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October 1973

TIME, SPACE, POSITION, INFORMATION (TSPI) STUDY

Calspan Corporation

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Rome Air Development Center
Air Force Systems Command
Griffiss Air Force Base, New York

TIME, SPACE, POSITION, INFORMATION (TSPI) STUDY

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et al

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FOREWORD

This is the final report on a study conducted by Calspan Corporation (formerly Cornell Aeronautical Laboratory, Inc.), Buffalo, New York, under Contract No. F30602-72-C-0528, Job Order No. 11670002. This study was sponsored by Rome Air Development Center (RADC) of the Air Force Systems Command, Griffiss Air Force Base, New York. The study was under the direction of IRAQ. Technical consultation during the study was provided by Mr. R. Raposo and Sgt. W. Ziesenitz of IRAQ, Griffiss Air Force Base, New York.

The Calspan Project Engineer for the study effort reported herein is Mr. Thomas Mellenger of the Systems Research Department. The following personnel provided major technical and documentary contributions to this report in the areas indicated:

D. J. Newton	Measurement Techniques
T. Reiman	System Evaluation
W. P. Jenney, C. Dziuba	Computer Requirements
D. Meagher	Display Technology
H. G. Reif	System Costs
C. Wolf	Data Rate Requirements

Mr. George Sargis and the Technical Services Department assisted in the publication of this report with graphic art work and reproduction services.

The work described was performed during the period of July 1972 through January 1973. The draft was submitted by Calspan on 1 March 1973. It has been assigned Calspan Report No. TD-5187-D-1.

The data presented is intended to provide recommendations for ranging systems to track multiple vehicles in a realistic threat environment.

This report has been reviewed and is approved.

APPROVED: William Ziesenitz

WILLIAM ZIESENITZ, Sgt, USAF
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ABSTRACT

This study was performed to identify tracking techniques and systems that could be used to track multiple targets in a realistic threat environment. The work performed provided technical support to IRAQ for analysis and evaluation of tracking systems and techniques for a Continental Operating Range (COR).

The tracking requirements for the COR are twofold. The near term (or initial system) requirements (1-5 years) are for tracking 16 aircraft within a 75 n.mi. diameter circle. The far term (or future system) requirements (5-10 years) are for tracking 60 aircraft and 40 ground vehicles within a 200 n.mi. diameter circle. The study was to provide guidelines of techniques that would satisfy near term requirements as well as having long term growth potential for satisfying the far term requirements.

The study included the investigation of measurement techniques, navigation systems, range measurement systems, range displays and computer requirements. Major emphasis was given to the analysis of hardware developed ranging systems that could, with modifications, satisfy the Air Force's near term tracking requirements. The two systems which will most likely satisfy the near term requirements are Cubic Corporation's Air Combat Maneuvering Range (ACMR) and General Dynamic's Range Measurement System/Data Collection System (RMS-2/DCS).

Appendix C (Secret) of this report, prepared for RADC and published separately, will discuss ALSS technology and its relationship to TSPI requirements.

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SECTION I

INTRODUCTION

1.1 BACKGROUND

There has been a great deal of interest in the development of ranges for evaluating aircraft performance for a variety of missions. These include air-to-air combat, bomb scoring, threat penetration tactics, defensive maneuvers, and ECM evaluation. In order to perform the evaluation, accurate tracking data is required for the participating aircraft at a centrally located reporting station. The tracking data consists of position information (X,Y,Z), attitude information (yaw, pitch, roll) and velocity information (speed, direction). Each mission has its own tracking accuracy and data requirements which must be correlated with other range functions.

Calspan's role in the TSPI study has been to identify techniques and systems that can satisfy the tracking requirements as defined in the Statement of Work. The requirements are such that they should satisfy a variety of missions that could be conducted on the range. The study does not integrate or provide recommendations for integrating the tracking data with the other range functions, although it is realized that successful range operation depends on the correlation of all range data.

1.2 STUDY OBJECTIVES AND SCOPE

The overall objective of the TSPI study is to perform for the USAF a study of the various techniques of performing multiple target tracking in a realistic threat environment. Since a near term and far term set of requirements are defined, the study shall provide guidelines to indicate what technique(s) provide long term growth potential as well as meeting initial USAF requirements. The near term system, for the next one to five years, must be capable of tracking 16 aircraft within a 75 n.mi. diameter circle and the far term system, for the next five to ten years, must be capable of tracking 60 aircraft and 40 ground vehicles within a 200 n.mi. diameter circle.

Since the objectives did not define any specific techniques, the study evaluated navigation systems, proposed and hardware developed ranging systems, and general measurement techniques.

1.3 STATEMENT OF WORK REQUIREMENTS

1.3.1 Range Member Performance Parameters

A near term and far term set of performance parameters is defined. The near term system must be capable of tracking aircraft with velocities of 100 to 2000 feet per second, accelerations of -2.5 to +8.5 g's, roll rates of up to 360 degrees per second, altitudes of 2000 to 50,000 feet above ground level and for all aircraft attitudes. The far term system must be capable of tracking aircraft with velocities of 0 to 4000 feet per second, accelerations of -2.5 to +8.5 g's, roll rates of up to 360 degrees per second, altitudes of

200 to 80,000 feet above ground level and for all aircraft attitudes. In addition, the far term system must be capable of tracking ground vehicles with velocities of 0 to 100 feet per second, accelerations of -1 to +1 g's, and zero altitude for line of sight.

1.3.2 Member Tracking and Data Rate Requirements

The near term system must be capable of tracking 16 aircraft within a 75 n.mi. diameter circle and the far term system must be capable of tracking 60 aircraft and 40 ground vehicles within a 200 n.mi. diameter circle. The following general tracking and data rate requirements are common to both systems. The position accuracy in X, Y, and Z must be within a 150 foot spherical error probable (SEP) relative to a fixed ground station. The system must be capable of resolving aircraft separated by 200 feet or more, providing attitude data (yaw, pitch, roll) within $\pm 2°$ and velocity vector within $\pm 3°$ and 10 knots. The position, attitude, and velocity data must be updated at a rate of 0.1 second.

In addition to the general requirements defined above, each system has a unique set of specific requirements. The near and far term system must be capable of selecting four aircraft that are within a 25 n.mi. radius of the center of the range and tracking them with a position accuracy in X, Y, and Z of 20 feet SEP and be able to resolve members to within 40 feet SEP. The attitude and velocity vector accuracy is the same as the general requirements. All the data on the four aircraft must be updated at a rate of 0.02 seconds.

For the far term system, higher accuracy and data rate requirements are defined with respect to selectable geographic locations. Within a 5 n.mi. radius of up to and including 20 operator selectable locations within the range, the required position accuracy in X, Y, and Z is 5 feet SEP. The attitude and velocity vector accuracy is the same as the general requirements. All the data on the vehicles (possibly all 100 participating members) must be updated at a rate of 0.01 second.

1.3.3 Study Requirements

The study is to evaluate tracking techniques and then identify those techniques that satisfy near term requirements as well as having growth potential for satisfying the far term requirements. A brief technical description of each technique studied is to be provided which describes limitations, capabilities, high risk areas, and problem areas. Cost estimates for one, two, and three of the suitable candidate systems are to be provided. In addition, existing systems capable of tracking multiple targets are to be identified.

1.3.4 Technical Requirements

The technical requirements are to study and investigate the general techniques of radar tracking, interferometry, multilateration, and any other suitable precision locating systems. Included in the multilateration study are the various schemes for ranging and reporting. These include time frequency ranging, time phase ranging, phase lock loop ranging, pseudo noise ranging, time of arrival, hybrid inertial, time ordered reporting, and selective reporting. These technical requirements are to be investigated with respect to satisfying the range member performance parameters and member tracking and data rate requirements.

1.3.5 Operating Conditions

The system must be able to operate day and night and in all types of weather. The all weather criteria is restricted to aircraft flying weather. It must be compatible with U.S. air traffic control and be able to operate in a radar and jamming environment, although no jamming will be directed at the TSPI system.

1.3.6 System Requirements

The TSPI system must be transportable. Transportability means that the system must be able to be moved on location either by ground vehicles or helicopters. Once located, the system will most likely remain in place, but it still must be able to be relocated if necessary.

No modifications are allowed to the aircraft except the installation of pods. The pods should be mountable on standard aircraft racks and not adversely impair aircraft performance. Electrical power for pod cperation and aircraft event data may be tapped off.

The system must interface with high-speed data processing and display equipment. Although the system is self-contained in that it has its own computers and displays, it must be compatible with the other range systems so that TSPI data can easily be integrated with other range event data.

The system must provide automatic self-survey of range elements within one hour of installation. The initial installation of any system will require weeks to set up. The intent of this requirement is that after the system is operational, it must be ready for daily use within one hour after being turned on.

The system must provide two-dimensional displays for range targets and major events and also provide growth capability for three-dimensional displays. The near term system will have two-dimensional displays. The growth provision is for the far term system which may initially have two-dimensional displays but must have the capability of incorporating three-dimensional displays if required.

1.4 STUDY APPROACH

The approach taken for this study was to define five major tasks that would satisfy the Statement of Work technical requirements. The following major tasks were defined:

- Navigation Systems
- Contractor Proposed and Developed Systems
- Measurement Techniques

- Data Handling, Storage, and Retrieval
- Displays

As part of the study, a review of the currently operational, navigation systems was made. LORAN, DECCA, OMEGA, TACAN, and INS are some of the systems that were reviewed and evaluated. The review provided a data base for the study and also indicated the capabilities of these navigation systems. These systems may not satisfy Air Force requirements, but possibly combinations of systems with modifications may meet the near and far term requirements.

In recent years there has been considerable interest in TSPI systems by the Armed Services. As a result, industry has developed new TSPI systems. These systems, which either exist or are documented, were evaluated. A questionnaire was prepared and sent to contractors to obtain information on their systems. The contractors were also asked to send documentation on their systems along with an invitation to visit Calspan to discuss the operation of their systems.

Each system employs some type of measurement technique to obtain position data. The purpose of this task was to evaluate general measurement techniques. The techniques evaluated were radar tracking, interferometry, and multilateration.

Digital computers will be used for data handling, storage, and retrieval. This task investigated and defined the data processing requirements.

The display task provided a summary of techniques and technologies, briefly analyzed display requirements, and investigated an existing display system. Conclusions and recommendations to satisfy near and far term Air Force requirements were also made.

Technical guidance and direction was received throughout the study from RADC. The broad scope of the study required inputs from the technical monitor in the areas of systems analyzed and depth of analysis, computing techniques analyzed, and specific display requirements.

1.5 SUMMARY

This section provides the summary, conclusions, and recommendations of the TSPI study. The Statement of Work requirements were used as a guideline for system evaluation. The selection of candidate systems was based on satisfying the near term system requirements with possible growth potential for the far term system.

In addition to the evaluation and selection of candidate systems, the study investigated measurement techniques, computer requirements, and display technology as related to TSPI requirements. The results of these investigations are contained in the report while a brief summary is provided in this section.

1.5.1 Statement of Work

The statement of work required the investigation of various techniques for tracking multiple targets and providing guidelines of techniques that will provide long term growth potential as well as meeting initial AF requirements. The various techniques include radar tracking, interferometry, and multilateration. In addition, real time data processing and two dimensional displays are required with growth capability to include three dimensional situation displays.

The important requirements used for system evaluation are multiple target tracking capability, central location reporting capability, and agreement with accuracy and data rates. For the near term, the TSPI system must be able to track 16 aircraft within a 75 nmi diameter circle. Position accuracy ranges from 150 ft SEP on all 16 aircraft down to 20 ft SEP on four aircraft within 25 nmi or range center. Position updates range from 10 times per second on all 16 aircraft up to 50 times per second on four aircraft within 25 nmi of range center. For the far term, the TSPI system must be able to track 60 aircraft and 40 ground vehicles within a 200 nmi diameter. Position accuracy ranges from 150 ft SEP down to 5 ft SEP on all vehicles. The 5 ft SEP requirement is only for 20 selected range locations. Position updates range from 10 times per second to 100 times per second. For both systems velocity and attitude are required at the current update rates.

Other system requirements are transportability, no aircraft modifications except pods, all weather day and night operation, and compatability with threat radar, jamming and air traffic control frequencies.

1.5.2 Measurement Techniques

This task investigated radar tracking, interferometry and multilateration with respect to satisfying TSPI requirements.

1.5.2.1 Radar Tracking

The use of a single scanning pulsed radar, located in the center of the range was evaluated. The advantage of a single radar is that all equipment is located at a central site. The minimum scan rates needed to satisfy the update intervals of 0.1, 0.02, and 0.01 seconds are 600, 3000, and 6000 rpm. These scan rates require phased array techniques. The minimum azimuth beamwidths needed are 10.4 and 47.7 degrees for the 0.1 and 0.01 second update intervals. However, with these required beamwidths the angular position resolution is greater than the gross accuracy requirement of 150 ft SEP.

1.5.2.2 Interferometry

An interferometer radar system with a minimum of two antennas spaced a distance D apart was evaluated. Measurements of angle are made by using interferometric principles. To obtain the required resolution an antenna spacing of 4000 λ is required which is approximately 360 ft at I band or 100 ft at L band.

An interferometric radar required to measure elevation and azimuth angles can be configured with a horizontal and vertical leg or with two horizontal legs. However, due to geometrical dilution of precision, a vertical-horizontal configuration is required. The vertical requirement along with an antenna spacing of 360 ft at I band would create vertical mechanical stability problems and if an antenna height of 100 ft were used at L band then sufficient power would not be available at this frequency to satisfy S/N requirements.

1.5.2.3 Multilateration

Trilateration and multilateration systems were evaluated. Neither system can satisfy the Z accuracy requirements for all geometries due to geometrical dilution of precision with an assumed six foot range accuracy measurement.

A seven station multilateration system, with six stations equally spaced on a circumference of a circle and one at the center was analyzed. The standard deviation of a multilateration system is reduced by a factor of the square root of the number of combinations which for a seven station system is $\sqrt{35}$. This reduction is not sufficient to satisfy the altitude accuracy requirements of the initial system.

1.5.2.4 Conclusions and Recommendations

From the analyses performed, it is concluded that a single track-while-scan radar, interferometric radar or a trilateration radar system will not meet the requirements of the initial system (or future system). A seven station multilateration system can meet the x, y position coordinate accuracy but cannot meet the required altitude accuracy of the initial system. It is recommended that a multilateration system be used, with an aided system (inertial or altimeter) to improve the altitude accuracy.

1.5.3 Computer Requirements

The computational requirements of TSPI systems represent a substantial problem area that can seriously impact overall performance. Conventional approaches to the design of computer systems are illustrated by ACMR, yielding a large, expensive system that would be very difficult to expand, although it meets the near-term TSPI requirements. This approach was compared to that of a "network" of several minicomputers interconnected such that all can compute in parallel. For "compute-bound" applications whose structure allows "partitioning" of the total task into smaller parallel tasks (such as TSPI and most other applications), the minicomputer network was found to have substantial advantages of cost, expandability, size and maintainability.

Whatever the nature of the computer system elected for TSPI, other COR functions requiring computer support will benefit greatly from the use of the same model or family of models of computer hardware. By avoiding a proliferation of manufacturers and models of computers servicing COR, the problems of interfacing hardware, maintenance and software compatibility will be greatly reduced, resulting in substantial benefits of cost, operational versatility and maintainability. A survey of the computational requirements of other COR functions should be completed in time for the selection of computers for development of the first COR application.

1.5.4 Display Technology

The purpose of the display task was to explore the problem of displaying information derived from TSPI systems and to identify present solutions and investigate potential solutions available for future use.

1.5.4.1 Human Factors

Since displays are one of the methods of transfering range data to operating personnel, the human factors aspects that should be considered are discussed. These include brightness, color, motion, blinking, angular and depth perception, size, shape, quantities, and orientation. These visual factors are discussed in terms of their available and useful limits with respect to operator perception.

1.5.4.2 Available Technology

A survey of off-the-shelf and new technologies was made. The off-the-shelf technology included discrete indicators, CRTs, and direct view storage tubes while the new technologies included plasma panels, liquid crystals,lasers, light emitting diodes and films, and solid state devices. A description of each device is provided along with typical applications.

1.5.4.3 Large Screen Displays

Descriptions of several methods for large screen displays, currently in use, are provided. These include CRT projection, film projection, photochromatic, oil film, deformable plastic tapes, lasers, and arrays. Along with a description, the advantages and disadvantages of each type are discussed.

1.5.4.4 3-D Displays

Methods for displaying true three dimensional images are described. These include the volumetric or cubic method, flat stereo pair, and holography. In addition, pseudo 3-D, as can be implemented on CRT displays is discussed. Pseudo 3-D techniques should be adequate for TSPI applications.

1.5.4.5 Conclusions and Recommendations

The display studies to date have identified several areas that warrant further consideration and have produced several conclusions. Because of the complexity of the data to be presented, the many uses that the system may have and the requirements of interfacing with a number of range functions, the TSPI displays must be of the general purpose, programmable type, providing a highly flexible and expandable display system. To make maximum use of these programmable displays, both powerful and versatile high-level languages should be used in their display processors. Special hardware functions, such as display rotation or data selection, should be considered to complement the programming functions. The state of the art of plasma displays has progressed to the point that they offer a serious contender to standard CRT displays for the TSPI system, and a tradeoff should be performed between these two techniques. It is important to consider all of the functions of the Continental Operating Range when determining the technical requirements to be imposed on the TSPI display system. Thus, the displays should be designed with requirements of range operations, range safety, training and debriefing fully considered. Because of the interaction of the display system with other parts of the range, as well as other parts of the TSPI system, the display formats and requirements must be determined early in the design of the complete system.

1.5.5 Navigation Systems

1.5.5.1 Systems Analyzed

DECCA, OMEGA, LORAN, LORAN/Inertial, TACAN and TRANSIT were evaluated with respect to satisfying the TSPI requirements. All of these systems are user oriented and do not have a central location reporting capability - a prime requirement for a TSPI system. All of the systems are passive with the exception of TACAN which requires the user to transmit pulses.

DECCA, OMEGA, and LORAN are hyperbolic position systems. The user determines position from the intersection of two known hyperbolic lines. These lines are determined by measuring the range difference between the user and land-based stations, properly spaced and normally operated in groups of three. The LORAN/Inertial system is a hybrid configuration which combines the long term accuracy of LORAN with the short term accuracy of an inertial measuring unit. The overall system is inherently more accurate than either system used independently.

TACAN is a line-of-sight system with ground-based stations from which users obtain range and bearing. The user must transmit an RF signal to the TACAN stations to obtain a range measurement. Bearing is obtained by phase measurement.

