Electron Irradiation	A.G. Stanley	IEEE Trans. Nucl. Sci. NS-13, 248 (1967), DDC 652058
2991 (MS-1851)	Effect of Electron Irradiation on Carrier Mobilities in Inversion Layers of Insulated Gate Field Transistors	A.G. Stanley	IEEE Trans. Nucl. Sci. NS-14, No. 6, 266 (1967), DDC 668184
3072 (MS-1957)	Anomalous Interface States and Breakdown Effects Produced by Low Energy Electron Irradiation in MNS Structures	A.G. Stanley H.C. Pao*	Solid-State Device Research Conference, Univ. of California, 19-21 June 1967

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MS No.			
1270	Space Radiation Effects on Low Current Circuits Employing High Gain Silicon Planar Transistors	A.G. Stanley	Unpublished
1505	Radiation Induced Surface Ionization Effects in Silicon Planar and MOS Devices	A.G. Stanley	Silicon Interface Specialists Conference, Las Vegas, 15-16 November 1965
1546	Minimum Electron Energy for Surface Ionization Effects in Silicon Planar and MOS Transistors	A.G. Stanley	Unpublished
1651 (JA-2849)	Comparison of MOS and Metal-Nitride-Semiconductor Insulated Gate Field-Effect Transistors Under Electron Irradiation	A.G. Stanley	IEEE Annual Conference on Nuclear and Space Radiation Effects, Palo Alto, California, 18-22 July 1966
1691	Radiation Effects in Silicon Nitride Insulated Gate Field-Effect Transistors	A.G. Stanley	Symposium on Silicon Nitride, Philadelphia, 9-14 October 1966
1697	Effect of Space Radiation Environment on Micro-Power Circuits Using Bipolar, Junction-Gate and Insulated-Gate Field Effect Transistors	A.G. Stanley	NEREM Record (1966), DDC 649363

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MS No.			
1755	Effect of Electron Irradiation on Insulated Gate and Junction Gate Field Effect Transistors	A.G. Stanley	Symposium on Radiation Effects in Semiconductor Components, Toulouse, France, 7-10 March 1967
1835	Effect of Electron Irradiation on Characteristics of MIS Devices	A.G. Stanley	Silicon Interface Specialists Conference, Las Vegas, 1-3 March 1967
1851 (JA-2991)	Effect of Electron Irradiation on Carrier Mobilities in Inversion Layers of Insulated Gate Field Effect Transistors	A.G. Stanley	IEEE Conference on Nuclear and Space Radiation Effects, Ohio State Univ., 10-14 July 1967

X. ABSTRACTS OF MEETING SPEECHES

MS-1221 D.M. Snider

Design of a High Efficiency 213 mcs
Power Source

A need has been demonstrated for a high efficiency dc to rf power converter. Such a converter has been developed which delivers seven watts at 213 mcs with a dc to rf conversion efficiency of 72 percent. The high degree of performance was achieved by the mode of transistor operation, bias arrangement, device characterization and component and circuit construction. The converter has a 1 db variation in output power from +50°C to −30°C and a 3 db signal bandwidth of 8 percent.

MS-1370 D.D. Tang

X-Band 0° – 180° Binary Phase Modulater
Using Step Recovery Diode

The pico-second abrupt transition property of step recovery diode was utilized in the design of a 0° – 180° binary phase modulator operating at 10 Gc with 1-watt cw input power. The modulating frequency can be varied from 0 to a few hundred megacycles with no performance degradation or the need for retuning. The insertion loss is about 2.0 db, and is independent of modulating frequency or power levels. The modulating frequency can be either a square wave or a sinusoid. The carrier suppression is in the neighborhood of 40 db for both cases. This modulator has the advantage that it enables one to use UHF sinusoidal modulating frequency.