TRANSIT is a space-borne navigation system which uses satellites as reference stations. The user measures the doppler frequency of the satellite and translates this into hyperbolic lines of position on the surface of the earth.

1.5.5.2 LORAN/Inertial

Of all the navigation systems evaluated, the LORAN/Inertial comes the closest to satisfying the near term requirements. However, the following modifications and analysis are needed:

- Range Member Identification
- Range member reports of positions, attitude, velocity and discrete events
- Range member reception of digital data
- Centrally located master station
- Pod with LORAN/Inertial system and transponder
- Determination if Z axis position data available
- Determination of position accuracy for subset
- Estimation of size, weight, cost ard transportability

1.5.5.3 Conclusions and Recommendations

None of the above systems have a central location reporting or display capability and in general user oriented systems are not suitable for COR. With the exception of LORAN/Inertial the systems generally do not meet the accuracy and data rate requirements. Also, the LORAN/Inertial is the only system that measures attitude and velocity.

1.5.6. Contractor Systems

1.5.6.1 Single Target Trackers

Of the contractors contacted by Calspan, three responded with data on systems of their own manufacture which are capable of tracking only a single target. All of these systems except the Sylvania Precision Automated Tracking System (PATS) are radar systems. The Sylvania equipment uses laser ranging and tracking techniques.

These systems may be useful in a COR application for particular tracking tasks but the cost and technological problems inherent in attempting simultaneous operation of, say, sixteen colocated units (as would be required for the near term system) for general range instrumentation are sufficiently forbidding to remove such a scheme from further consideration.

Significant characteristics of the single target tracking systems are shown in Table I.

1.5.6.2 Multiple Target Trackers

Five of the responding contractors have systems for tracking multiple aircraft.

Singer Company - Inertial Tactical Navigation System (ITNS)
International Business Machines - Task 4
Raytheon Company - Air Force Weapons Effectiveness Testing-Weapons Effectiveness System Test Environment (AFWET-WESTE)
General Dynamics - Multiple Target Tracking and Identification System (MTTIS)
Radio Corporation of America - Phased Array Radar Trilateration System (PARTS)

Of these five, three systems have operating hardware in various stages of development. The remaining two are in the conceptual stage. The significant characteristics of these systems together with comments regarding their suitability to the TSPI task are presented in Table II. A more detailed discussion of the reasons why none of these systems were considered to be candidates for the COR can be found in Section 6.3 of this report.

Table I Comparative Specifications of Single Target Trackers

SINGLE TARGET TRACKERS	RANGE SIZE-RADIUS (nmi)	ACCURACY-RANGE (ft)	ACCURACY-ANGULAR (mils)	POSITON UPDATE RATE (Hz)	RESOLUTION RANGE (ft)	RESOLUTION AZIMUTH (°)	OPERATE 24 hours/day	COMPATIBLE WITH USATC	TRANSPORTABLE	SETUP TIME	CHECK-OUT TIME	COST @	AIRCRAFT MODIFICATION REQUIRED	SYSTEM DISPLAYS	DISPLAY TYPE	DATA PROCESSING COMPUTER
RCA AN/TPQ-27	300	CLASSIFIED	CLASSIFIED	250	6	1	YES	YES	YES	30 min	10 min	$1.25M	NONE	YES	NS	AN/ UYK-7
RCA AN/MPS-36	32,000	3	0.15	640	375	NS	YES	YES	YES	8 h 4 MEN	8 h	$2.1M	NONE	YES	"A" SCOPE CCTV	DDP-124
RCA AN/FPS-105	32,000	15	0.35	640	375	NS	YES	YES	NO	N/A	N/A	$1.6M	NONE	YES	"A" SCOPE CCTV	NOVA 800
RCA DIGITAL INSTRUMENTATION RADAR	125	15	0.5	640	750	NS	YES	YES	YES	2 MEN 1 h	1/2-1 h	$500K	NONE	YES	A-N CRT	NOVA 800
TASKER-MAIR	240	15	0.25	320 640 1280	105	1	YES	YES	YES	8 h 2 MEN	2 h	$700K	NONE	YES	TWO DUAL-TRACE CRT's	TASKER DIGITAL EQUIPMENT
SYLVANIA-PATS	16.5	30	0.3**	100	NS	NS	YES*	YES	YES	1 h	NS		RETRO-RELECTOR	YES	A-N DIGITAL	SYLVANIA DIGITAL EQUIPMENT

* ONLY WITH VISIBILITY CONDITIONS GREATER THAN 10 nmi AND NO PRECIPITATION

** AT MAXIMUM RANGE

NA: NOT APPLICABLE

NS: NOT SPECIFIED

Table II Characteristics of Contractor Systems for Multiple Target Tracking

SYSTEM	STATUS	RANGE DIAMETER (nmi)	NUMBER OF RANGE AIRCRAFT	POSITION UPDATE RATE (Hz)	1-σ POSITION ACCURACY X, Y, Z (ft)	RESOLVABLE AIRCRAFT SEPARATION (ft)	AIRCRAFT ATTITUDE DATA	COMPATIBLE WITH USATC	ALL-WEATHER OPERATION	AIRCRAFT MODIFICATIONS REQUIRED	REMARKS
SINGER-ITNS	HARDWARE DEVELOPED	300	16	12-AIRCRAFT-10 4-AIRCRAFT-50	50	75	YES	YES	YES	YES	1, 2, 3
IBM-TASK 4	HARDWARE DEVELOPED	80	7	10	20	NS	NO	YES	YES	NO	4, 5
RAYTHEON-AFWET-WESTE	OPERATIONAL	100	15	10	400	50	YES	YES	YES	YES	6, 7
GENERAL DYNAMICS MTTIS	CONCEPT	60	16	10	50	0.5	YES	YES	YES	NO	8, 9, 10
RCA PARTS	CONCEPT	75	200	50-AIRCRAFT-50	1.7, 1.7, 43	1000	NO	YES	YES	NO	11, 12, 13, 14

NS: NOT SPECIFIED

REMARKS

1. OTHER NUMBERS OF VEHICLES AND UPDATE RATES ARE POSSIBLE
2. POSITION ACCURACY DOES NOT INCLUDE GDOP AND MULTIPATH ERRORS
3. AIRBORNE EQUIPMENT NOT POD MOUNTABLE; MUST BE CARRIED ONBOARD
4. POSITION ACCURACY GIVEN IS FOR X AND Y ONLY; Z ACCURACY NOT SPECIFIED
5. TRANSPONDER IS POD MOUNTED BUT NO INERTIAL MEASURING UNIT IS INCORPORATED
6. POSITION ACCURACY GIVEN IS FOR DECCA EQUIPMENT, (X AND Y ONLY); Z ACCURACY NOT SPECIFIED
7. AIRCRAFT'S INSTRUMENTS USED TO SENSE INERTIAL DATA; DEDICATED RANGE AIRCRAFT REQUIRED
8. POSITION ACCURACY BASED ON INTERFEROMETER MEASUREMENTS OVER SMOOTH TERRAIN
9. IMU AND TRANSPONDER POD MOUNTED; NO AIRCRAFT MODIFICATIONS REQUIRED
10. GENERAL DYNAMICS DOES NOT RECOMMEND MTTIS FOR TSPI BECAUSE OF MULTIPATH ERRORS EXPERIENCED BY CW SYSTEMS
11. RANGE SHAPE IS PARALLELOGRAM, NOT CIRCLE
12. UNIQUE IDENTIFICATION OF AIRCRAFT IS DIFFICULT IN BEACON MODE, IMPOSSIBLE IN SKIN TRACK MODE
13. POSITION ACCURACY INCLUDES GDOP BUT NOT LOW-ELEVATION MULTIPATH ERRORS
14. SEPARATE DATA LINK WOULD BE REQUIRED FOR IMU AND DIGITAL DATA TRANSMISSION

1.5.6.3 Candidate Systems

1.5.6.3.1 Air Combat Maneuvering Range (ACMR) Cubic Corporation

1.5.6.3.1.1 Description

The Cubic Corporation ACMR is a continuous-wave tracking system for location and identification of cooperative aircraft. By simultaneously obtaining multiple ranges from a network of ground reference stations to the aircraft of interest it is possible to perform a multilateration computation and solve for the time-space position of the aircraft.

Side tone ranging techniques enable the system to unambiguously determine range within 1 ft to a maximum range of 173 n.mi. Line-of-sight and signal-to-noise ratio limitations on the system performance determine the maximum usable range size.

An inertial measuring unit (IMU) is mounted in an AIM-9D pod carried by member aircraft and senses the accelerations and angular attitude rates of the aircraft. This data is processed in the pod to obtain the Euler parameters, velocities and accelerations of the aircraft. The resulting information is downlinked to the ground and incorporated into range safety and aircraft position computations. The hybrid position computation algorithm provides greater overall accuracy than either the ranging or inertial measurement schemes can provide separately.

Aircraft position, attitude and safety related parameter values are displayed to ground personnel in near real time to enable control and analysis of the mission.

1.5.6.3.1.2 Analysis of Ranging Technique

The ACMR system used continuous wave phase measurement techniques to determine range to member aircraft. The results of an analysis of the errors typical of equipment using this ranging technique are presented in Table III.

1.5.6.3.1.3 Computer Requirements

The ACMR system uses Xerox Sigma 3 and Sigma 5 computers for data handling and processing. The system has a real-time data and display capability for tracking multiple aircraft and provides estimates of aircraft position, velocity, acceleration and attitude. Data is also recorded to allow post flight analysis.

1.5.6.3.1.4 Estimated Costs

The cost for an ACMR system for the near term requirements is approximately 6.3 million dollars. Included in this estimate is test equipment, spares, data and initial setup.

Table III Summary of Range Errors - CW/DME System

		$\sigma_R^2 (ft)^2$	CONDITIONS
(1)	PROPAGATION	1.4	R = 20 nmi.
(2)	SIGNAL TO NOISE	8.3	$(SNR)_L$ = 35 dB $B_L = B_{iopt}$
(3)	RANGE OSCILLATOR OR VOLTAGE-CONTROLLED OSCILLATOR INSTABILITY	8.3	$B_L = B_{iopt}$
(4)	INSTRUMENT ERROR	3.0	ASSUMED
(5)	AIRBORNE TRANSPONDER ERROR	3.0	ASSUMED
(6)	MULTIPATH	21.0	B = 20
(7)	QUANTIZATION	0.1	Δ = 1 ft
(8)	DATA PROCESSING	2.0	ASSUMED
	TOTAL	47.1	σ_R = 6.9 ft

It should be noted that the Cubic Corporation system employs a deviation ratio (B) of 10 rather than 20 as assumed in the example above. Since the maximum multipath error is inversely proportional to deviation ratio the actual total range accuracy (σ_R) for ACMR would be 10.6 ft under the same conditions assumed for the example in Table III.

1.5.6.3.2 Range Measuring System - Data Collection System (RMS-2/DCS) General Dynamics

1.5.6.3.2.1 Description

The RMS-2/DCS system used leading edge pulse-type ranging techniques to obtain slant range information, in sequence, from a number of ground reference stations to a range member (cooperative) aircraft. Using these multiple slant range values it is possible to compute aircraft position in accordance with a multilateration algorithm.

The range member transponder can be mounted onboard an aircraft or carried by personnel or vehicles in the field. At present no inertial measuring equipment has been incorporated into the system, however, a pod containing the transponder and an IMU is being designed by G-D and is expected to be flight tested by the first quarter of 1973.

General Dynamics is also developing software to obtain real-time data analysis capability.

Work is being done in the area of incorporating range situation and alphanumeric displays into the RMS-2/DCS system, and G-D has developed a large screen projection-type interactive display.

1.5.6.3.2.2 Analysis of Ranging Technique

The leading edge ranging technique as used by the General Dynamics RMS-2/DCS system can be expected to achieve ranging accuracy on the order of that computed for the example in Table IV. Leading edge ranging has an inherent advantage over the CW-DME technique in that errors due to multipath can be gated out.

Table IV Summary of Range Errors - Leading Edge System

		$\sigma_R^2\ (ft)^2$	CONDITIONS
(1)	PROPAGATION	1.4	R = 20 nmi
(2)	SIGNAL TO NOISE	1.1	S/N = 20 dB
(3)	RANGE OSCILLATOR OR VOLTAGE-CONTROLLED OSCILLATOR INSTABILITY	1.6	R = 20 nmi
(4)	THRESHOLD LEVEL INSTABILITY	20.0	$V_T/V_T = \pm 1$ dB
(5)	INSTRUMENT ERROR	3.0	ASSUMED
(6)	AIRBORNE TRANSPONDER ERROR	3.0	ASSUMED
(7)	MULTIPATH	0	ASSUMED GATED OUT FOR LEADING EDGE
(8)	QUANTIZATION	0.1	Δ = 1 ft
(9)	DATA PROCESSING	2.0	ASSUMED
	TOTAL	32.2	σ_R = 5.7 ft

1.5.6.3.2.3 Computer Requirements

The RMS-2/DCS system uses a Varian 620/F computer for data handling and processing. The system is nonreal time and has the capability of providing estimates of position on aircraft, troops and ground vehicles. The range and event data are recorded in real time on magnetic tape for post data processing, analysis and display.

1.5.6.3.2.4 Estimated Costs

The cost for an RMS-2/DCS system for the near term requirements excluding displays, is approximately 5.5 million dollars. Included in this estimate is test equipment, spares, data and initial setup. If displays similar to the ACMR system are used then the initial cost would be approximately 6.4 million dollars.

1.5.6.4 Comparison of ACMR and RMS-2/DCS for the Near Term COR System

Tables V and VI compare the principal specifications of the Cubic and General Dynamics systems in the areas relating to their suitability as COR near-term systems. Since the RMS-2/DCS is only a data collection system at present, remarks on these tables reflect the capability of this system as General Dynamics proposes to configure it for the near-term COR requirements. Sections 1.5.6.3 and 7.2 of this report contain additional information defining the present state of development of the RMS-2/DCS system. General Dynamics estimates that development of software and hardware required for the COR near-term application should be completed late in 1973.

Cubic Corporation forsees only a limited amount of software development being required to adapt the ACMR system to the COR.

1.5.6.5 Potential of the ACMR and RMS-2/DCS to be Expanded to the Far Term COR Requirements

Several areas of performance need to be improved to enable either the Cubic or G-D system to meet the far term COR requirements. Tables VII and VIII list these problem areas and provide a brief description of possible solutions and comments regarding implementation of these proposed solutions. Additional information regarding these problems can be found in Sections 7.1.4.2 and 7.2.4.2 for the ACMR and RMS-2/DCS systems respectively.

1.5.6.6 Conclusions and Recommendations

1.5.6.6.1 Conclusions

1. Leading edge ranging (RMS-2/DCS) is superior to CW-DME (ACMR) in area of multipath performance.

2. Cubic ACMR has the advantage in hardware and software development.

3. Cubic Corporation has real time data processing and display capability. G-D is working to acquire this capabilitiy in 1973.

Table V Comparison of ACMR and RMS-2/DCS Specifications for Near-Term COR System

PARAMETER	CUBIC CORPORATION ACMR	GENERAL DYNAMICS RMS-2/DCS	REMARKS
NUMBER OF AIRCRAFT	*16	*16	*OTHER SCHEMES POSSIBLE BUT SYSTEM SOFTWARE IS DESIGNED FOR 16 AIRCRAFT
RANGE DIAMETER (nmi)	*75	**88	*POSITION ACCURACY BASED ON NEAR-TERM REQUIRED RANGE SIZE. **LIMITED BY S/N RATIO AND GEOGRAPHY
POSITION ACCURACY: X, Y, Z (ft)	+* $<10, <10, >500$	** 6, 6, 48	+EXTRAPOLATED Z ACCURACY *SIMULATION DATA – NO IMU **COMBAT-HUNTER DATA
POSITION UPDATE RATE (Hz)	* 20 4 AIRCRAFT 0.83 12 AIRCRAFT	* 4 4 AIRCRAFT 1 12 AIRCRAFT	*FULL-TIME SUBSET CONFIGURATION
MINIMUM RESOLVABLE AIRCRAFT SEPARATION (ft)	* <200	* <200	*AIRCRAFT DISCRETELY ADDRESSABLE; NO AMBIGUITY
IMU DATA AVAILABLE	YES	*YES	*GD EXPECTS BY FIRST QUARTER 1973
ANGULAR POSITION ACCURACY (°)	± 2	* ± 2	*GD WILL USE SAME LSI IMU PACKAGE AS ACMR
VELOCITY ACCURACY (knots, °)	NS	NS	
AIRCRAFT VELOCITY: 100 TO 2000 ft/s	YES	YES	
AIRCRAFT ACCELERATION: -2.5 TO +8.5 G	YES	YES	
AIRCRAFT ROLL RATES: 360°/s	YES	YES	
AIRCRAFT ALTITUDE: 2000- TO 50,000-ft AGL	*YES	*YES	*AT LOW ALTITUDES, POSITION ACCURACY IS DEGRADED
ALL AIRCRAFT ATTITUDES	*YES	*YES	*POD ANTENNA SHADOWED BY AIRCRAFT IN SOME ATTITUDES
SUBSET OF 4 AT HIGHER DATA RATE	YES	YES	
SUBSET AREA DIAMETER (nmi)	50	50	
UPDATE RATE OF SUBSET AIRCRAFT POSITION (Hz)	20	4	
UPDATE RATE OF SUBSET AIRCRAFT ATTITUDE (Hz)	20	10	

NS: NOT SPECIFIED

Table VI Comparison of ACMR and RMS-2/DCS Specifications for Near-Term COR System

PARAMETER	CUBIC CORPORATION ACMR	GENERAL DYNAMICS RMS-2/DCS	REMARKS
SUBSET POSITION ACCURACY: X, Y, Z (ft)	*+<10, <10, ≈190	**6, 6, 48	*SIMULATION DATA: NO IMU +EXTRAPOLATED Z-ACCURACY **COMBAT HUNTER DATA
RELATIVE POSITION ACCURACY (ft)	NS	NS	
AIRCRAFT MODIFICATIONS REQUIRED	NO	NO	
INTERFERE WITH THREAT FREQUENCIES	NO	NO	
COMPATIBLE WITH USATC	YES	YES	
INTERFACE WITH DATA-PROCESSING EQUIPMENT	YES	YES	
DIGITAL DISCRETE EVENT DATA CAPABILITY	YES	YES	
UP-LINK MESSAGE SIZE (bits)	*112	**42	*USED FOR IMU CORRECTION **SEPARATE INTERROGATION REQUIRED FOR DISCRETE EVENT DATA
DOWN-LINK MESSAGE SIZE (bits)	71	*42	*SEPARATE INTERROGATION REQUIRED FOR DISCRETE EVENT DATA
AUTOMATIC SELF-SURVEY CAPABILITY	YES	YES	
2-D DISPLAY CAPABILITY (REAL-TIME)	YES	*YES	*GD EXPECTS DURING 1973. HAVE POST-REAL-TIME DISPLAYS NOW
ALL-WEATHER OPERATION	*YES	*YES	*ANY WEATHER IN WHICH RANGE AIRCRAFT CAN FLY
TRANSPORTABLE	YES	YES	