MS-1381 W.L. Black

Some Simple Reliability-Improving
Redundancy Techniques

For certain satellite applications it is impractical to increase the reliability of logic systems by large increases in equipment complexity. None-the-less there are some simple measures that may be taken to improve reliability. Under these conditions, one is interested not in techniques that permit arbitrarily good performance at correspondingly high equipment costs, but rather in techniques that afford some improvement at tolerable equipment cost. In this paper I shall discuss several such schemes and compare them to the canonical majority-vote approach. Exact expressions for the failure probabilities will be derived.

Since with so little redundancy it is impossible to greatly improve basically poor systems, it is of value to consider the behavior of these probability expressions for systems with low initial failure probabilities. I shall show that under these conditions the failure probability of the redundant system has a simple dependence on the failure probabilities of the component subsystems – one that may be easily written down by inspection. In low redundancy systems, the question inevitably arises as to whether the improvement attainable by redundancy is worth the increase in cost, weight, etc. Hence I shall also discuss the decision problem involved in the system design.

MS-1562 W. L. Black
B. Howland
L. J. Travis
E. A. Vrablik

A Magnetic Satellite Spin Axis Orientation System for Use at Near Synchronous Altitudes

This paper describes an orientation system built and flown on Lincoln Laboratory's communication satellite LES-4. The system is designed to erect the satellite spin axis to within 2 or 3° of perpendicularity to the orbital plane of a circular, near synchronous orbit. It does this by taking optical fixes of the Earth at two places in orbit where the Earth is favorably illuminated, and generating an inertially fixed magnetic moment which interacts with the geomagnetic field to create the torque necessary to remove the components of angular momentum in the orbital plane. The system uses electromagnets with Supermendur cores to provide a total of 37 amp-meter^2 of magnetic moment while consuming only 500 milliwatts of D.C. power. The system is self-contained and requires no ground command for operation. LES-4 was launched on 21 December 1965 but failed to reach the circular, near synchronous orbit necessary for operational system evaluation.

MS-1716 J. L. Ryan
V. J. Sferrino

LES-4 Observations of Inner and Outer Zone Electrons Since 21 December 1965

A Silicon Surface Barrier Detector Electron Telescope measuring Integral and Differential Electron Energy Spectra over the range of 130 KEV to 4.5 MEV was placed into orbit on 21 December 1965 on the LES-4 satellite (1965-108B). The initial orbit had an inclination of 26.6°, apogee of 33,600 KM, perigee of 200 KM, and a mean orbital period of 589.6 minutes.

The data from the experiment is presented in terms of single orbit passes on selected days showing outer zone maxima in omnidirectional flux intensity for 130 KEV, 700 KEV, and 2.5 MEV, integral Spectra in the region near L=4, and a minimum near L=3.5 which characterizes the slot between the inner and outer zones. Diurnal variations are characterized by flux changes which show marked correlation with K_p index at L=6. The degree of correlation decreases with decreasing L value. Spectral steepening is seen to occur during periods of increased geomagnetic activity. The diurnal flux changes also exhibit energy vs. time dependencies with the higher energy electron fluxes generally reaching their maximum later in time.

MS-1781 A. I. Grayzel*

Enhancement of Spurious Signals in Frequency Multipliers

Frequency multipliers find many applications in both frequency synthesizers and in stable frequency sources. The multiplication process unfortunately enhances spurious signals that may be present. If one performs many multiplications or a single high order multiplication, large spurious signals may appear in the output.

In this paper the spurii enhancement, i.e., the increase in the ratio of spurious to desired signal power after multiplication, is calculated. First the varactor multiplier of order n is investigated. It is shown that a low level spurious signal (single sideband) will be enhanced by a factor of n. If the spurious signal has two symmetrical sidebands about the desired signal then for the FM case the spurious is enhanced by n^2 while for the AM case it is enhanced by $n^2/2n-1$. This result is shown to be the same whether a single high order multiplication or a cascade of many low order multiplication stages is used. These results are shown to be consistent with the Manley Rowe relationships. The resistive multiplier is also treated and it is shown that the enhancement in a resistive mixer is similar to that for the varactor multiplier.