NS: NOT SPECIFIED

Table VII Problem Areas Encountered when Applying RMS-2/DCS System to Far-Term COR Requirements

PROBLEM AREA	POSSIBLE SOLUTION	COMMENTS
RANGE SIZE	(1) INCREASE ANTENNA HEIGHT AND OUTPUT POWER OF GROUND REFERENCE NETWORK TRANSMITTERS	LONGER LINE-OF-SIGHT DISTANCES BETWEEN STATIONS WILL BE POSSIBLE
	(2) MULTIPLE COLLOCATED SUBSYSTEMS	ONE CARRIER FREQUENCY REQUIRED
NUMBER OF RANGE MEMBERS	(1) REDUCE POSITION UPDATE RATE	SYSTEM WILL NOT MEET DATA RATE SPECIFICATIONS.
	(2) INCREASE SYSTEM DATA RATE BY CONVERTING TO SIMULTANEOUS RANGING	LARGER NUMBER OF VEHICLES COULD BE TRACKED WITH THE SAME POSITION UPDATE RATE. (GD IS CONSIDERING THIS SCHEME)
	(3) COLLOCATING MULTIPLE SYSTEMS	MULTIPLE CARRIER FREQUENCIES REQURIED
AIRCRAFT OPERATING ALTITUDES (GDOP ERRORS AT LOW ALTITUDE)	OPTIMIZATION OF GROUND REFERENCE STATION PLACEMENT FOR SPECIFIC EXERCISES	ADDITIONAL SURVEYED TRANSPONDER LOCATIONS REQUIRED
AIRCRAFT MAXIMUM VELOCITY (POD COOLING AT 4000 ft/s)	SHORT TIME OF OPERATION AT 4000 ft/s	NOT A SERIOUS SHORTCOMING CONSIDERING TYPICAL RANGE ACTIVITIES
SUBSET POSITION ACCURACY (Z-AXIS ACCURACY $>$5 ft)	SOME IMPROVEMENT WILL BE POSSIBLE WITH HYBRID-INERTIAL SYSTEM	ACCURACY DATA IN THIS REPORT DOES NOT REFLECT THE IMPROVEMENT POSSIBLE USING IMU DATA
POSITION UPDATE RATES	DATA RATE CAN BE INCREASED BY CONVERTING TO SIMULTANEOUS RANGING	GD IS CONSIDERING THIS SCHEME TO INCREASE DATA RATE. APPROXIMATELY A FOURFOLD INCREASE IN RANGING SPEED IS POSSIBLE. SPECTRUM REQUIREMENTS WILL INCREASE, SINCE DISCRETE B-C LINK PATHS ARE SIMULTANEOUSLY REQUIRED

Table VIII Problem Areas Encountered when Applying ACMR System to Far-Term COR Requirements

PROBLEM AREA	POSSIBLE SOLUTION	COMMENTS
RANGE SIZE	(1) MULTIPLE COLLOCATED SYSTEMS (2) RELAY TRANSPONDERS	LARGE RF SPECTRUM REQUIREMENTS EXPENSIVE REDUCED SYSTEM DATA RATE
NUMBER OF RANGE MEMBERS	(1) REDUCE POSITION UPDATE RATE (2) MULTIPLE COLLOCATED SYSTEMS	SYSTEM WILL NOT MEET DATA RATE SPECIFICATIONS LARGE RF SPECTRUM REQUIREMENTS EXPENSIVE CANNOT BE USED ECONOMICALLY TO SOLVE RANGE SIZE AND/OR NUMBER OF RANGE MEMBERS
CANNOT TRACK GROUND MEMBERS	CUBIC CORPORATION UNABLE TO FORESEE APPLYING ACMR TO GROUND ELEMENTS	MULTIPATH ERRORS PROBABLY PRECLUDE USING CW SYSTEM FOR GROUND ELEMENTS
AIRCRAFT OPERATING ALTITUDES (MULTIPATH ERRORS AT LOW ALTITUDE)	OPTIMIZATION OF ANTENNA HEIGHT	LIMITED EFFECTIVENESS, SINCE ERRORS NOT EASILY PREDICTED
AIRCRAFT MAXIMUM VELOCITY (POD COOLING AT 4000 ft/s)	SHORT TIME OF OPERATION AT 4000 ft/s	NOT A SERIOUS SHORTCOMING CONSIDERING TYPICAL RANGE ACTIVITIES
SUBSET POSITION ACCURACY (Z-AXIS ACCURACY $>$ 5 ft)	SOME IMPROVEMENT WILL BE POSSIBLE WITH HYBRID INERTIAL SYSTEM	ACCURACY DATA IN THIS REPORT DO NOT REFLECT THE IMPROVEMENT POSSIBLE USING IMU DATA
POSITION UPDATE RATES	SOME INCREASE POSSIBLE, IF PHASE-LOCK-LOOP LOCKUP TIME CAN BE REDUCED	COMPUTER CAPACITY ALSO A PROBLEM AT HIGH POSITION UPDATE RATES

4. Cubic Corporation has a operational pod-mounted transponder with IMU and preprocessor. G-D is pod-mounting their transponder and the LSI IMU and preprocessor with an estimated flight test scheduled for the first quarter of 1973.

5. The RMS-2/DCS can presently track ground vehicles. Cubic Corporation feels ACMR cannot be applied to track ground elements.

1.5.6.6.2 Recommendations

1. A study of position accuracy vs. update rate should be conducted to establish the accuracies and data rate requirements.

2. A study of the magnitude of improvement in position accuracy possible when using a hybrid-inertial computational algorithm should be done.

3. Examine the possibility of using faster update rates only for those parameters of the position and attitude computation which are varying rapidly. Some economy of data transmission capability may be realized by not updating all parameters every interrogation.

4. Investigate multiprocessor computer systems for tracking, filtering, and data reduction. Studies indicate that multiple small computers can substantially increase the throughputs for TSPI calculations, while significantly reducing the dollar investment in hardware.

5. Examine the use of a single display system or a single family of displays. The advantage of commonality in hardware procurement, maintenance, and software development could be substantial in a large application such as COR.

6. Perform an analysis (computer aided) of the siting of the measurement and relay stations of the multilateration system and the aircraft maneuvers involved so that an accurate assessment of the system can be obtained.

SECTION II

MEASUREMENT TECHNIQUES

The purpose of this task was to satisfy the technical requirements defined in the Statement of Work which required a study and investigation of the general techniques of radar tracking, interferometry, and multilateration. Each of these techniques was analyzed with respect to the range member performance parameters and member tracking and data rate requirements. The main emphasis was placed on satisfying the near term system requirements with consideration given to the far term system requirements if the technique appeared suitable.

2.1 RADAR PARAMETERS REQUIRED TO SATISFY PERFORMANCE OBJECTIVES

2.1.1 Introduction

A system configuration to satisfy the technical requirements and a mandatory one for study is a single, scanning, pulsed radar located in the center of the range. The advantage inherent to this configuration is that all the required equipment can be located at a central site.

2.1.2 Target Information Requirements

Three distinct position information rates that must be satisfied are:

(1) Provide position information on at least sixteen (16) cooperative aircraft within a 75 n.mi. diameter circle not less than every 0.1 seconds (an initial system requirement).

(2) Provide position information on any four (4) selectable aircraft within 25 n.mi. of the center of the range at least every 0.02 seconds (an initial system requirement).

(3) Provide position information at 20 selectable positions within a 100 n.mi. radius at a rate of 100 positions/sec on each selected member (a future system requirement). This is equivalent to an information update time of 0.01 seconds.

The future system must retain the capability of the initial system.

2.1.3 Minimum Radar Scanning Requirements

To satisfy the above data rate conditions, the following minimum scanning rates (RPM) are required for a single antenna scanning radar.

Condition	Min. Information Update Time (sec)	Min. Scanning Rate (RPM)
1	0.10	600
2	0.02	3000
3	0.01	6000

These scanning rates preclude the use of a mechanically driven antenna system and point toward utilizing inertialess scanners or phased array techniques. To obtain 360 degree coverage with a single, centrally located antenna system, an electronically scanned ring array can be used to satisfy the scanning and azimuth coverage requirements. Recent developments (Reference 1) in step scanned circular array antenna by researchers at the Naval Electronics Laboratory, San Diego, have established the feasibility of this antenna technique. Other configurations to obtain the required azimuth coverage utilizing linear arrays can be envisioned; such as three linear arrays arranged in an equilateral triangle, or four arrays arranged in a square. However, a major disadvantage of the linear array is that the beam-width is a function of the scan angle and the frequency being transmitted, whereas the beam pointing angle in a circular array is independent of frequency and scan angle.

2.1.4 Minimum Time on Target/Minimum Azimuth Beamwidth

In any pulsed radar system operating with a cooperative target, the antenna must remain on the target to accommodate:

(1) the transmission time from the radar to the target and return;
(2) the delay through the airborne transponder;
(3) the processing time to identify the target and data.

A comparison of the specified parameters and the resultant azimuth antenna beamwidth are shown in Table IX.

Table IX A Comparison of the Specified Parameters and the Resultant Azimuth Antenna Beamwidth

	Initial System	Future System
Range (max)	37.5 n.mi.	100 n.mi.
Propagation time	450 μsec	1200 μsec
Assumed transponder delay	100 μsec	100 μsec
Max. no. of aircraft	16	60*
Max. no. of identification pulses	5	7
Assumed code length	20 μsec	25 μsec
Min. total time on target	570 μsec	1325 μsec
Min. position update time	0.02 sec	0.01 sec
No. of azimuth elements	35	7
Min. azimuth beamwidth	10.4 degrees	47.7 degrees

As can be seen from the table, to extend the initial system into the future system, which has an increased data rate, longer range and more targets, a larger azimuth beamwidth is required because of the longer minimum time on target and higher position information rate.

* It is assumed that the ground vehicles will be handled by a separate system.

2.1.5 Position Information Accuracy

The technical requirements specify that aircraft position be accurate to 150 feet (spherical probable error). This implies that the error coordinate be equal, i.e.:

$$1.54\,\sigma_R = 150 \text{ feet}$$

$$1.54\,R\sigma_\phi = 150 \text{ feet}$$

$$1.54\,R\sigma_\theta = 150 \text{ feet}$$

where σ_R , σ_ϕ , σ_θ are the standard deviation in the measurement of range, elevation and azimuth angle. From these considerations and using the fact that state-of-the-art, Track While Scan (TWS) radars can resolve angular position to about one-fiftieth of a beamwidth, the following comparisons can be made:

	Initial System	Future System
Range (n.mi.)	37.5	100
θ (degrees)	10.4	47.7
σ_θ required (rad)	0.39×10^{-3}	0.083×10^{-3}
σ_θ possible (rad)	3.62×10^{-3}	16.6×10^{-3}

2.1.6 Conclusions

(1) A single, centrally located, inertialess scanning antenna radar system does not appear to be an acceptable technique to satisfy the technical requirements.

(2) The high position information rate, coupled with the need to provide 360° coverage, dictates the size of beamwidth and hence the angular accuracy that can be obtained.

2.2 PARAMETERS REQUIRED TO SATISFY PERFORMANCE OBJECTIVES USING RADAR INTERFEROMETRY

2.2.1 Introduction

In Section 2.1, it was shown by simple calculations that a single centrally located scanning radar would not be an acceptable technique to satisfy the technical requirements. Satisfying the position update rates and still maintaining 360° azimuth coverage will require large beamwidths that could not be consistent with the angular accuracy that is required. The question arises: "Can more than one radar in an interferometer configuration satisfy the angular accuracy requirements?" It is assumed that a dedicated radar to each individual target is not an acceptable solution. Also, subdividing the azimuth coverage into many sectors and assigning a radar to cover an individual sector is a least desirable solution because of the problems involved in transferring data from one radar to another as the target moves from sector to sector.

2.2.2 Angular Accuracy Requirements

The following performance conditions specified in the technical requirements relate to the required angular accuracy.

(1) Provide position information on all members relative to a fixed ground position accurate to 150 feet spherical error probable (SEP = 1.54 σ).

(2) Resolve targets separated by more than 200 feet.

(3) Provide position information accurate to 20 feet (SEP) within 25 n.mi. radius from the center of the range.

(4) Provide relative position between aircraft accurate to 40 feet within 25 n.mi. radius from the center of the range.

(5) Provide position data accurate to 5 feet (SEP) within a 5 n.mi. radius of selected coordinates (a future system requirement).

The future system must retain the capability of the initial system. An attempt to tabularize the various requirements listed above in order to determine the angular accuracy that must be provided is given below.

	Range (n.mi.)	Position Accuracy (SEP - feet)	Resolution (feet)
Initial System	25	20	40
	37.5	150	200
Future System	100	5	200
	100	150	200

To satisfy the above conditions (1) to (4), the following standard deviations (σ) in the measurement of angle for position accuracy and the following beamwidth (α) for resolution are required.

Condition	System	Standard Deviation (σ) or Beamwidth (α)
(1)	Initial	$1.54\,\sigma(\theta) = \frac{150}{R} = \frac{150 \times 10^{3}}{37.5 \times 6} = 0.66 \times 10^{-3}$ radians
(1)	Future	$1.54\,\sigma(\theta) = \frac{150}{R} = \frac{150 \times 10^{-3}}{100 \times 6} = 0.26 \times 10^{-3}$ radians
(2)	Initial	$\alpha = \frac{200}{R} = \frac{200 \times 10^{-3}}{37.5 \times 6} = 0.88 \times 10^{-3}$ radians
(2)	Future	$\alpha = \frac{200}{R} = \frac{200 \times 10^{-3}}{100 \times 6} = 0.33 \times 10^{-3}$ radians

Condition	System	Standard Deviation (σ) or Beamwidth (α)	
(3)	Initial	$1.54\ \sigma(\theta) = \frac{20}{R} = \frac{20 \times 10^{-3}}{25 \times 6} = 0.13 \times 10^{-3}$	radians
(3)	Future	$1.54\ \sigma(\theta) = \frac{20}{R} = \frac{20 \times 10^{-3}}{25 \times 6} = 0.13 \times 10^{-3}$	radians
(4)	Initial	$\alpha = \frac{40}{R} = \frac{40 \times 10^{-3}}{25 \times 6} = 0.26 \times 10^{-3}$	radians
(4)	Future	$\alpha = \frac{40}{R} = \frac{40 \times 10^{-3}}{25 \times 6} = 0.26 \times 10^{-3}$	radians

Condition (5) above could be interpreted that a position accuracy of 5 feet is required at the maximum range of the future system (100 n.mi.) or that the position accuracy of 5 feet is required at 5 n.mi. from the selected coordinates. In the latter case the measurement equipment is moved to the selected coordinates and the measurements made. The standard deviations necessary to satisfy condition (5) for both interpretations are listed below:

Condition	System	Standard Deviation (σ)
(5)	Future R = 5 n.mi.	$1.54\ \sigma(\theta) = \frac{5}{R} = \frac{5}{5 \times 6000} = 0.16 \times 10^{-3}$
(5)*	Future R = 100 n.mi.	$1.54\ \sigma(\theta) = \frac{5}{R} = \frac{5}{100 \times 6000} = 8 \times 10^{-6}$

2.2.3 Interferometer Radar

An interferometer radar is a system that is configured with two or more antennas spaced a distance D apart and measurements of angle made by using interferometric principles. From examining conditions (1) through (5), it can be seen that, to obtain the required resolution, a beamwidth α of less than 0.26×10^{-3} radians is required. To obtain this beamwidth, which is inversely proportional to the width of the interferometer, the following relationship must be satisfied:

$$\theta_I = \lambda / D$$

or $D \geq 4000\lambda$, for θ_I to be less than 0.26×10^{-3} radians.