* Presently at NASA Electronics Research Center, Cambridge, Massachusetts.

MS-1786 D. Parker

Field Theory of a Solid State
Traveling Wave Amplifier

Using a linearized field theory four conditions are derived for a growing surface wave to exist in a semiconductor surrounded by a helical slow wave structure. The carrier drift velocity must be comparable to the velocity of light in the surrounding dielectric whose permittivity must exceed the permittivity of the semiconductor. A cut-off frequency is defined below which the wave is evanescent. For effective gain, a constraint is placed on the thickness of the dielectric separating the semiconductor and the slow wave structure.

MS-1828 A. Braga-Illa

Solar Energy Conversion
Techniques for Communications
Satellites

The solar cell, a device capable of converting solar energy into electrical energy, is the source of power most frequently used in scientific and communications satellites. Since its discovery, the solar cell has become a very well known and reliable component of many satellite systems. In this note the fundamentals of solar power systems are reviewed from several points of view: first, the physical principles on which solar energy converters operate will be discussed briefly; then the behavior of the solar cell when used in space will be summarized, to illustrate the major considerations to be made in designing a satellite power system; finally, this note will examine rapidly some typical power systems and some of the problems encountered in using the energy available from the source with maximum efficiency.

Many of the topics touched upon here are extensively treated in the literature, from which a selected list of references has been extracted. Some of the material presented, especially that relevant to the overall system design and to the stability problem of dc-dc power converters is derived from the author's work at the MIT Lincoln Laboratory.

MS-1888 D. Parker
A.I. Grayzel*

Traveling Wave Varactor Frequency
Multipliers for Increased Power
Handling Capability

A class of frequency multiplier circuit configurations are described which use an arbitrary number, n, of identical varactors to handle n times the power of a single diode at the same efficiency. The varactors are spaced periodically along a transmission line or separated by phase shift networks of appropriate impedance levels so that each diode handles the same input and output power. The necessary phase shift and required impedance level for each network separating the diodes are derived. Three basic circuit configurations are discussed; one where the diodes are effectively in series, one where they are effectively in parallel, and a third where they are in a series-parallel combination. Experimental results of a 500 Mhz to 1 Ghz doubler using stripline for the phase shift networks will be discussed.

MS-1930A A. Braga-Illa

Automatic Geosynchronization
of Artificial Satellites

Many automatic operations performed on satellites require measurements of

a. the orbital period, or the angular velocity relative to the earth,

b. the orbital eccentricity,

c. the position of the orbit major axis,

d. the satellite longitude in a geocentric reference frame.

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* Presently at NASA Electronics Research Center, Cambridge, Massachusetts.

The measurement of the angular velocity relative to the earth is necessary, for instance, in the electronic switching of antennas on a spinning communication satellite. Satellite longitude, orbital eccentricity and major axis location must be measured to control the satellite position or the characteristics of its orbit with closed-loop systems.

When the satellite is in a circular equatorial orbit, angular velocity and longitude measurements are simple and accurate. The technique prevailing in spinning satellites requires optical or infrared sensors which deliver a pulse when their directions of sight are collinear with the sun or earth center. The coincidence in time of the pulses from an earth sensor and a sun sensor whose lines of sight form a known angle, uniquely defines a position in orbit (Fig. 1). The spin axis of the satellite is assumed to be perpendicular to the orbital plane. Using more than one earth sensor establishes several longitude reference points in the orbit. Thus angular velocities can also be measured, by recording the time elapsed between coincidences.

MS-1970 R. W. Brockett

The Controllability and Observability
of Satellites in Near Circular Orbits

Of the new concepts which have come out of modern control theory, certainly the ideas of controllability and observability have been among the most interesting and broadly applicable. However, thus far the majority of "applications" have been in theoretical work where conditions for controllability and observability are used as technical devices which allow one to complete the proofs of some theorems. The object of this talk is to show how these ideas can be used in the preliminary design of control systems. This is accomplished by examining the problem of building a closed-loops control system for keeping a satellite stationary over a fixed point in the earth without ground command. The analysis is based on a linearization about a circular orbit. The effects of constraints which make it possible to observe and control only at certain points in the orbit are of special interest and an analysis of some particular cases will be considered.

MS-2098 W. L. Black
B. Howland
E. A. Vrablik

An Electromagnetic Attitude Control
System for a Synchronous Satellite

This paper describes an attitude control system for a spinning satellite in a synchronous, equatorial orbit. The purpose of the system is to keep the spin axis of the satellite perpendicular to the plane of its orbit. The system has at least three novel aspects. First, it employs a closed control loop that maintains the proper orientation without any intervention from the ground. Second, it uses electromagnets to torque against the weak geomagnetic field at synchronous altitudes. Finally it uses optical earth sensors that operate in the visible spectrum.

The optical sensors detect orientation errors at two selected points in orbit. On the basis of these two measurements the appropriate corrective action is initiated. This consists of generating a magnetic moment, fixed in inertial space, that interacts with the geomagnetic field and produces the desired torque for the rest of the orbit.

In the paper we describe the system in more detail and discuss some of the problems and limitations of this type of erection system.

MS-2102 A. Braga-Illa

Orbit Determination
from the Satellite

The control of satellite orbits has been traditionally achieved by command from the ground. Automatic and self-contained techniques, which require less ground support and are not subject to interference, can be used if the orbital parameters are measured on the spacecraft itself. All the methods which have been proposed up to now are implementations of the classic solutions to the orbit determination problem: the necessary calculations can be performed only by rather complex on-board computers, whose use is not justified in a typical communication satellite.

This paper presents a simple orbit determination procedure, accurate to third order in eccentricity. The instruments necessary for the measurement are a sun or star sensor, an earth sensor and a clock, which together form an orbital goniometer, or angle-finder. This method is based on an expansion of the satellite law of motion in terms of the orbital eccentricity and on the determination of a set of orbit parameters, which differ from the classic and are easily measured and computed. The parameters are of the type $\epsilon^n \cos n\Theta_0$ and $\epsilon^n \sin n\Theta_0$, where ϵ is the orbital eccentricity, Θ_0 the anomaly of the point of measurement and n is an integer. It is shown that these parameters can be obtained as linear combinations of times of flight through known angles in orbit. The computation is particularly simple if the measured angles in the plane of the orbit are $\pi/2n$ in width. The method does not require prior knowledge of the satellite orbital position at the time of measurement: thus the sun can be used as a reference and its motion relative to the orbit taken into account separately, whenever necessary.

This procedure also leads to a simple reconstruction of the law of motion of the satellite in a central force field, which can be updated at each orbit.

The properties of the solution to second order in eccentricity are discussed in some detail because of their important applications to synchronous satellites and of their remarkable simplicity. It is seen that errors in the measurement of the orbital period from times of flight are second order in eccentricity if the measurement angles are opposed with respect to the focus. The same property holds for the measurement of satellite position, or time of transit at a known angle. This fact is particularly important in the automatic geosynchronization, or stationkeeping, of satellites, because it permits to measure the spacecraft position without determining the orbital eccentricity nor accounting for the relative motion of the apsidal line and of the points of measurement.

An Appendix gives formulas for the solar transit time on satellites in general earth orbits, a quantity which must be known to obtain high accuracy when the sun is used as a reference. The formulas include the effect of the earth's orbital eccentricity to second order and are valid for any orientation of the satellite and of its orbital plane.

This paper also briefly reviews the literature on orbital navigation to this day and is completed by a bibliography of 31 references.