One of the primary difficulties with an interferometric radar is that there are ambiguities in angle which must be resolved. Walters (Reference 2) has analyzed an amplitude comparison monopulse - Interferometer System, which is shown in block diagram form in Figure 1. The operation of the system is simple in that the output of amplitude comparison monopulse portion (output of difference amplifier) is quantized to the number of lobes present in the interferometer and represents a coarse angular measurement,

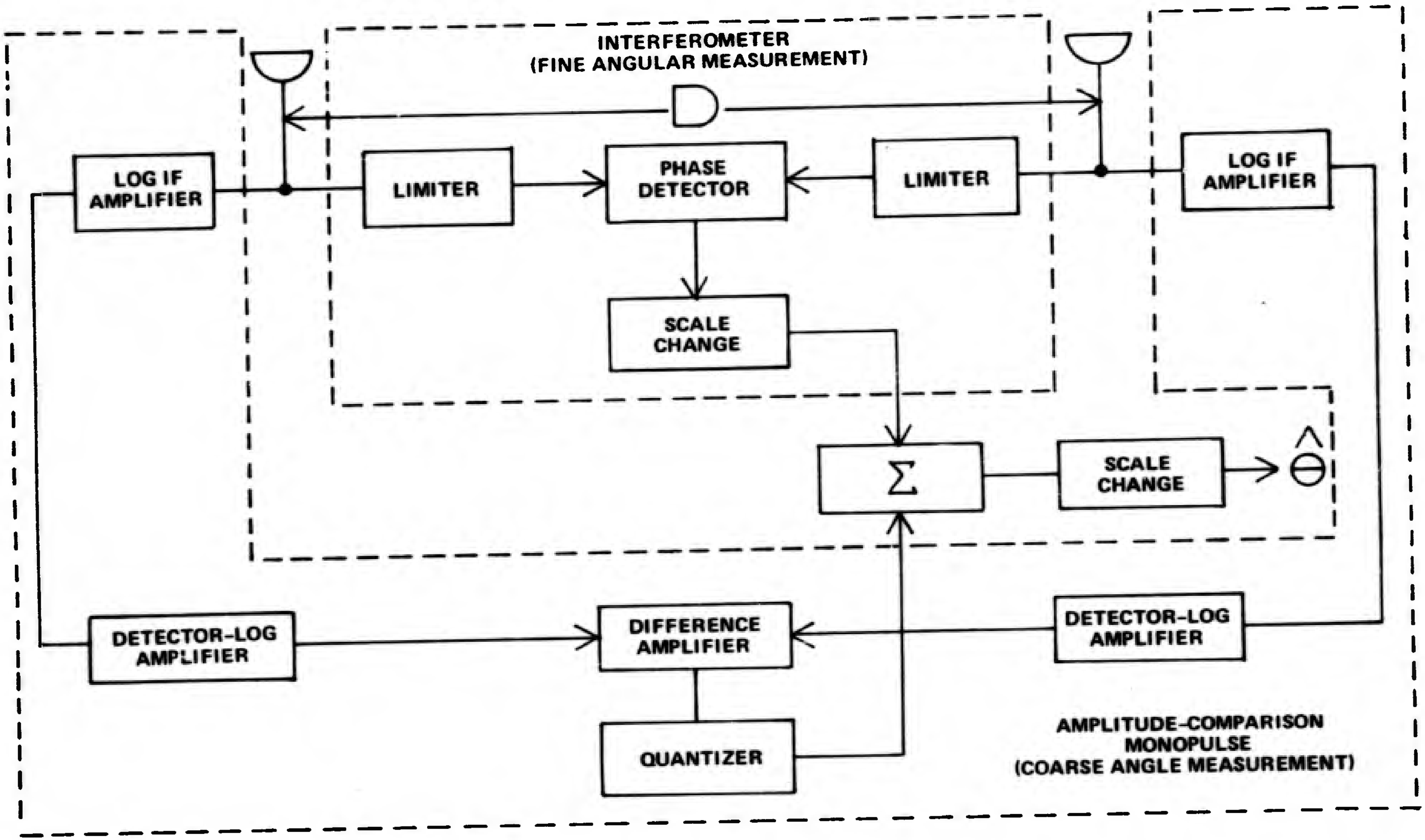


Figure 1. Amplitude-Comparison Monopulse Interferometer System

while the fine grain measurements are made using the interferometer angular measurement. By using the interferometer output, it should be possible to satisfy condition (5)*, if sufficient signal to noise is present. The signal to noise required, for measurement of angle in the azimuth and elevation direction if a vertical interferometer is used, is:

$$\frac{S}{N} = \frac{\lambda^2}{\pi^2 D^2} \cdot \frac{1}{\sigma^2(\theta)} \doteq 100$$

As discussed in Reference 2, the amplitude measurement monopulse measurement must be accurate to within a lobe width of the interferometer. For large S/N ($\geq$ 14 dB) the probability, P, that the angular measurement made using the amplitude comparison monopulse system is within the lobe width is given (Reference 2) as:

$$P = erf\left\{\frac{S}{N} \cdot \frac{\sigma_M(\theta)}{\theta_B} \cdot \frac{16\pi \ln 2}{\sqrt{17}}\right\}$$

for a target at a maximum angle from boresight. Solving this equation for S/N we have:

$$\frac{S}{N} = 0.118 \frac{\theta_B}{\sigma_M(\theta)} \cdot erf^{-1}(P)$$

Choosing a high probability P (say, 0.98) that the standard deviation in the measurement of off boresight angle will be less than the lobe width of the interferometer, reduces the above expression to:

$$\frac{S}{N} = 0.195 \frac{\theta_B}{\sigma_M}$$

since erf^{-1} (0.98) = 1.65. A sum pattern beamwidth θ_B of 45 degrees is required to satisfy the maximum position update rate at a reduced maximum range of 100 n.mi. The standard deviation in the measurement of the off boresight angle must be less than the lobe width of the interferometer, hence $\sigma_M(\theta) \leq 0.26 \times 10^{-3}$ radians. Substituting these conditions into the above expression yields:

$$\frac{S}{N} \geq 27.8 \text{ dB}$$

The S/N ratio required to make the angular measurement is high, but considering that a cooperative transponder is to be used, it can be obtainable.

2.2.4 Geometrical Dilution of Precision (GDOP)

An interferometric radar which is required to measure elevation and azimuth angles can be configured with a horizontal and vertical leg or with two horizontal legs. If the interferometer is configured with only horizontal legs, the measurement of elevation angle will be degraded by the so-called Geometrical Dilution of Precision (GDOP). This is due to the fact that the effective baseline D' varies as the sine of the elevation angle θ_E, i.e., $D' = D \sin \theta_E$.

2.2.5 Conclusions

1. Azimuth and elevation angular measurements will require two orthogonal pair (4 antennas) to be utilized.

2. Signal to noise ratios required to obtain the specified accuracies are high, but obtainable with cooperative transponders operating at X-band or at a lower frequency.

3. Possible interferometric radar configurations that can be used are shown in Figures 2 and 3. If a vertical leg is used to avoid the GDOP effect and if tower heights are restricted to some reasonable heights (for example, 100 feet), then the frequency of operation must be greater than 60 GHz for an antenna spacing of 60 feet. At this frequency, it is not practical to provide the power necessary for the high signal to noise ratios required.

4. If the frequency of operation is restricted to X-band or a lower frequency, a spacing, D, between antennas of 360 feet would be required. This would result in a vertical tower height (H) of approximately 400 feet which presents mechanical stability problems.

5. A configuration using only horizontal legs will be degraded by the GDOP effect. Hence, either the spacings or the signal to noise ratio would have to be increased. To measure an elevation angle of six degrees, the baseline D would have to be extended to 40,000 λ or the signal to noise ratio increased to 40 dB. This high value of S/N becomes impractical to obtain and maintain. Measurement of elevation angles below six degrees becomes impractical.

6. An interferometric radar, although possible, will be limited in its use. Since range data are inherently more accurate than angular data at ranges beyond a few miles, systems based upon range only measurements (trilateration, multilateration) will be investigated in Section 2.3.

2.3 ANALYSIS OF A TRILATERATION AND MULTILATERATION POSITION MEASURING SYSTEM FOR THE TSPI STUDY

2.3.1 Introduction

A radar trilateration configuration is shown in Figure 4. The target is assumed to be at coordinates (x_o , y_o , z_o), Radar A at coordinates (0,0,0), Radar B at (x_B , y_B , 0) and Radar C at (x_C , y_C , 0). The distance R_{AB} , R_{BC} and R_{CA} are known to an accuracy σ_{R_S} . Ranges R_{OA} , R_{OB} and R_{OC} are measured to an accuracy σ_{R_A} , σ_{R_B} , and σ_{R_C} . These accuracies are a function of the signal-to-noise ratio, atmospheric propagation, multipath, the transmitted spectrum, errors in cooperative target, quantization, and the range measurement technique used (i.e., CW-FM pulse, etc.).

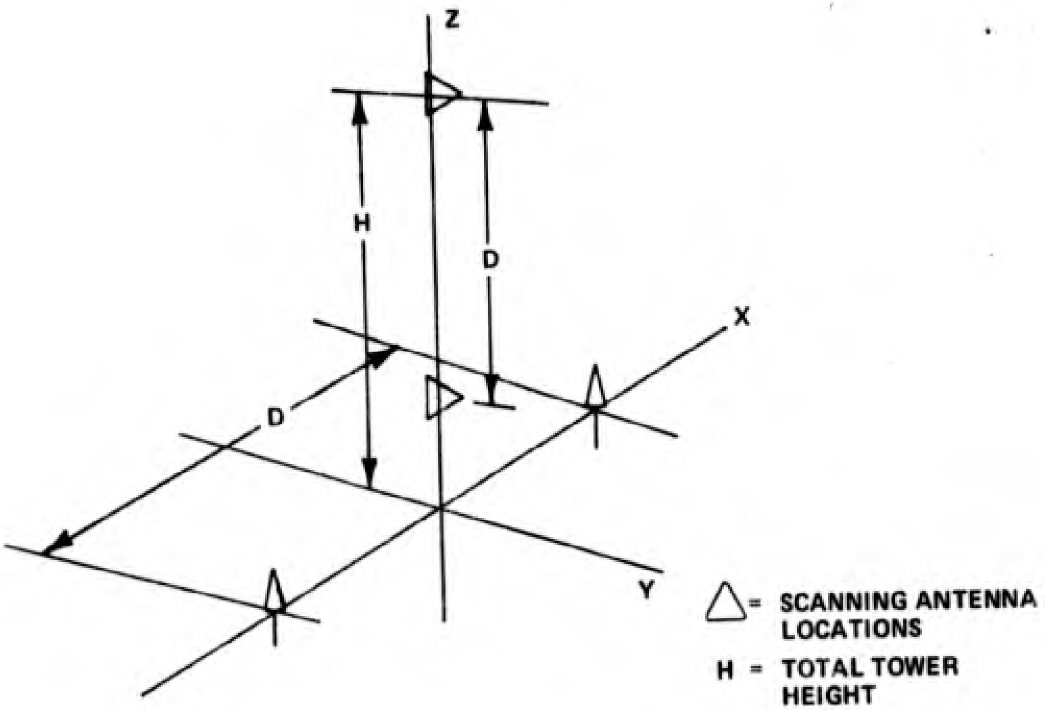


Figure 2. Horizontal-Vertical Interferometer Configuration

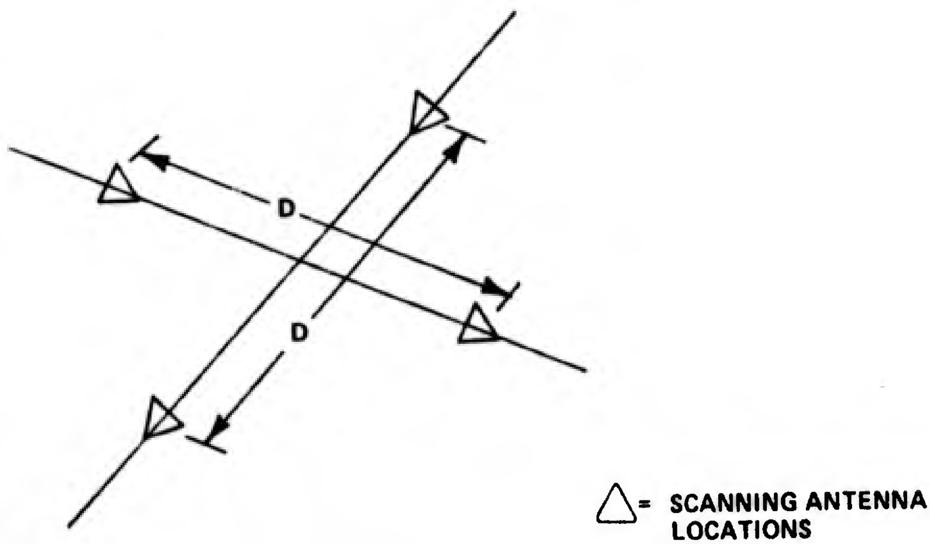


Figure 3. Horizontal-Horizontal Interferometer Configuration

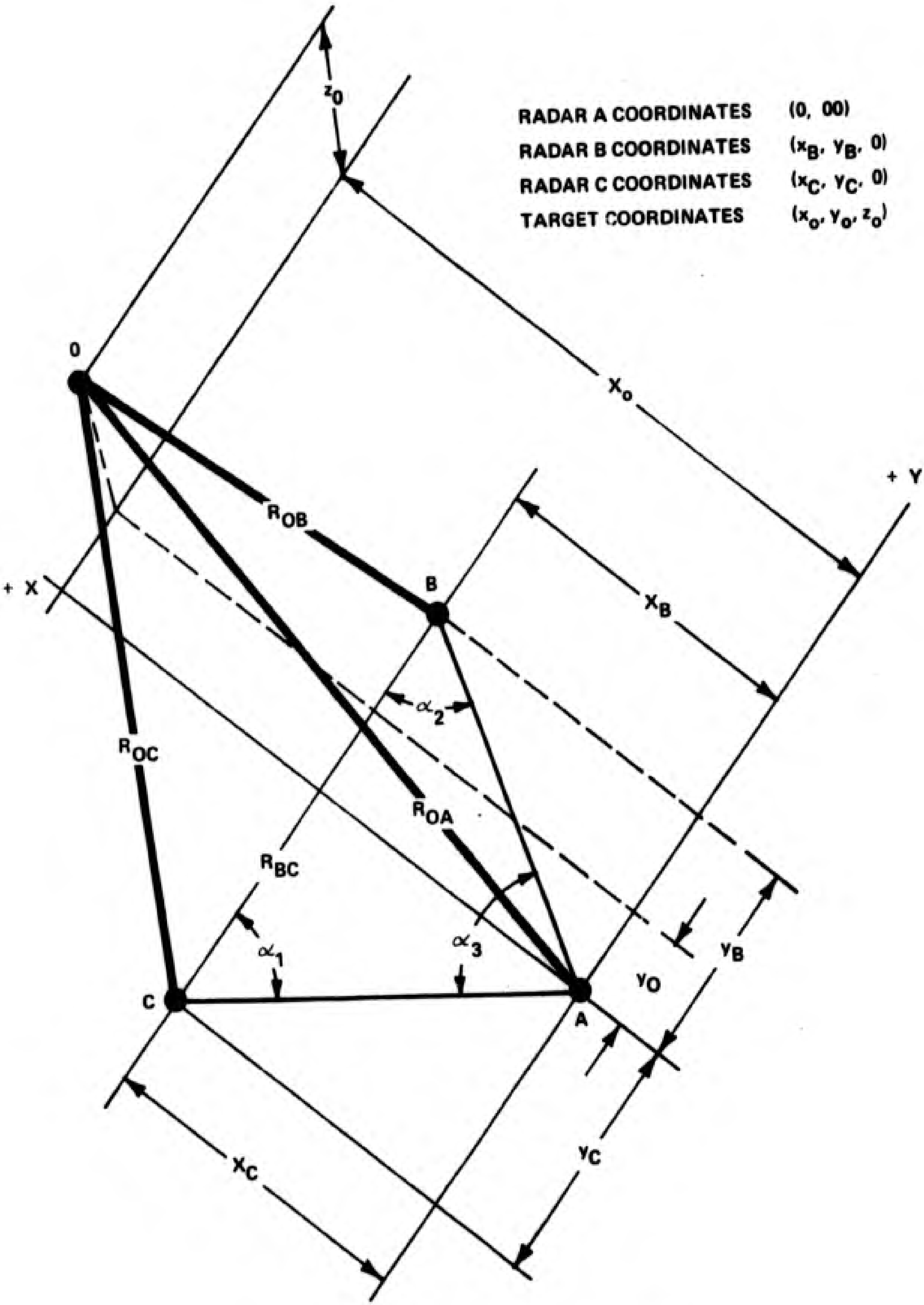


Figure 4. Radar Trilateration System

2.3.2. Analysis (Trilateration)

From Figure 4, the following equations can be easily obtained:

$$z_o^2 = R_{OA}^2 - (x_o^2 + y_o^2) \tag{1}$$

$$z_o^2 = R_{OB}^2 - \left[(x_o - x_B)^2 + (y_o - y_B)^2\right] \tag{2}$$

$$z_o^2 = R_{OC}^2 - \left[(x_o - x_C)^2 + (y_o - y_C)^2\right] \tag{3}$$

Expanding (1), (2) and (3) and subtracting (1) from (3) and (1) from (2) yields:

$$R_{BA}^2 + R_{OA}^2 - R_{OB}^2 = 2x_o x_B + 2y_o y_B \tag{4}$$

$$R_{CA}^2 + R_{OA}^2 - R_{OC}^2 = 2x_o x_C + 2y_o y_C \tag{5}$$

Solving for the variables x_o and y_o :

$$x_o = \frac{1}{2}\left(\frac{1}{x_B y_C - x_C y_B}\right)\left[y_C\left(R_{BA}^2 + R_{OA}^2 - R_{OB}^2\right) - y_B\left(R_{CA}^2 + R_{OA}^2 - R_{OC}^2\right)\right] \tag{6}$$

$$y_o = \frac{1}{2}\left(\frac{1}{y_B x_C - y_C x_B}\right)\left[x_C\left(R_{BA}^2 + R_{OA}^2 - R_{OB}^2\right) - x_B\left(R_{CA}^2 + R_{OA}^2 - R_{OC}^2\right)\right] \tag{7}$$

Expressions (6) and (7) can be simplified by noting that:

$$\begin{aligned} y_B &= R_{BA}\cos\alpha_2 & x_B &= R_{BA}\sin\alpha_2 \\ y_C &= R_{CA}\cos\alpha_1 & x_C &= R_{CA}\sin\alpha_1 \end{aligned} \tag{8}$$

Therefore,

$$y_B x_C - y_C x_B = R_{BA} R_{CA} \sin(\alpha_1 - \alpha_2) \tag{9}$$

and

$$y_0 = \frac{1}{2}\left(\frac{1}{R_{CA}R_{BA}\sin(\alpha_2-\alpha_1)}\right)\Big[R_{BA}\sin\alpha_2\,(R_{CA}^2+R_{OA}^2-R_{OC}^2) - R_{CA}\sin\alpha_1\,(R_{BA}^2+R_{OA}^2-R_{OB}^2)\Big] \tag{10}$$

$$x_0 = \frac{1}{2}\left(\frac{1}{R_{CA}R_{BA}\sin(\alpha_1-\alpha_2)}\right)\Big[R_{BA}\cos\alpha_2\,(R_{CA}^2+R_{OA}^2-R_{OC}^2) - R_{CA}\cos\alpha_1\,(R_{BA}^2+R_{OA}^2-R_{OB}^2)\Big] \tag{11}$$

z_0 can be determined from Equation (1), (10) and (11). When $\alpha_1 \rightarrow 0$; $\alpha_2 \rightarrow 0$ hence the expressions are no longer valid because the original equations are then not independent. This is because range R_{OA} can be determined from R_{OC}, R_{OB}, R_{CB} and R_{BA} and therefore will not require an independent measurement. Whereas, in the trilateration configuration the dihederal angle between plane OCB and ABC can only be established by a knowledge of range R_{OA}. The leg BC has been chosen parallel to the y axis for convenience in analysis of the system. Also, for simplicity the legs AC, CB and AB are chosen as equal. Under these assumptions, we have $\alpha_2 = \frac{\pi}{3}$, $\alpha_1 = \frac{2\pi}{3}$ and $R_{CA} = R_{BC} = R_{BA} = R_S$.