MS-2103 A. Braga-Illa
D.M. Snider

Transmitted Power Maximization
in Communication Satellites

A very important performance parameter for communication satellites is the efficiency with which the available d.c. power is transformed into r.f. power and transmitted. When the power plant is a solar cell array, as is usually the case today, the generator characteristics are non-linear and vary as a function of time, mainly because of accumulated radiation damage to the array and satellite orientation changes in time. The traditional technique has been to design the power system with sufficient margin to ensure operation in the worst conditions at the end of the satellite operational life. The penalty for this was the need for larger arrays which resulted in higher power plant costs and greater satellite volume and weight per watt transmitted. Successively, satellites have been flown in which the excess power available at the beginning of life was used to charge storage batteries, which then supplied power to the transmitter during the satellite shadow period.

This paper presents a system which maximizes the r.f. transmitted power by matching the final amplifiers, i.e., the actual useful load, to the solar cell array for most operational conditions. In this way all d.c.-d.c. converters are eliminated, thus making available to the transmitter the power margin plus the power usually lost in the conversion process. The extra d.c. power which can be obtained in this manner is at least 30 per cent and can be as high as 50 per cent of the d.c. power delivered with the conventional technique. Since batteries are not required, a major contribution to system unreliability is eliminated, whenever the penalty of interrupting operation during the satellite shadow periods can be tolerated.

This method requires that a) the locus of solar array peak power points during normal operation throughout the satellite life be determined, and b) the E-I characteristics of the amplifiers, when paralleled to the other fixed and housekeeping loads, follow this locus. While the first part is relatively simple, UHF transmitters operating with high efficiency and with prescribed input d.c. characteristic over a wide voltage range had not been realized up to now.

The input d.c. E-I characteristics of a tuned r.f. transmitter can be matched to the time varying output d.c. E-I characteristics of a solar cell array by controlling the conduction angle of the output amplifier. The necessary conditions to achieve this purpose efficiently are that a) the output terminals be appropriately loaded at the fundamental and harmonically related frequencies and b) the initial input r.f. drive be increased beyond that value which corresponds to conventional "Class B" operation. The latter situation is referred to as the over-driven mode of operation.

A computer program has been written to calculate the effect of decreased conduction angle and over-drive on the input d.c. characteristics, effective gain, collector efficiency and overall stage efficiency of an amplifier initially designed for tuned Class B operation. The results of this program reveal that the d.c. input power demand of a transmitter whose output stage has been initially over-driven by 1 db can be reduced by 2 db with a resulting decrease in overall d.c. to r.f. conversion efficiency of only 15 per cent and a decrease in output power of about 2 db. In this way, a net increase in transmitter output power ranging from at least 20 per cent to 50 per cent is possible.

In order to show the advantages of this method, the paper describes a transmitter which was built according to this theory operating at 250 mc with a maximum output power of 115 watts and an overall d.c. to r.f. conversion efficiency of 69 per cent and an end of life output power of 65 watts and 55 per cent efficiency.

MS-2105 D. Parker
A.I. Grayzel*

The Generation of High Microwave Power Using Arrays of Varactor Diodes

Solid-state frequency multipliers are limited by the power handling capability of a single varactor diode. This paper will discuss methods for using an arbitrary number, n, of similar varactors in an array such that each varactor handles the same power and the total power handling capability of the array is n times that of a single diode. The efficiency of multipliers using these arrays is essentially the same as that for a single diode although in those arrays where the diodes are essentially in series and the impedance level increased the efficiency of the multiplier has been increased. Methods to prevent spurious oscillations in large arrays will also be discussed.

The varactors in an array are separated by networks with appropriate characteristic impedances and phase shifts such that the power divides equally between the diodes and that output powers add in phase at the load. The most simple and useful arrays are those where the varactors are separated by transmission lines which are a half wave length long at the input frequency. A diplexer is connected at one end of the array to isolate the input and output frequencies. It is expected that this technique will play a significant role in future all solid-state satellites because it permits high power generation while distributing the sources of heat.