The expressions for x_0 and y_0 then become:

$$y_0 = \frac{1}{2R_S}\left[R_{OC}^2 - R_{OB}^2\right] \tag{12}$$

$$x_0 = \frac{1}{2\sqrt{3}}\left[\frac{2R_{OA}^2 + 2R_S^2 - (R_{OC}^2 + R_{OB}^2)}{R_S}\right] \tag{13}$$

The sensitivity of the individual coordinate to errors in the measurement of R_S, R_{OA}, R_{OB}, and R_{OC} can be determined by evaluating the differentials dx_0, dy_0, and dz_0. Hence, from (1):

$$dz_0 = \frac{R_{OA}}{z_0}\,dR_{OA} - \frac{x_0}{z_0}\,dx_0 - \frac{y_0}{z_0}\,dy_0 \tag{14}$$

from (13):

$$dx_o = \frac{2R_s^2 - 2R_{OA}^2 + R_{OB}^2 + R_{OC}^2}{2\sqrt{3}\,R_s^2}\,dR_s + \frac{2\sqrt{3}}{3}\,\frac{R_{OA}}{R_s}\,dR_{OA}$$

$$- \frac{R_{OC}}{\sqrt{3}\,R_s}\,dR_{OC} - \frac{R_{OB}}{\sqrt{3}\,R_s}\,dR_{OB} \qquad (15)$$

and from (12):

$$dy_o = \frac{1}{2}\left(\frac{R_{OB}^2 - R_{OC}^2}{R_s^2}\right) dR_s - \frac{R_{OB}}{R_s}\,dR_{OB} + \frac{R_{OC}}{R_s}\,dR_{OC} \qquad (16)$$

The differentials dR_S , dR_{OA} , dR_{OB} and dR_{OC} are taken equal to the standard deviation in the measurement of these parameters, i.e., σ_S , σ_{R_A} , σ_{R_B} , and σ_{R_C} . Because these quantities are random and without bias, the sign of these errors are unknown. Accordingly, a maximum result for the error in any coordinate could be obtained by assuming that the sign of the errors (standard deviations) are such that the errors add in one direction. However, this result is not indicative of an average accuracy of the system.

A summation based on a mean square basis is commonly used to describe a total error in a parameter when there is no correlation between the various factors upon which the parameter depends. This procedure is commonly known in statistical literature as the propagation of error method (Reference 3). Summations of this nature give a more realistic assessment of the system performance. Using this procedure, Equations (14), (15) and (16) become:

$$\sigma_{\gamma_o}^2 = \left[\left(\frac{R_{OA}}{\gamma_o}\right)\sigma_{R_A}^2 + \left(\frac{x_o}{\gamma_o}\right)^2 \sigma_{x_o}^2 + \left(\frac{y_o}{\gamma_o}\right)^2 \sigma_{y_o}^2\right] \qquad (17)$$

$$\sigma_{x_o}^2 = \left[\left(\frac{2R_s^2 - 2R_{OA}^2 + R_{OB}^2 + R_{OC}^2}{2\sqrt{3}\,R_s^2}\right)^2 \sigma_{R_s}^2 + \left(\frac{2R_{OA}}{\sqrt{3}\,R_s}\right)^2 \sigma_{R_A}^2 \right.$$

$$\left. + \left(\frac{R_{OC}}{\sqrt{3}\,R_s}\right)^2 \sigma_{R_C}^2 + \left(\frac{R_{OB}}{\sqrt{3}\,R_s}\right)^2 \sigma_{R_B}^2\right] \qquad (18)$$

$$\sigma_{y_o}^2 = \left[\left(\frac{R_{OB}^2 - R_{OC}^2}{2R_s^2}\right)^2 \sigma_{R_s}^2 + \left(\frac{R_{OB}}{R_s}\right)^2 \sigma_{R_B}^2 + \left(\frac{R_{OC}}{R_s}\right)^2 \sigma_{R_C}^2\right] \qquad (19)$$

From Equations (17), (18) and (19) many of the characteristics of the Trilateration system can be deduced. To illustrate some of the characteristics two cases will be examined.

Case A: Let $R_{OA} = R_{OB} = R_{OC}$ and $\sigma_{R_A} = \sigma_{R_B} = \sigma_{R_C} = \sigma_{R_S}$.

This case represents the condition when the target is directly over the Trilateration system at an altitude H which is less than range (R_S) between stations. In this case the maximum range would be approximately the maximum aircraft operating altitude. From (12), (13) and (1):

$$y_o = 0 \tag{20}$$

$$x_o = \frac{R_S}{\sqrt{3}} \tag{21}$$

$$z_o = \sqrt{R_{OA}^2 - \frac{R_S^2}{3}} = H \tag{22}$$

From (17), (18) and (19) we have:

$$\sigma_{z_o}^2 = \frac{3\left(\frac{R_{OA}}{R_S}\right)^2 + 1}{3\left(\frac{R_{OA}}{R_S}\right)^2 - 1}\,\sigma_{RA}^2 = \frac{3\left(\frac{H}{R_S}\right)^2 + 2}{3\left(\frac{H}{R_S}\right)^2}\,\sigma_{RA}^2 \tag{23}$$

$$\sigma_{x_o}^2 = \left(\frac{1}{3} + 2\left(\frac{R_{OA}}{R_S}\right)^2\right)\sigma_{RA}^2 \tag{24}$$

$$\sigma_{y_o}^2 = 2\left(\frac{R_{OA}}{R_S}\right)^2 \sigma_{RA}^2 \tag{25}$$

Case B: $R_{OA} = R_{max} \approx R_{OB} = R_{OC}$; $x_o = R_{OA}$

$y_o = 0$, $z_o = H$; $\sigma_{RA} = \sigma_{RB} = \sigma_{RC} = \sigma_{RS}$; and $R_{OA} \gg R_S$

This case represents the target at a position of (R_{max}) and an altitude (H).

$$\sigma_{x_o}^2 = \sigma_{y_o}^2 = 2\left(\frac{R_{max}}{R_S}\right)^2 \sigma_{RA}^2 \tag{26}$$

$$\sigma_{z_o}^2 = 2\left(\frac{R_{max}}{H}\right)^2\left(\frac{R_{max}}{R_S}\right)^2 \sigma_{RA}^2 \tag{27}$$

From Equations (23) and (27), it can be seen that as $H \longrightarrow 0$, the position error in $z \rightarrow \infty$. This is because of the Geometric Dilution of Precision (GDOP) effect characteristic of baseline systems.

From the above equations the following can be deduced:

(1) The position accuracy in the x_o , y_o coordinates are approximately equal,

(2) The altitude position accuracy obtainable is dependent upon the altitude and increases to an infinite value as the altitude H approaches 0. The altitude position accuracy approaches a value equal to the standard deviation of the ranging accuracy as the altitude is increased to infinity (Equation 23).

(3) As the altitude is increased, the accuracy in the x_o and y_o coordinates decreases.

(4) In the maximum range case (Case B) the altitude accuracy is obtainable as a function of the maximum range to altitude ratio as well as the maximum range to baseline distance (Equation 27).

The ranging accuracy (σ_R) that is required to satisfy the initial system position accuracy (σ_{x_o}, σ_{y_o}, σ_{z_o}) can be ascertained from Equations (23) through (27). Some combinations of parameters listed in the initial system specification will be examined in order to assess the minimum range measurement accuracy.

Let $\sigma_{x_o} = \sigma_{y_o} = \sigma_{z_o} = \sigma_R = 20'$, H = 2000 ft, the cooperative target at a position directly over the center of the trilateration system (Case A). Therefore, for an assumed baseline of 10 n.mi., range will approximately equal $R_S/\sqrt{3}$ (5.76 n.mi.), so that:

$\sigma_R = \sqrt{\frac{3}{2}}\,\sigma_{y_o}$ = 24.5 ft (to satisfy the y_o coordinate specification)

$\sigma_R = \sigma_{x_o}$ = 20.0 ft (to satisfy the x_o coordinate specification)

$\sigma_R = \sqrt{\frac{3}{2}}\left(\frac{H}{R_S}\right)\sigma_{z_o}$ = 0.8 ft (to satisfy the z_o coordinate specification)

It is clearly evident that the accuracy required to satisfy the altitude position can only be satisfied with a shorter baseline (R_S) system of the order of magnitude of the altitude. However, a shorter baseline system would require an extreme range measurement accuracy to satisfy the maximum range-minimum altitude requirement as indicated below.

$$\sigma_R = \frac{1}{\sqrt{2}} \frac{H R_S}{(R_{max})^2} \sigma_{\gamma_0} = \frac{1}{\sqrt{2}} \frac{H^2}{R_{max}^2}$$

$$\sigma_R = 5 \times 10^{-3} \text{ ft} \quad \text{for} \quad R_S = H = 2000 \text{ ft}$$

$$R_{max} = 20 \text{ n.mi.}$$

Using a state-of-the-art accuracy of 6 feet for the ranges involved, it is evident that a single trilateration system cannot satisfy the altitude requirements of the initial system (or the future system).

2.3.3 <u>Analysis</u> (Multilateration)

A radar multilateration system using a hexagonal configuration is shown in Figure 5. The multilateration configuration is assumed to cover the total area specified by placing the stations on the perimeter of the configuration. Using the seven stations, a maximum of

$$C_3^7 = \frac{N_S!}{3!(N_S-3)!} = \frac{7!}{3!4!} = 35$$

trilateration configurations can be formed. Therefore, thirty-five independent measurements could be made and at most the standard deviation in the measurement of position could be reduced by a factor of $\sqrt{35}$. This reduction is not sufficient to satisfy the altitude accuracy requirement of the initial system.

Since the terrain is seldom optimum to insure line of sight between all stations, the increase in accuracy mentioned above is seldom realized.

A seven station multilateration system cannot provide the required altitude accuracy. Hence, an aided system (inertial or altimeter) to improve altitude accuracy must be utilized.

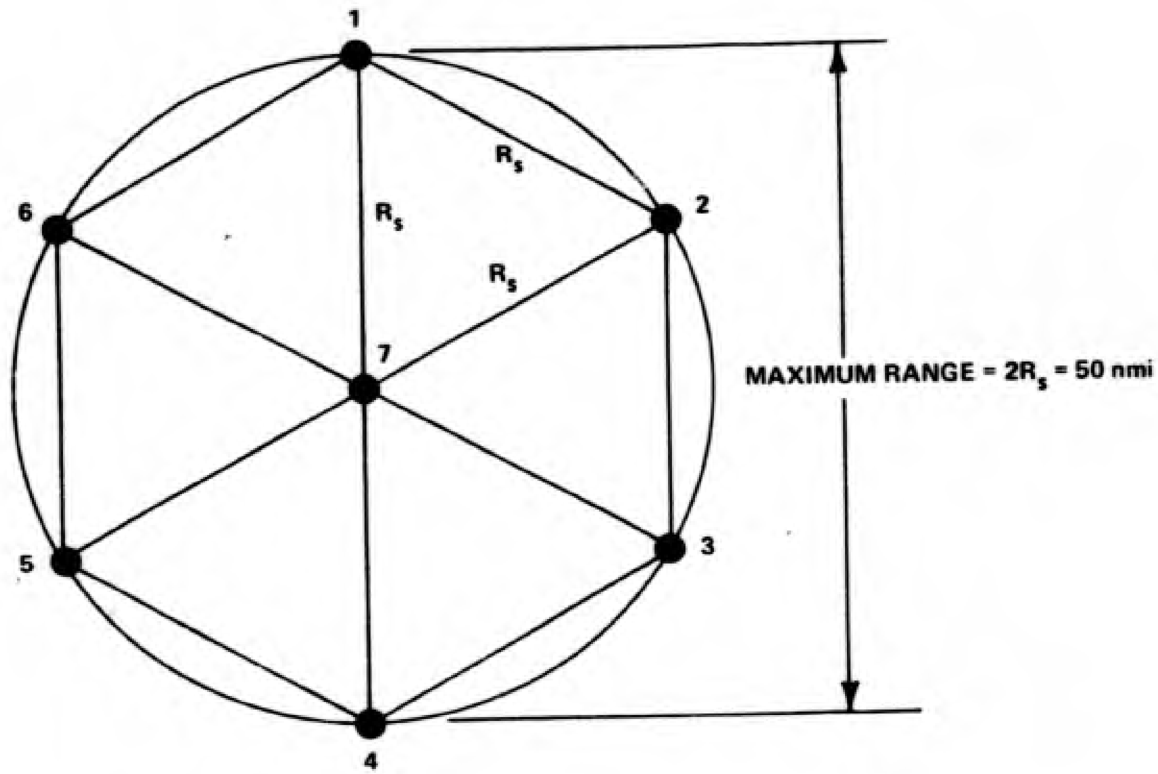


Figure 5. Seven-Station Multilateration Configuration

SECTION III

COMPUTER REQUIREMENTS

The high accuracies and rapid responses that are required of candidate TSPI systems translate into a large computational load. For aircraft tracking, the largest component of this load is the (Kalman) filtering equations that must be solved in a real-time environment for multiple range elements. Less time-consuming tasks consist of solving ranging equations for ground-based field elements and computations related to control of the ranging hardware and displays. Due to these large computational loads, none of the computer systems used by candidate TSPI systems appears capable of meeting the far term requirements without substantial expansion of hardware and software at substantial cost. An attractive solution to this problem is discussed in Section 3.2. This section also summarizes the problems of computer systems and presents recommendations for satisfying the requirements of TSPI systems both in the near term and in the future.

3.1 MODERN MINICOMPUTERS

It is well known in the computer field that the performance/cost ratio is rapidly rising year after year. Other than those whose work involves minicomputers, few computer people realize just how rapidly this ratio has increased. The ramifications to conventional data processing applications are substantial, as today's system designers can obtain computational power from a $20,000 minicomputer that he would not have been able to duplicate a few years ago for $100,000. Although the performance/cost ratio of peripheral equipment (disc and tape drives, card readers, etc.) has been substantial, it has been overshadowed by the improvement in the all-electronic sections of the computer system (central processing units, semiconductor memory, floating-point processors, etc.).

Manufacturers of minicomputers have been alert to the advantages of miniaturization in their designs, so that integrated circuits are being replaced by Medium-Scale-Integration (MSI) circuits. Manufacturers of semiconductor memories are well down the road to the replacement of MSI by Large-Scale-Integration (LSI) memories-on-a-chip. An industrial control minicomputer installed at Calspan almost one year ago has memory chips of 1,024 bits each, organized into 8,192-word boards of 16-bit words at $3,000 per board. The 4,096-bit chip successor, likely to prove to be the new industry standard, is now being marketed and will surely bring further substantial reductions in the cost per bit of memory systems. Advances in the non-memory sections of minicomputer electronics have not been as dramatic, but are nevertheless substantial.

The modern minicomputer can be equipped with most of the high-performance features usually associated with medium or large computers, such as: memory cycle times down to 300 nanoseconds, overlapped (interlaced) memory banks, execution times as low as 200 nanoseconds for register instructions, integral floating-point hardware instructions, multiple registers dedicated to multiple operational modes, microprogrammed (and writable) control memory, multiple-port memory and multiple-channel access to such memory addressable up to 256,000 (8-bit) bytes.

Attractive as these features may be for some applications, however, they simply do not add up to the capabilities of large, multimillion dollar computers. Their 16-bit word organization puts them at a disadvantage to medium-size machines with 32-bit or 36-bit words. Their software support, although constantly improving, is not as good as the software available for larger machines costing orders of magnitude more. Software capabilities, it should be noted, are strongly dependent on the specific computer vendor and model; some minicomputers boast a software package that far out-classes those of many larger machines.

In summary, the modern minicomputer possesses attributes that make it an attractive candidate for all but the largest applications. Even for large compute-bound jobs, there may be some inherent structure of the processing tasks that could allow multiple minicomputers operating in parallel to satisfy the requirements of the application. This multiprocessing configuration is explored further for the TSPI application in the next section.

3.2 DISTRIBUTED OR MULTIPROCESSING SYSTEMS

When a system designer finds that the candidate computer for his application is insufficient in some resource (speed, memory, etc.), he is faced with several unattractive alternatives:

(1) buy a larger model of the same family of computers. He then discovers that large computers break large budgets;

(2) buy two or more of the candidate computer, interface them and distribute the tasks among them (multiprocessing). Interfacing requires a candidate designed for such a multiprocessing environment, both in hardware and software features. This approach assumes that the tasks can be partitioned into a number of parallel tasks, one for each computer, not always easy when the application consists of serial processing of data. This is the approach taken by CUBIC for their ACMR (Section 9.1.2.3).

(3) buy special processors to alleviate compute-bound tasks. Included here are floating-point processors, array and transform processors and any other special hardware the system designer can justify.

Until the advent of the modern minicomputer, alternative No. 2 could often be disastrous to one's budget. In compute-bound applications, replication of central processing units might involve hundreds of thousands of dollars per unit. This has provided a strong incentive to the development of special processors (alternative No. 3).

Consider the multiprocessing system consisting of three central processing units shown in Figure 6. Each central processor has two I/O busses, although CPUs No. 2 and No. 3 have very little traffic on their "left-side" bus. The "right-side" bus is dedicated to one port of a dual-port memory bank. Therefore, if the software is designed with discretion, there will be no interference with the computations performed by these two CPUs. All three CPUs can operate on three parallel tasks of a compute-bound application totally overlapped.

Before considering TSPI-related functions in such an environment, the question of costs should be addressed, since multiprocessing systems have been considered to be very expensive until quite recently. Using the PDP-11/45 as an example, the complete configuration shown in Figure 6 is available from a current catalogue for approximately $120,000. The peripheral equipment and memory speed are representative of the "middle-line" of the catalogue at this price; 300-nanosecond memory is available, for example, to augment the quoted 450-nanosecond memory. Additional CPU/8K-memory combinations can be added at a cost of approximately $20,000 each. The economy and physical ease of "plugging in" an additional CPU should prove to be a substantial advantage in a TSPI application when compared to other types of computer configurations.

The multiprocessing system of Figure 6 is "tuned" to be most effective in an environment such as the near-term and far-term TSPI requirements--a heavy computational load and a medium input/output load. However, the problem of distributing the TSPI tasks among the processors remains to be solved. It seems clear that one CPU must remain in control throughout the mission, and CPU No. 1 has been designated the "control" computer here. The remaining CPUs (in this case, the pair labelled "compute") have the advantage of dedicated memories and floating-point processors, so that the TSPI filtering equations, for example, could be efficiently solved in two parallel halves. After each solution iteration, the control computer uses its "memory-only" bus to transfer the small number of words between the three memories as required for the succeeding iteration. Since there is no interference from overlapping I/O operations on the other bus, this operation requires only a few microseconds per word transferred, totalling only a small fraction of a millisecond for all TSPI data.

Although there are similarities of structure between this configuration and that of the CCS used in the ACMR (Section 9.1.2.3), this discussion does not mean to imply that three minicomputers could take over the load that presently consumes the processing resources of three Sigma-5 computers. Since the pay-off would be substantial, however, a detailed comparison of the two approaches seems justified, and the following section begins such a comparison.

3.3 COMPARISON OF CANDIDATE SYSTEMS

Since the ACMR is the only TSPI system which has implemented real-time tracking for multiple high-performance aircraft, it seems a logical choice to provide the framework for our comparison. The CCS and its computations are described in detail in Section 9.1.1 and Appendix A. The comparison will be governed by the following assumptions:

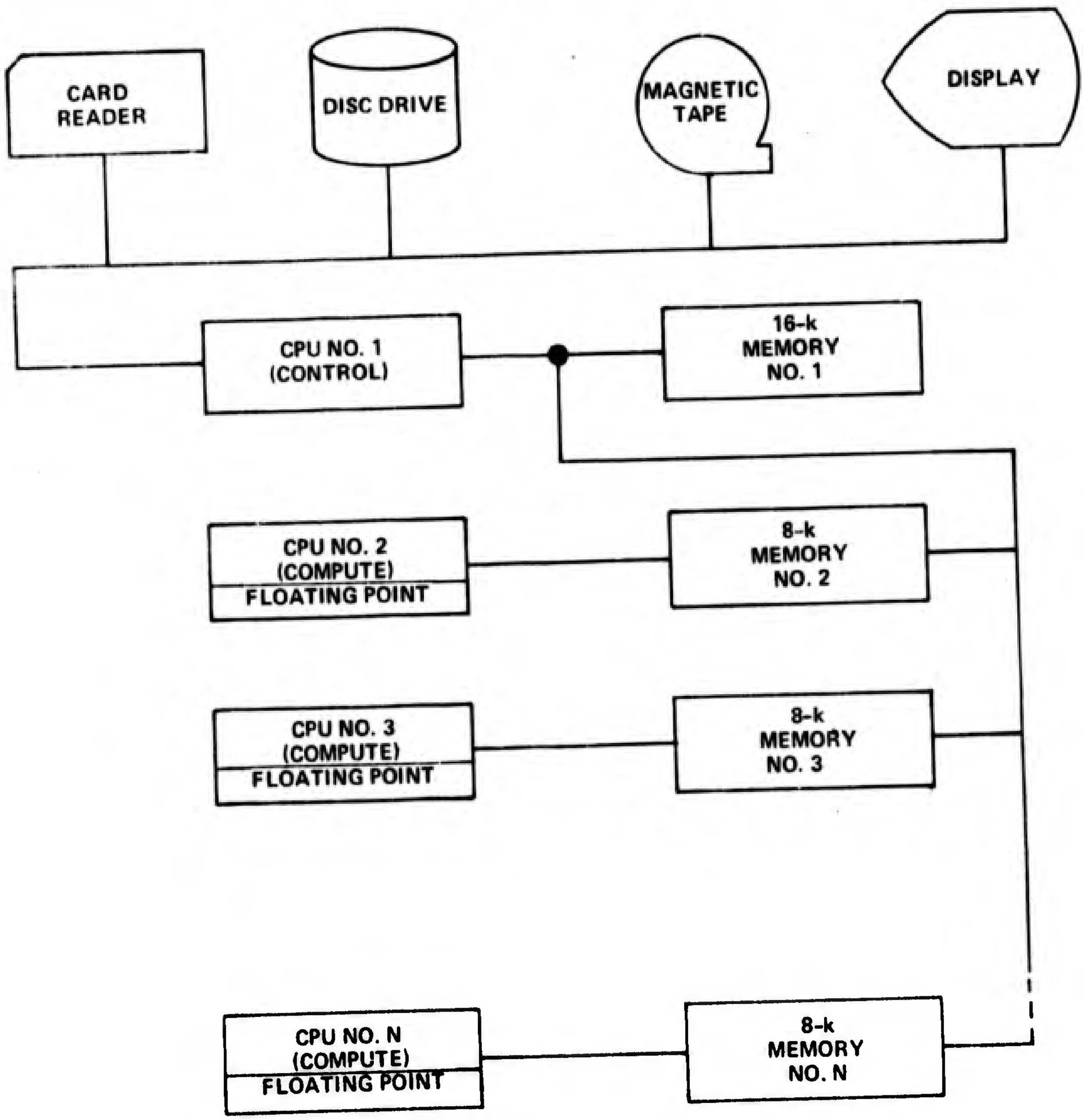


Figure 6. Multiprocessing System Based upon a Modern Minicomputer

(1) the number of distributed minicomputers required lies between 3 and 6;

(2) the remainder of the distributed configuration is similar to Figure 6, using 300-nanosecond memories on all CPUs except No. 1;

(3) the PDP-11/45 will be the comparison CPU, even though more economical machines are presently available.

3.3.1 Cost Comparison

The cost of the three Sigma-5s used in the CCS, including peripherals and excluding display interfaces, is in the neighborhood of $800,000. The savings expected in the use of Sigma-8s (successor to the Sigma-5) are non-existent or negative. The minicomputer "network" under discussion is substantially under $200,000.

3.3.2 Speed of Computation

As discussed in Section 9.1.3, the filtering equations are solved by floating-point operations with a large complement of multiplication required. Instruction execution speeds are therefore dominated by the floating-point processors, which are closely matched. The Sigma-5 requires 950 nanoseconds to access one 32-bit word for this processor, while the 16-bit minicomputer requires two accesses of 300-nanoseconds each.

3.3.3 Operational Constraints

The functions performed by the CCS are distributed among three computers, resulting in some operational inconvenience. Since the minicomputer approach requires another level of distribution, some incremental inconvenience will be experienced in this case. This depends strongly on the ease with which the filtering functions of the CCS can be partitioned into two or more parts. The computational block diagrams of Figure 7 show this to be a straightforward task, since they display a wide variety of parallelism. The missile-simulation Sigma-5 should be easily partitioned into two parts, if necessary, since it simulates two missiles simultaneously.

3.3.4 Expandability

Figure 6 shows that, from the CPU No. 1 on down, additional CPUs can be added in modular fashion by plugging them into the two I/O busses. This assumes that the software is structured in a modular fashion such that basic software operations are independent of the number of CPU's currently in the network. The tasks supported by these "new" CPUs would operate under control of CPU No. 1, which may or may not be dedicated to TSPI functions in the COR environment, and have access to all TSPI-related state variables (positions attitudes, range time, etc.). This expandability assures that future TSPI requirements (such as the 100 field elements) can be met quickly and economically. In contrast, the CCS configuration has little room for expansion. The memory ports are already overcrowded and it often proves necessary, as in the

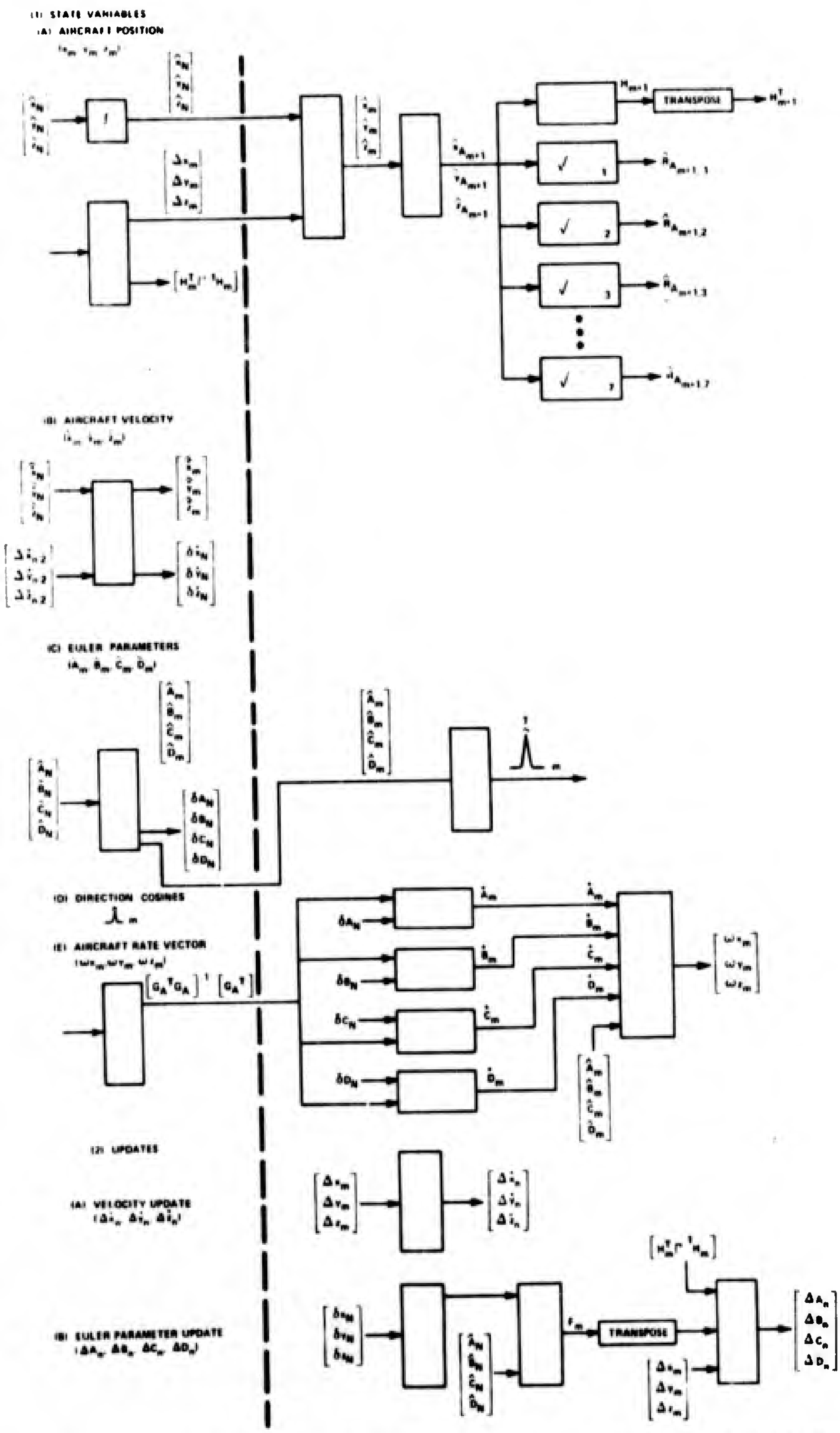


Figure 7. Block Diagrams of Data Flow For Computations of State Variables and Updates

Yuma installation, to provide a "front-end" minicomputer for the TIS processing (although this is range-dependent.)

3.3.5 Physical Requirements

Since the COR has a "transportability" requirement, the physical size, weight and power requirements become important; here the advantages of the minicomputer approach are even more dramatic than for cost comparisons. Each of the CPU/8K-memory floating-point processor combinations will fit within 21 inches of a standard (19-inch) electronics rack. Allowing space for more memory and power supplies, all three CPUs could fit within one rack. The peripheral equipment compares closely in physical requirements with XDS peripherals of comparable capability. The weight, power and cooling requirements are lower by an amount proportional to size. Contrast this with the Cubic system's three Sigma-5s as described in Section 9.1. If present TSPI functions require this much physical support, it is not pleasant to contemplate future TSPI functions and additional COR computer requirements.

3.3.6 Reliability

Since we are comparing the all-electronic parts and assuming comparable peripherals, the reliability question is resolved by noting that problems among the electromechanical peripherals will dominate. It would be unfair not to use the Sigma-8 in our comparison, but it has no more of a track record than the PDP-11/45. Undoubtedly both will have the excellent reliability associated with miniaturization of electronics.

3.3.7 Maintainability

A network of identical CPU's and modular "plug-in" memories is capable of setting new standards for maintainability. A complete minicomputer is sufficiently economical to justify one or more spares plugged into the network, waiting to take over the tasks(s) of faulty members of the network. By taking advantage of the modular structure of the governing software, any suspected fault diagnosed in a "compute" CPU or its dedicated resources could be compensated immediately by loading a spare or low-priority CPU with the errant task, reinitializing that task, and then loading the suspected CPU with maintenance software so that it starts immediately its self-diagnosis independent of the remaining members of the network. Critical peripherals should be replicated in a similar manner, again taking advantage of the modular software's device-independence. The down-time for tasks in the network could be no more than one or two seconds.

Contrast this with the maintainability problems of the CCS, where any Sigma-5 problem translates into range down-time. Loss of one Sigma-5 might allow tracking functions to continue, but no missiles could be simulated and off-line self-diagnosis of the ailing sigma-5 would not be possible during such an exercise. Back-up capability at the CPU level is unthinkable for a Sigma-5, so that a large complement of spare modules and vendor's field engineers are used to reduce down-time using conventional trouble-shooting techniques.

3.3.8 Software

The Sigma-5 has an advantage over the minicomputer in most areas of software capability, only a few of which are applicable to our TSPI environment. The Fortran compiler produces more efficient object code and the file management structure presents fewer constraints, for example, but it is difficult to find any substantial impact upon our comparisons.

3.3.9 Summary of Comparison

A distributed network of minicomputers offers substantial advantages for both near-term and far-term TSPI functions. Although more CPUs are probably required for the application used for comparison, there is little to offset the distributed system's striking advantages of cost, expandability, physical requirements and maintainability.

3.4 COMPUTER PROCESSING SPEED ENHANCEMENTS

This section describes some of the hardware and software techniques that hold promise of significant increases in processing speeds for an individual computer in a TSPI environment. These techniques can be applied independently of the multiprocessing concepts discussed in Section 3.2 with the result that improvements in any single processor will be reflected in all members of the distributed network.

Speed enhancements in the peripheral input/output elements of TSPI computers are easily achieved by the use of high-speed models and by replication of these models and their I/O channels. Except for the possibility of off-line data reduction operations, these computers would never be I/O-bound; consequently, the following techniques should be applied to alleviate the compute-bound processors.

3.4.1 Microprogramming

Since microprogramming falls between hardware and software, it is often called "firmware" by computer designers. Most modern computers have their processors and I/O channels controlled by such firmware, usually obtained from an economical "read-only memory" or "control store." The bit patterns emerging from the control store determine which instruction to execute and which data paths to open or close. It follows that the use of a writable (alterable) control store allows the user to create special instructions which execute much faster than the series of standard instructions required for the same function. Since a writable control store is available on many microprogrammed computers, their instruction sets should be reviewed and matched with TSPI calculations for possible improvements. An obvious candidate is the square root instruction; others might be array operations (see Section 3.4.3) or evaluation of trancendental functions. Other potential uses of microprogramming, such as high-speed table look-up, should be closely evaluated. Implementation of "micro" programs should be supported by software to at least the level of a vendor-supplied "micro" assembler.

3.4.2 Adaptive Update Rates

Recognizing that the computers, displays, inertial measurement units, tracking hardware and other TSPI subsystems can each operate at a different update rate, we concentrate in this section on the updating of filtering equations. Section 4.2 discusses the factors involved in display update (refresh) rates, while the important question of tracking update rates is discussed at length in Section 11.3.

Given the assumption that update rates which are fixed by the TSPI variables with the largest dynamic rates-of-change yield a tremendous waste of computer processing resources, the question arises as to the best method of recovering these resources. Here there exists a family of software techniques that can be applied to the TSPI algorithms such that the update rates adapt themselves automatically to the rates of change of the TSPI variables being computed. These adaptive techniques might use the covariance data that is generated as a by-product of Kalman filtering. The processing time saved by reducing the update rates on slowly-changing variables will be dependent upon range activity; many range operations would place a very light load upon the computers, freeing them for low-priority tasks such as data reduction and software development for new applications.

3.4.3 Array Processors

These are special-purpose data processing machines designed to perform array and matrix operations at high speed. Interfaced directly to memory and to the I/O bus of a general-purpose computer, they perform such operations as convolution of two functions (arrays) or "multiply-add" of the conformable elements of two arrays. Although they must steal a memory cycle for each word accessed, their arithmetic operations are performed on an interrupt-driven basis; the CPU can be performing additional functions while waiting for the array processor to complete its overlapped instructions. For large arrays, these machines can perform multiplications averaging less than four microseconds. Costs are becoming more attractive as a larger community of users apply them to compute-bound tasks.

There would be little advantage in the use of array processors to the ACMR algorithms as presently constituted, as these algorithms have been designed with great care to avoid such array operations. Conventional implementation of a Kalman filter, on the other hand, requires a quantity of array and matrix operations that grows exponentially with the order of the filter. Such processors would undoubtedly prove effective for the 16-state-variable Kalman filter presently being considered for the RMS system.

3.5 CONCLUSIONS AND RECOMMENDATIONS

The computational requirements of TSPI systems are seen to represent a substantial problem area that can seriously impact the accuracy, speed, cost and reliability of the overall system. The development of computer systems for real-time TSPI applications is not a mature field; only one such system (ACMR) has been deployed to date, with final acceptance still pending. Although the ACMR appears capable of meeting the near term TSPI requirements, several problems with its computer system should be closely evaluated before extending it to meet the far term requirements. Among the most serious are the size, cost, maintainability and expandability problems discussed in Section 3.3.

If ACMR is deployed within COR, either as the sole TSPI system or in conjunction with others, the initial computer system used should be the Sigma-8, successor to the Sigma-5 presently installed at Yuma. These computers should be leased, however, pending decisions concerning conversion to a more suitable computer system. If the minicomputer approach is elected, then the functions of the Sigma-8 processors should be transferred to the minicomputers in three phases:

(1) The missile simulations should be implemented (if required) in one or more minicomputers and run in parallel with the Sigma-8 for checkout, after which the big computer can be taken off lease;

(2) Next, the filtering computer should be duplicated or expanded in the same manner, releasing the second big machine to the manufacturer;

(3) The control computer and peripheral equipment should be converted last, since its many machine-dependent functions dictate that it be programmed in assembly language. This will leave sufficient time to precisely define all the far term TSPI (and perhaps non-TSPI) requirements under control of this equipment.

Since the first two Sigma-8s use a high-level language (FORTRAN) almost exclusively, conversion costs would consist mostly of a small amount of "systems" engineering required to partition their computational tasks into parallel tasks as discussed in Section 3.2. This type of conversion should cost approximately 10% of the original cost of programming the tasks.

The control computer, on the other hand, has three components of cost associated with its "conversion": translation of tasks from one assembly language to another, upgrading the operational environment to allow "plug-in" independence for processors as well as peripherals (Section 3.2) and, most costly, the "systems" engineering and programming associated with deployment of ACMR in the COR environment.

An interesting alternative to complete replacement would be to retain one or more of the Sigma-8s while expanding the configuration with minicomputers. Although this approach defeats some of the advantages of the minicomputer network, there might be a net saving due to conversion costs.

The importance of integrating the computer requirements of the TSPI function with those of other COR functions cannot be overstated. Even if only a few of the other COR activities prove to require computational power of the same level as the TSPI function, an overall computer system designed without benefit of an integrated approach could present COR with a problem of monstrous proportions. On the other hand, a network of distributed minicomputers of a single common type, as recommended for TSPI, appears to be a logical starting point for an overall computer configuration to meet the COR computational requirements.