Experimental results for frequency doubler and frequency tripler circuits using arrays of varactors separated by half wavelength lines will be presented. A frequency doubler from .9 GHz to 1.8 GHz using both series and series-parallel arrays have been built. Two different types of diodes have been used in these circuits. For example, two Type II diodes in series have given double the power of a single diode at the same efficiency of 85%. Up to four Type I diodes in series have been used to give 78% efficiency compared to 65% efficiency for a single diode. Eight Type I diodes in a series-parallel array which had the same impedance level as two Type I diodes in series has operated at the same efficiency as for two diodes in series. The power handling capability was limited by the power available from the source.

A sixteen diode array is being designed which will handle from 140 to 200 watts depending upon the particular diodes used. A doubler circuit from .9 GHz to 1.8 GHz using this array should be about 70 to 80% efficient. The same array will also be used in a frequency tripler with an output frequency of 2.7 GHz. Experimental results for this high power array should be available by the time of the meeting.

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* Presently at NASA Electronics Research Center, Cambridge, Massachusetts.

MS-2108 F.W. Sarles
L.P. Cox
E.A. Vrablik

Solar Cell Calibration Experiments
on the Lincoln Experimental Satellites

As part of a continuing effort on component test and evaluation on the Lincoln Experimental Satellite program, two solar cell calibration experiments have been flown on LES-4 and LES-5. The LES-4 experiment consists of five temperature monitored one-cm by two-cm cells of the following types and with the measurements indicated:

1. n on p Si with a 0.030" antireflectance coated cover slide. Open circuit voltage measured.
2. n on p Si with a 0.030" antireflectance coated cover slide. Short circuit current measured.
3. n on p Si with a 0.006" antireflectance coated cover slide. Short circuit current and current through a 6.2 ohm load measured.
4. Experimental thin film CdTE cell. Short circuit current and current through a 24 ohm load measured.
5. Experimental thin film CdTE cell. Short circuit current and current through a 24 ohm load measured.

The LES-5 experiment is identical with that on LES-4 excepting that cells 4 and 5 are CdS thin film cells.

Both satellites were designed to be launched into a near synchronous equatorial orbit. However, a launch malfunction left LES-4 substantially misaligned from its intended orientation in a highly elliptic transfer orbit in which its attitude control system could not function. As a result, accurate AM0 measurements near normal solar incidence could not be made during the initial orbits. Extrapolations from later measurements indicate that the initial cell output currents at AM0 were approximately 1.07 greater than the prelaunch measurements at AM1.

Since it was felt that the results of the LES-4 experiment might be suspect because of the launch difficulties, the experiment was repeated on LES-5. The same anomalous ratio of AM0 to AM1 cell outputs was noted.

The instrumentation for this experiment is relatively simple, involving several switched operational amplifiers read out by the satellite telemetry system. Because the data sampling is controlled by the telemetry system, this sampling is asynchronous with respect to the satellite rotation. Hence a computer program is being setup to reduce this data. From this, accurate curves of output versus mode on incidence are available and plots of solar cell degradation during the life of the satellite will be made.

AM1 calibration of the solar cells was performed by a solar panel manufacturer using a silicon n on p cell which had been calibrated at Table Mountain. Calibration of the instrumentation and telemetry system were done at Lincoln Laboratory. Assumption of the extremes of all known possible errors still does not allow the AM1/AM0 ratio of 1.17 which is usually assumed in the literature.

MS-2109 N.R. Trudeau
F.W. Sarles
G.H. Ashley
B. Howland

The Design of Visible Light Sensors
for Use at Quasi-Synchronous Altitudes

Numerous satellite control systems such as earth directed antenna systems, attitude control systems and orbital control systems require appropriate detection of the earth and the sun for control information. Sun sensors for these applications are normally designed using photovoltaic devices, because of the high intensity of solar radiation available. The earth, however, has usually been detected with infrared detectors because of the relatively uniform disk appearance of the earth at suitably chosen infrared wavelengths.