SECTION IV

DISPLAY TECHNOLOGY

4.1 SCOPE AND LIMITATIONS OF DISPLAY STUDY

The purpose of the display task was to explore the problem of displaying information derived from TSPI systems and to identify present solutions and investigate potential solutions which would be available perhaps 3 to 10 years in the future.

Display technology, like many other advanced technologies, changes rapidly. For this reason, and because the actual hardware implementation is several years away, emphasis was placed on trends and trade-offs in techniques and technologies that could be used to fulfill TSPI display requirements. The nature, characteristics, and features of representative available display systems were investigated. A detailed comparison of competitive hardware implementations was not made, however. Comprehensive studies on the subject are regularly available in literature.

A summary of relevant display techniques and technologies is provided in Section 4.2. Section 4.3 briefly analyzes possible TSPI display requirements, discusses potential solutions, and details existing TSPI display systems. Section 4.4 lists displays for existing TSPI systems and Section 4.5 lists the conclusions and recommendations.

4.2 DISPLAY TECHNIQUES AND TECHNOLOGIES

4.2.1 Introduction

Computers are able to process and generate vast amounts of data very quickly. In some cases, such as certain process control applications, little, if any, of the data must be made available to human operators. In most cases, however, varying amounts of information must be presented. As the rate, volume, or complexity of the information increases so must the sophistication of the conveyance technique.

Of the five human senses available, the three exploited for display purposes are sight (through visual display), hearing (through aural display), and touch (through tactile display). Other more exotic communications mechanisms such as direct electronic stimulation on the brain or extra-sensory perception have been suggested for possible future use.

The visual display is the one most commonly used, beginning with the standard indicator lamp and extending to high levels of sophistication.

The aural or audio display can range from simple bells and buzzers to speech generated completely by computer. Verbal communication between a human operator watching a visual display and other personnel if often employed, but the non-trivial application of computer generated audio signals is rare.

The tactile transmission of information has been studied and found to have potential usefulness in certain situations such as warning a pilot or astronaut of some situation during a period of high activity. Most of the emphasis has been on developing devices for the handicapped. Limited tactile sense is built into the keyboards of many displays to indicate that a command or character has been received.

Most of the emphasis of this report will be on visual displays.

4.2.2 Display Characteristics

A large variety of electronic displays exists and precise classification is difficult. The characteristics discussed below are the ones most often used for classification purposes.

Displays can be divided according to whether or not they produce a hard copy output. This can be defined as an output which does not have to be electronically regenerated in order to be viewed. Teletypes, line printers and plotters produce hard copy while indicator lamps and typical CRT displays do not. Equipment is available to produce a hard copy output from most displays. The output medium can be paper, a picture, film, microfilm, or other.

A distinction can be made between alphanumeric (A/N) and graphics displays. The A/N display presents information in the form of alphabetic, numeric and special characters while the graphics display is equippped to present arbitrary shapes. Beyond this is the pictorial display where every display point has a defined black, white or gray level. Small quantities of A/N characters are typically displayed using discrete indicators, while larger quantities are presented on screens or panels. A limited graphics capability can be realized using characters on some A/N display, but good results require special data structures.

The number of intended viewers can be used as a classification characteristic. Large screen displays are usually designed to serve several people while individual or console displays typically serve one to three viewers.

Displays can be provided with two dimensional or three dimensional capabilities. Some confusion exists concerning the display of 3-D information. In this report, 3-D images presented on a 2-D medium will be referred to as "pseudo 3-D" images. The effect is the same as with conventional TV. Schemes in which different views of an object are presented to the two eyes of a viewer, giving real depth perception, are referred to as "true 3-D."

Some displays are equipped with color capability. The number of primary colors available and the ability to combine them to form new colors are important considerations.

4.2.3 Human Factors and Display Parameters

Human factors can play a critical part in the design of a display system. Many are highly subjective and difficult to relate to hardware specifications.

Among the visual factors employed in electronic displays are brightness, color, motion, blinking, angular and depth perception, size, shape, quantities and orientation. The following discussion relates visual factors, human factors and display parameters.

4.2.3.1 Brightness

Brightness is usually defined in terms of intensity per unit area of display surface and is typically expressed in foot-lamberts.

Under conditions of low ambient light, brightness in the range of 1 to 20 foot lamberts is required. In areas of higher illumination such as in an office where the viewer must be able to write with pencil and paper, brightness between 20 and 30 foot lamberts may be necessary.

4.2.3.2 Contrast

Contrast is a measure of the difference in brightness between the image and the background usually expressed as a ratio or percentage. Different definitions are used for color and black and white.

4.2.3.3 Resolution

Resolution is defined in many ways. In optics, it is typically the number of black lines per inch which can be distinguished when separated by white lines of the same width. Brightness and contrast strongly affect this parameter. It should be noted that, by this definition, the 525 lines of standard TV would have a resolution equal to one-half this number divided by the height of the screen.

The resolution of the human eye is defined in terms of the angular resolution measured from the eye and is related to display resolution by the distance to the screen. An average person can distinguish details down to about 300 microradians. Display resolution greater than this is sometimes required so that curves and lines at certain angles will be smooth and accurate.

Because of the fact that the resolution of the eye is a function of angle, large screen displays are not necessarily able to provide higher resolution or more information to the viewer than small displays. In fact, it is much easier for a person at a console display to move closer to the screen in order to increase his resolving ability.

The actual amount of data which can be displayed to a viewer at one time is a function of the total angle through which he views the screen. In addition, when rapidly changing information or fast moving images are involved, better performance can often be obtained by restricting the angle of view and therefore the screen size. This is because of the time it takes for an operator to scan the entire screen before focusing his attention on a particular area.

4.2.3.4 Flicker

Flicker can be a problem for displays without inherent storage. In many systems an image is produced by sequentially generating individual parts such as line segments. Each time the image is completed, the process starts over. The rate at which this occurs is called the refresh rate expressed in frames per second. The more complex an image is in terms of the number of lines or total length of the lines required per image, for example, the longer it takes to complete a frame and the lower the refresh rate. Below certain limits image flicker can occur. The problem can be reduced in CRT displays by using high persistence phosphors but the legibility of a changing image is reduced.

It is generally agreed that above 60 frames per second there is no detectable flicker. Most displays are adequate when refreshed at a rate between 50 and 60 frames per second. Rates of 20 to 50 frames per second can be objectionable depending on the circumstances. The greater the brightness of the display, the higher the refresh rate required. In general, anything below 20 frames per second is not acceptable. Flicker in the range of the alpha rhythm of the human brain, usually 10 to 15 Hz, causes many people to become physically upset even to the point of violent illness.

4.2.3.5 Color

Color in the display can improve contrast as well as aid recognition and understanding. The maximum number of useful colors in a display is about 12. Typically 6 or 7 are used. If fast and accurate recognition are important, no more than 4 should be implemented. When poorly used, color can degrade operator performance. It may become an extraneous additional factor which must be mentally decoded before action is taken.

In the past, color has been expensive, difficult to implement, and often resulted in the degradation of other display parameters. Much work is being done in this area and the situation is improving.

4.2.3.6 Half-Tones

Half-tone capability is the ability to display gray levels. It is usually expressed as the number of available gray levels between black and white. Two level (black and white) displays are called bi-stable. Alternate half-tone definitions exist for color displays. Most conventional TV's display between 5 and 10 levels, while the human eye can distinguish about 8 to 10 levels on a television type system. Some high resolution equipment can utilize up to about 100 levels.

Half-tones can be used in a computer generated display to give a line or object the illusion of depth. A few highly advanced systems are able to remove hidden lines from objects, and remove and shade surfaces in real time.

4.2.3.7 Image Fidelity

Various characteristics can be included in a measurement of image fidelity. Among them are linearity, gray level rendition, color rendition, accuracy of positioning, accuracy of registration (alignment of super-imposed images), and image stability.

4.2.3.8 Response

The three classes of response in a display system are tracking response, update response and query response.

Tracking response is the ability of the display to follow the data. The faster the data changes the greater the tracking response required. Many displays, particularly those with inherent storage require relatively long periods to write and erase an image and therefore are not suitable for displaying rapidly changing data.

Update response concerns the delay between the event and its display. There is always a certain data processing or conversion delay in any system. This is a strong function of how sophisticated the processing is and what hardware is available to do it. In many cases, such as in a TSPI system with many vehicles involved, there is a delay caused by the data update rate. This can usually be changed in software subject to overall system considerations.

Query response concerns the time delay between the initiation of an operator request and the fulfillment of the request by the system. In addition to the obvious degradation of control performance brought about by long delays, there is a limit to the tolerance of the operator to such delays. Studies have shown that under ordinary conditions if the delay is about 3 seconds, the probability is about one-half that the operator will have forgotten what he had requested. The performance gets progressively worse as the delay increases. This is more of a problem when the operator is busy.

4.2.3.9 Readability

This is not a specifically defined display parameter, but is a function of other parameters including operator ability. Measurements of general display readability are sometimes made by testing the performance of large numbers of viewers.

4.2.3.10 Selectivity

This refers to how selective an operator can be in choice of format or data in order to have the information that he really needs in any particular situation. The display system would be very ineffective if the operator had to do much interpretation of the data presented. This is usually more a function of data processing support and software sophistication than of the display itself.

A definite problem exists in the determination of how much data should be presented to a viewer. There is a finite limit to the amount of information which a person can handle. Most current display systems are capable of easily exceeding this limit when presenting low level information such as numbers. Improved hardware adds to performance when it provides a better presentation such as a more effective format. The trend is toward higher level display such as computer-generated graphical presentations of real situations. Computers are being allowed to monitor input data and decide on a priority basis what should be viewed. Manual backup and fail-safe checks are, of course, required.

4.2.4 Off-The-Shelf Technology

There are many physical mechanisms which can be exploited for display generation. This fact combined with the variety of display applications and requirements has resulted in the development of many diversified technologies.

4.2.4.1 Discrete Indicators

Digital discrete indicators are used to display individual numbers, characters, or symbols. Included are light emitting diode (LED), plasma panel, liquid crystal (LC), NIXIE, incandescent, rear projection, edge lighted, electro-luminescent, gas ionization, mechanical or other displays. Analog indicators such as meters and gauges usually indicate magnitudes or quantities.

These devices provide excellent low cost displays for specialized applications where the amount of data is small and when hard copy is not required. The cost advantage quickly disappears, however, when the number required is large. Discrete indicators are often added to more advanced visual displays to present auxiliary information, but too many can cause distraction and confusion.

4.2.4.2 CRTs

Cathode ray tube (CRT) displays dominate the display market. CRTs have had the benefit of many years of development and possess a singular ability to be configured for diversified applications.

The CRT is essentially a vacuum tube with a phosphor screen which can be bombarded by an electron beam. The electrons are generated by an electron gun and can be accelerated by high voltages to various energies (speeds) and focused into a very narrow beam. Phosphor is a substance which emits light when struck by electrons. The greater the number of electrons or the greater the energy, the higher the light output. The beam is moved or swept across the face of the screen magnetically or electrostatically by the deflection system. The density of the beam can be dynamically modulated to vary light intensity or blanked (turned off). The electrons in effect "paint" a line or picture on the screen to be seen by the viewer. This can be done very quickly because the beam is almost inertialess. The vacuum is required to keep the air molecules from interfering with the electrons.

Electromagnetic deflection is usually used in CRT displays. Electrostatic deflection systems provide higher spped but also require higher voltages and are usually limited to the smaller tubes. Some systems, especially those required to rapidly display many A/N characters, combine the two using the electromagnetic system for gross positioning and the electrostatic system for high speed writing.

Picture generation speed can be increased by adding electron beams. CRTs with up to several hundred have been built. Multi-beam tube use (except for conventional color CRTs) has been limited to very specialized applications because of the added complexity, lower production yields, interbeam registration problems, etc.

Phosphor coatings vary in persistence, efficiency, color and other characteristics. Phosphor research is an area of intense activity. Presently under development are such features as high performance transparent phosphors.

Various techniques are used for image generation. In the dot method, the beam is directed to individual points on the screen and then unblanked. In the stroke system, random vectors are produced by adding special hardware to the deflection system. Typically, the digital coordinates of 2 points on the screen are first converted to voltages by digital to analog (D/A) converters. The voltage difference for each dimension can then be integrated to provide differential sweep voltages resulting in the generation of a smooth line between the points. Care must be taken to maintain line intensity with changing sweep rates. Similar hardware can be implemented to modulate the beam intensity with a depth variable defined for each point. This is often called "Z modulation." This provides pseudo 3-D capability. Ten thousand or more inches of lines can be required to generate a complex image.

Hardware can be implemented to generate curves such as conic sections. This is typically done by providing integrators to solve parametric equations. Hardware such as this is expensive to implement, but can produce curves much faster and with greater precision than other methods.

In the TV raster scan, the beam is swept across the tube from left to right and successively incremented from top to bottom. The beam can be either bi-stable or half-tone modulated. Conventional TV uses 525 scan lines (US) while high resolution TV typically uses 1000 or more.

Raster scanning has not been popular in computer generated displays in the past. For displaying objects made of lines and curves, much time is wasted scanning blank areas and the resolution is less than with most displays using the stroke techniques. Advantages are that it permits the use of standard TV hardware, allows the display to present pictorial data, and often simplifies image transmission and storage. Images can be converted to raster scan from other forms by a scan converter. Some dual mode systems are available in which, for example, each raster scan is followed by a period for random vector generation.

It is possible to project a slide, microfilm or other image on the screen of the CRT. This can be done from the viewer's side, or from the rear when using a special "ported" tube. Registration problems are sometimes encountered and can require the use of automatic alignment equipment.

Many techniques for providing color in a CRT have been demonstrated. The two which are readily available are the shadow mask tube and the phosphor penetration or "penetron" tube.

In a shadow mask tube three electron guns exist and three beams are produced corresponding to the primary colors red, green and blue. Each sweeps the entire screen. Before hitting the screen, however, the beams must pass through thousands of tiny holes in a metal plate or shadow mask. On the screen dots of red, green and blue phosphor are properly placed so that, by geometry, each beam strikes only the properly colored phosphor.

Such a tube provides full color but the resolution is restricted by the resolution of the phosphor dots and is usually much worse than the resolution of a B&W tube. Standard color TV provides for 525 raster lines. Higher resolutions shadow mask tubes such as a 729 line system for NASA have been produced but are not readily available.

Tubes using the phosphor penetration technique utilize a two-layer phosphor screen. Two or more acceleration voltages are used to vary the depth of electron penetration. By using different color phosphors in the layers, two primary colors and a few combinations of the two are possible. Red and green are usually used because at least two easily recognizable combinations are possible (orange and yellow). All colors are not available. The resolution is essentially the same as with a B&W tube. A single electron beam is used and therefore the colors must be written sequentially. It takes a relatively long period to change colors because of power supply problems. Early versions were three layer, three color tubes but performance was poor and they are not generally available.

Very high quality color images can be generated by superimposing three single color images from three CRTS. Alternately, three color filters can be quickly placed between the B&W image and the operator while the appropriate images are presented. This can be used to provide color in a console or projected display. These methods are seldom used because of cost and complexity.

4.2.4.3 Direct View Storage Tubes

The direct view storage tube (DVST) is a special CRT which has the ability to store an image. A typical DVST unit is the bi-stable Tektronics 611 display. It makes use of a special screen and two types of electron guns. A high energy focused electron beam is used to selectively create positively charged areas on the screen by making use of the secondary emission principle. Flood guns are used to bathe the whole screen with low speed electrons. This acts to store the charge pattern and illuminate the image. A non-view mode can be incorporated to extend the storage life of the image. The writing beam can be operated with reduced energy allowing for a write-through capability. This is the ability to illuminate points without causing storage and is used for such things as a movable cursor.

Advantages of this type of display include a flicker free image, reduced electronics requirements including no need for a refresh memory, low cost graphics capability and the ability to randomly add lines without regenerating the entire image. Disadvantages are slow erase (about .5 seconds), inability to display moving images, small screen size, limited image storage life (about 15 minutes), limited screen life (about 2000 viewing hours), complicated deflection system requirements, and single color. Some of these disadvantages are eliminated in more advanced DVST's being developed.

4.2.4.4 Character Generation

There are several methods of character generation in a CRT display. The shaped beam CRT contains a metal stencil within the tube through which the beam can be selectively directed. High quality characters can be produced very quickly. This technique is not often used today because of expense, added complexity, and the inability to change or modify characters. A similar method makes use of an additional small CRT device called a monoscope. A template, scanned by an electron beam, is used to generate driving signals for character generation on the visual CRT. Symbols can be modified by changing monoscopes.

Other techniques include using complex combinations of standard functions to generate differential deflection voltages and programmed stroke or dot methods. Standard single-chip solid-state read-only memories (ROM's) are available for programmed character generation. When a raster scan is used some form of program dot technique is usually employed.

4.2.4.5 Display Generation

Image generation commands and data are given to the actual display device by some form of display processor. In most cases these commands are in digital form and D/A converters are used to provide analog driving signals.

The display processor can be thought of as a generalized computing element which determines how the available data is to be displayed and issues commands to the display hardware to accomplish this. Typical commands could be "draw a line from point A to point B," "draw a circle centered at point C with a radius of X" or "generate the letter N at location (X, Y)."

The display computing element could be the main computer controlling the system of which the display is a part. Very often it is found that cost and/or performance factors are enhanced when a separate processing unit is dedicated to the display. This is often a standard general-purpose minicomputer, but could also be a special-purpose digital or hybrid machine. For some applications, this processor and the display are operated as a stand-alone unit. Typically, the main computer will perform basic data reduction for the overall system while the dedicated display unit performs specific display processing.

4.2.4.6 Memory

Memory is used in a display system for various purposes. If the data is stored in the memory of a dedicated processor it is called a local memory. Sometimes the memory of the main computer is used.

Displays without inherent memory must be periodically refreshed from a refresh file. Data stored for a display utilizing stroke methods is relatively compact and is usually stored in the dedicated processor's memory. Raster scan data requires much more storage and is typically held on a disk, drum or in a delay line. In applications such as in an A/N display, the raster scan data may be held in compact format with the necessary display signal generated for each sweep.

General purpose display processors are programmable, with instructions usually held in the unit's memory. Actual data to be processed could be held locally, accessed in the memory of the main computer, or referenced from other memories, sensors, transducers, converters, or data sources.

Data communications between the display processor and other parts of the overall system can be an important consideration. Critical characteristics are data rates, delays, reliability and access time. Local display processing often reduces data rate requirement. Care should be taken to prevent crisis situations from occurring when any combination of data link failures occur.

Many display processors have several I/O channels through which multiple independent displays can be controlled. This can result in significant cost reductions on a per-display basis for multi-display systems. A typical processor provides 16 channels for 16 displays. For color or gray level displays, channels can be combined.