Because infrared detectors with satisfactory signal-to-noise ratios were not available in the times required during the initial phases of the Lincoln Experimental Satellite Program, development of sensors utilizing the "visible" portion of the optical spectrum was undertaken. Simple rugged detectors, e.g., silicon photovoltaic cells having responses from 0.4 to 1.0 micron, are readily available. Such detectors are relatively inexpensive and quite small, as well as having excellent signal-to-noise ratio in a properly designed earth sensor.

The price to be paid for this choice of detector is that the earth no longer appears constantly disk shaped but instead goes through various crescent phases. However, the fundamental problem is the same as with the infrared detector, i.e., the center of the earth must be determined from measurements of the edge of the earth. Moreover, this higher signal-to-noise ratio and faster response of photovoltaic devices allow a greater flexibility of sensor design over that permitted by presently available infrared detectors.

Two fundamental sensor fields of view have been used in all earth sensors on the LES Program: a so-called "pencil beam" generated by a photodetector at the focal point of a spherical mirror or lens and a "fan beam" generated by a photodetector located at one of the focal points of a toroidal mirror. Appropriate combinations of these fields of view with a single sensor and combinations of sensors are used to solve the earth detecting problems presented by various control situations.

Except for the very first sensors used on LES-1, all sensors on the LES Program employ reflective optics. Refractive optics are very susceptible to lens darkening, proton erosion and micrometeorite impingement. By using small entrance apertures with reflective optics, such problems are greatly reduced.

This paper will discuss solutions to various earth sensing problems and the limitations encountered in the various sensor designs. In particular, problems caused by the sun and the moon will be discussed, and some practical solutions to such problems will be presented. Operating data from the LES satellites will be given. An additional sensor to be presented is an "optical clock" which is designed to generate a fixed pulse train for each rotation of the satellite. This sensor is basically a simple array of slit optics which interrupts the sunlight as the satellite spins. On LES-4 and LES-5 this sensor provides 128 pulses for satellite rotation; a second design has been built for 256 pulses per rotation but has not yet been flown.

MS-2115 D.D. Tang

Proposal for High Power Varactor Package

The present diode packages were designed for electrical performance only, and no consideration has been given for efficient heat dissipation. These packages were adequate because there was no real heat dissipation problem until recently. A new package concept is proposed here which will satisfy both the requirements of better electrical performance and efficient heat dissipation for use with multi-chip stacked varactor package. This is achieved by separating the electrical path and the heat path. This results in smaller parasitics and at least an order of magnitude higher heat dissipation capability than existing packages.

MS-2123 A. Braga-Illa

Automatic Orbital Guidance of Satellites

This seminar is a review of published literature on the subject of automatic satellite navigation, with an emphasis on the problem of orbit determination from the satellite. Orbit determination from minimum observations made on board the spacecraft is discussed. The application of Kalman's filtering theory to the space navigation problem is presented, following studies by R.H. Battin. As an example of automatic guidance, the problem of geosynchronization of satellites is briefly described: the librations of synchronous equatorial satellites in the earth's gravity field are discussed on the basis of the data obtained through the Syncom satellites and of theoretical considerations.

MS-2128 D. Parker
A.I. Grayzel*

High Power Frequency Multipliers
Using Varactor Arrays

Experimental results will be given for a high power frequency doubler (0.9 to 1.8 GHz) which uses up to sixteen varactors in an array. New techniques for heat sinking the diodes and methods for eliminating all instabilities will be described. Data will be given demonstrating the stability of these arrays.

XI. AUTHOR INDEX

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This report comprises a bibliography of papers that pertain to Lincoln Laboratory's satellite communications program. More significantly, the purpose of this report is to provide a coherent program guide indicating the direction of this work and the accomplishments to date.

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