4.2.4.7 Functions

Many display functions are necessary or desirable. These can range from 2D image rotation and zoom through 3D rotation and instant replay and up to hidden line removal or half-tone surface shading. Most of these can be provided in software but the higher-level functions can require great amounts of processing and therefore long processing periods. When speed requirements are important, such as when 3D rotation in real time is required, it is often necessary to add hardware function processing. Various options are often available. In general, hardware implementation of functions is expensive but it can provide speed (and, therefore, capability), release processing capacity for other purposes and reduce programming costs.

The display function hardware, sometimes called the display generator, can be digital, analog or hybrid in nature and often utilizes specialized parallel processing or pipeline techniques.

The pipeline processing organization is arranged like an industrial production line. The data is manipulated or transformed by successive functional units. For example, a line in three dimensions may first be transformed by matrix operations in an array processor to conform to a rotated perspective.

The next section could implement a zoom feature while the last unit could remove any hidden part of the line before it was displayed. Speed is enhanced because of the fact that there can be several lines in various stages of processing in the pipeline simultaneously.

4.2.4.8 Display Control

Control of the display processor over such things as format, rotation and scaling can come from programming, external command, from the display operator or from a combination of these on a priority basis.

Functions can be programmed to be controlled by logical combinations of characteristics of any available data. This could include drawing on a data base containing such items as acceptable system parameters or operation scenarios. Control could also come from such external sources as the main computer, system sensors, command level system controllers, etc.

Many devices exist to allow the display operator to interactively enter commands or data into either the display system or the overall system. The most familiar of these are buttons, knobs, function switches and keyboards. When the position of points on the display surface of calligraphic information must be entered, various devices can be used. Included are the trackball, joystick, light pen, beam pen, Rand Tablet, "mouse," pressure sensitive screen, voltage pen and Lincoln Wand.

The light pen is relatively common. A pen-like instrument is touched to the CRT display surface. Simultaneously a raster scan is generated. By measuring the time of arrival of the pulse of light at the pen the coordinates of the location can be determined.

The Rand Tablet uses a pen-like instrument traversing a separate pad or tablet-like frame. Locations are generated as it is moved, usually at a constant data rate. It can be referenced by a cursor presented on the display screen. An advantage over the light-pen type device is that it does not obstruct the operator's view of the screen.

More conventional devices such as an intercom, telephone, or teletype can also be provided to the display operator.

4.2.4.9 Software

The software support for graphics displays has improved tremendously in recent years, but still leaves much to be desired. The evolution to higher level languages has been impeded by an almost complete lack of standardization among displays. No doubt this is a result of the wide variation found in display systems hardware. Much effort has gone into development of machine-independent languages, but most programming is still done in hardware-dependent "machine language."

4.2.4.10 Costs

The general trend in the display field is to decreasing hardware costs and increasing software costs. Most of the development work in recent years has had the goal of reducing display costs rather than increasing performance. The hardware cost reduction in certain areas such as low-cost graphics has been quite great. Software costs are a strong function of programmer salary levels which are gradually rising.

Predicting cost is a difficult endeavor especially when new technologies are involved. An attempt will be made, however, to provide a gross cost/performance comparison. Estimates are based primarily on CRT technology and include the display processor, if any, and standard operator I/O capability. Not included are software costs or reductions per display for multi-screen implementations. It should be noted that implementation costs are often not obvious from hardware cost comparisons. Optional hardware and software and other costs can quickly distort estimates.

Displays will be rather arbitrarily divided into 6 classes. Low and high performance A/N and low, medium, high and ultra-high performance graphics.

Low performance A/N displays are typified by the standard ASR 33 teletype. Cost is usually less than a thousand dollars.

The high performance version is usually a terminal-based CRT display such as an IBM 2260. Costs range from less than a thousand dollars for converted standard TV hardware to several thousand dollars. Expenditures for additional capability such as I/O or local buffered memory for editing can add to this.

The low performance graphics display typically makes use of a CRT storage tube such as that used in the Tektronic 611. The screens are small but very complex images can be displayed and the quality is usually good. The display is limited to relatively stationary images. Cost is from about 3 to 10 thousand dollars.

The medium performance graphics unit usually provides hardware facilities up to and including 2-D rotation and zoom. More advanced functions are programmable. Picture quality and options vary widely. Cost is from about $10,000 for modified TV equipment through about $50,000 for typical units and up to approximately $100,000 for the most advanced. An Adage AGT-110 would be an example of this type of display.

High performance graphics displays provide standard 3D capability. The more advanced in this group provide such things as hardware real-time 3D rotation and windowing. An example of this type of display is the Adage AGT-150. Costs range from about $100,000 to $200,000 and beyond.

An example of an ultra-high performance graphics display would be the one being installed at Case Western Reserve University in Cleveland by Evans and Sutherland. It provides real-time 3D, hidden line and surface removal, and surface shading on complicated objects able to be moved in 3 dimensions in real-time. This installation is priced at about $400,000. A superimposed color image version would cost about $500,000.

4.2.5 New Technologies

A discussion of CRT displays was presented first because they are firmly established in the industry and are the standards by which others are judged. There are, however, many technologies which are challenging the CRTs supremacy, at least in certain areas.

4.2.5.1 Plasma Panels

Early plasma panel development was done at the University of Illinois during the mid-60's. Later development work was done under license to the University by Owens-Illinois, which produced the first commercially available graphics unit, the Digivue.

The plasma panel makes use of gas ionization for light generation. This is the same mechanism used in neon lamps and signs. The plasma panel consists of a small volume of neon or other gas sandwiched between two sheets of glass with the edge sealed. Many parallel strips of metal, horizontal on one and vertical on the other, form an orthogonal grid of electrodes on the inner surfaces. The ends of the electrodes are brought out to a horizontal and vertical edge for electrical connection. When a sufficient potential is placed across any horizontal and vertical electrode, a gas discharge glow is produced. This occurs in the gap between them at the point of intersection as seen from the front or back. The electrical characteristics of the gas are such that a lower voltage is sufficient to sustain the flow. By maintaining this lower voltage across all horizontal and vertical electrodes, a point will stay "on" once ignited. By selectively reducing the voltage between two electrodes, individual glow points can be extinguished.

This is called an "open cell" plasma panel because the interior is a single continuous volume. Closed cell versions are sometimes used. The proper selection of voltage, gas pressure and geometry is required to prevent the firing of adjacent cells. The current-voltage characteristics necessitate the use of series limiting resistors when using direct current. This can be avoided by placing a dielectric between the electrodes and the gas and using AC at between 100 and 500 KHz.

The Digivue is an 8.5" square 512 point by 512 point AC plasma panel. Single point write or erase or bulk erase takes as little as 20 microseconds.

Plasma panels possess many advantages. They are very thin and rugged and should be low cost when mass produced. They are transparent and excellent results are obtained when images are projected on the rear surface. The panel possesses inherent non-fading memory capability, thus should be reliable and have a long operating life. It is addressed digitally which eliminates much of the circuitry required for CRTs. Points can be erased individually and parallel addressing can be implemented. The image produced is clear and bright. Disadvantages include low data rates for some applications, limited capacity and resolution, small screen size and lack of color and half tone capability.

Efforts are underway to add color and gray level capability. Attempts are being made to reduce the firing voltage (currently about 160 volts) so that conventional monolithic circuit construction techniques can be used. Many variations on the basic plasma panel are possible. A method for sequentially shifting the discharge points across the panel has been demonstrated. This could help solve addressing problems in some applications. Other companies besides Owens-Illinois working in the area are Univac, Burroughs, IBM, and Fujitsu.

The plasma panel offers an advanced, practical and available alternative to the CRT for the medium performance display. This position will no doubt improve in the next few years.

4.2.5.2 Liquid Crystals

The name liquid crystal (LC) covers a number of fluids which can be electrically stimulated to change transparency, reflectivity, optical rotation, refraction, light scattering and color characteristics. This occurs by such mechanisms as turbulence caused by the passage of current, or electrostatically induced structural changes at a molecular level. Two important classes are nematic liquids, which normally are optically clear but change to a light scattering state when current is passed through, and cholesteric liquids, which are normally light-scattering but convert to a clear state when an electric field (no current) is applied. Some liquids can be tailored to change properties at specific frequencies allowing frequency addressing.

Significant characteristics in relation to display applications are low voltage operation (usually below 10 volts), low current requirements (usually measured in microamps), low cost and great flexibility. Liquid crystals can be operated at power levels lower than any other available display technique. This is partly because no light is actually generated. Disadvantages of most currently available LCs are slow response, image degradation with time, lack of inherent memory, changing characteristics with temperature, changing optical characteristics with viewing angle and problems with addressing, driving and liquid life-time.

Several companies are actively developing LCs. Several discrete indicator displays are commercially available for wristwatches and electronic calculators. AEG-Telefunken has demonstrated a 100-point-by-100-point color LC display. A projection system with inherent image storage using LCs has been built by Hughes Research Labs. The image is written by using special light techniques and requires about .1 seconds for turn-on and .2 seconds for turn-off.

Various problems seem to prevent the near-term use of LCs for full scale displays, but many are optimistic about high-performance future applications.

4.2.5.3 Lasers

The basic characteristics of the laser have become well known to many through the popular media. A laser can generate a very narrow beam of high-intensity, coherent, monochromatic (single color) light. It can be used for at least three basic display applications, as follows:

Lasers can be used to present images directly to a console or large screen. The light beam performs a function similar to the electron beam in a CRT. The vacuum tube and phosphor are not needed, but modulation and deflection is more difficult. All three primary colors can now be obtained and superimposed for full color, but the basic lack of efficiency still restricts intensity and therefore brightness. Displays marginally better than CRTs have been built for specific purposes but the cost is high. General-purpose, high-performance, high-resolution, color displays at a reasonable cost are expected to be available in a few years.

The other two types of laser displays use holographic techniques for 2D or 3D presentation. A hologram is a photographic plate or other medium upon which light wave interference patterns are recorded. The interference patterns are usually produced by first dividing into two the light from a monochromatic, coherent source, usually a laser. Half the light is reflected off the object whose image is to be recorded and is allowed to interfere at the surface of the plate with the remaining part or reference illumination. After development, when the plate is properly illuminated by a reference source, the reflected light pattern of the object will be reconstructed. To someone viewing the plate a true 3D image will be seen. The viewing characteristics will be indistinguishable from those obtained by looking through a clear glass plate at the real object.

An unusual property of a hologram is that a view of the entire image is recorded at each point on its surface. If it is physically divided into two pieces only one of which is illuminated, the entire image would be visible, although the angle through which it could be viewed would be reduced. Obviously a huge amount of information is recorded in a hologram and a high resolution medium is mandatory.

Much R&D is being done on holography for a variety of reasons. Many of the goals are in the area of mass data storage, instrumentation, measurement and control.

When the object being recorded is two dimensional, extremely high resolution 2D reproduction results. Because the entire image is recorded at every point, imperfections in the recording medium cause a slight degradation in the quality of the whole image, instead of a great degradation over a small area. This means that it may be possible to generate a perfectly good and whole image from a plate that is almost completely destroyed. The data stored is highly redundant and therefore, from one viewpoint, the storage scheme is inefficient. It can be appreciated that by minimizing the redundancy and optimizing the volume of data recorded, very dense storage would result.

The above discussion concerns delayed-time reproduction of data directly recorded on the display surface. Methods are being developed for the real-time display of information transmitted over data channels requiring an easily accessible and hopefully reversible medium.

4.2.5.4 Light Emitting Diodes

Light emitting diode (LED) displays are confined mostly to the discrete indicator market. The LED works with low voltage, is bright, offers several colors and has an extremely long life time but it is expensive and inefficient in power use for applications requiring many units. Arrays of up to several hundred points have been built for applications where a relatively small number will be active simultaneously. For graphic applications large arrays of the currently available LEDs would require too much power to be practical.

4.2.5.5 Light Emitting Films

Light emitting films (LEF) are made by sandwiching a phosphor between a clear front electrode and a rear electrode. Current through the phosphor causes light to be emitted. The LEF is an advanced form of the electroluminescence (EL) devices commonly used for such things as nursery night lights. LEFs are used mostly for discrete indicators. They are relatively inexpensive and large arrays are possible, but about 150 volts driving potential is required and no inherent memory is possible.

4.2.5.6 Solid State Devices

Various solid-state materials and devices are the object of intense research for display-related applications such as image storage and light beam deflection, modulation and dynamic color filtering. A material being extensively investigated for these functions is BLZT (a lanthanum-modified lead zirconate titanate).

4.2.6 Large Screen Displays

While most console displays are CRT based, several methods for large screen displays are currently in use.

4.2.6.1 CRT Projection

Readily available at reasonable cost, CRT projectors are popular for real-time display. Special CRTs are used in which every effort is made to optimize light output. Disadvantages are very high operating voltages often necessitating the use of x-ray shielding and cooling, limited screen size (usually 6 ft x 6 ft) and generally a lack of brightness for moderate to high ambient light environments. Color can be added by using a shadow mask or other color CRT or by superimposing three single color images. Front or rear projection can be employed. At least one color rear projection unit (Sony) uses a black screen containing thousands of small holes for use in well-lit areas.

4.2.6.2 Film Projection

High quality wall size presentations can be provided by film projection systems. The image is recorded on film from a CRT and developed before projection. The development process typically takes less than 10 seconds. Color is usually implemented by superimposing three images from three CRTs. Advantages are availability, high brightness and resolution, no flicker and permanent hard copy. Various techniques and processes such as reusable film are continuously being developed, but general disadvantages are the processing delay, expense and logistics problems caused by continuous film and chemical use, complexity, alignment problems with color and wet processing.

4.2.6.3 Photochromatic

A photochromatic substance changes color when exposed to one color light and returns when exposed to another color. This property can be used to make reusable film. Typically, ultraviolet light is used to write an image, visible light is used for projection and infrared is used for erasure. Advantages include film reusability, dry processing, simpler hardware than film projection and very high resolution. Disadvantages are lack of contrast, lower light levels and high energy requirements of current materials. In addition, most photochromatic substances produce black on white, requiring subtractive techniques for color.

4.2.6.4 Oil Film

Distortion produced on a thin film of oil by an electron beam can be used to modulate the output of a high intensity projection lamp. The system is known as the Eidophor projection system and is often used for commercial TV projection. True real-time, high resolution (1000 TV lines), high quality color images can be produced. Many of the problems associated with the oil film technique, such as oil and cathode degradation with time, are eliminated in a new system developed by Toshiba.

This type of system is used when a high-quality, large-screen image is required, but is relatively expensive.

4.2.6.5 Deformable Plastic Tapes

Deformable plastic tapes are heated and then deformed by an electron beam. The result can be projected and then used. The process time is short, but the resolution is limited and special optics are required.

4.2.6.6 Laser

As mentioned above, lasers can be used to generate large screen images. Their use is currently limited by power, modulation and deflection expense and complexity.

4.2.6.7 Arrays

Various arrays of discrete elements can be used for large screen displays. Incandescent lamps are often used in this manner. Plasma panels could be used for large screen displays of limited size if they were expanded or if several smaller ones were employed. An added advantage of this would be inherent storage. Work has been done in recent years on various applications of fiber optics and light pipes to display information. One scheme uses a scanning electron beam to change the optical quality of an array of light pipes, effectively modulating the light. The results could be either directly viewed or projected.

4.2.7 True 3-D

Many techniques have been demonstrated which display a true 3-D image. Three methods are generally used. In the volumetric or cubic method, points in a three-dimensional volume are made visible. This is typically done by optical projection on a moving screen, by focusing a light or other beam at a point, or by intersecting two or more beams. In the flat stereo pair method, different images are presented to the viewer's eyes. This system is limited to a single view, while the volumetric method presents an almost unlimited number of views simultaneously. For transmission, the stereo pair requires no more than twice the bandwidth of single image while, in general, the volumetric system would require many times this capacity. The third technique, holography, could be considered a hybrid form of the first two.

The stereo pair is usually presented in one of three ways. A lenticular plate employs an embossed plastic sheet to direct alternate narrow strips of two stereo images to the proper eyes. This method is commonly used for 3-D picture post cards. Three dimensional TV and movies have been demonstrated using this techniques. Registration is usually a problem when projected.

The second method has the operator look into separate eye pieces. Stereo microscopes and hand-held stereo viewers use this method. A recent variation places separate miniature CRTs before the viewer's eyes. The apparatus is mounted on the head and is mechanically monitored so that the view changes in response to the viewer's movements.

The final technique makes use of stereo glasses. Shutters can be alternately opened and closed before the viewer's eyes in synchronism with alternating images from TV or movies. Another method uses a two-color image (usually red and green), and separate color filters to achieve separation. Commercial 3-D films typically use a separation-by-polarization technique allowing the use of full color. This has been adapted for some versions of 3-D TV.

4.2.8 Aural Displays

The omni-directional and attention-gaining properties of sound communication can be useful in a display system. Some form of computer controlled, single-level, sound signal is used in many interactive displays.

This could be provided by a teletype printing a character, a buzzer, tone generator, or other device. Some systems use modulated sound to represent one or more variables. The pitch and interval of a signal can be easily recognized by a human operator. When volume becomes variable, pitch determination becomes more difficult. It should be noted that this type of signal could interfere with normal verbal communications between the operator and other personnel.

Voice can be used for man-machine communications. The task of recognizing and understanding human speech by computer is a difficult one because of the almost unlimited variations.

Speech generated by computer is a mature technology. Most are programmed voice units for automated telephone response to bank deposit inquiries, stock quotation requests and so on. Most use a magnetic or optical recording of individual spoken words and patch the message together from them. This is usually too expensive ($10K - $100K) unless a specific need exists.

A low-cost synthesizer was recently introduced to this market. It uses sound generators to produce audio signals in a process analogous to the operation of the vocal chords. Words are generated when "phoneme" commands (a phoneme is a basic unit of speech) represented by an 8 bit word (byte) is received. Words generally require about the same number of phonemes as there are letters in the word. The unit has an unlimited vocabulary when externally commanded, can be programmed to change voice characteristics, and is relatively inexpensive ($2K - $3K).

4.2.9 Technological

The general trend in displays is to reduce costs in order to open new areas of application. This is one of the main thrusts behind research into new technologies. It also accounts for the trend toward the use of TV equipment. Production of equipment for commercial use is high and the hardware is well developed and available, as is transmission and storage equipment.

There is a strong tendency toward general-purpose, programmable display systems. This is especially so in command and control, an area that has traditionally required specialized hardware.

The field of graphic displays is competitive, with many companies involved, but except for the computer main-frame manufacturers, the companies currently marketing CRT graphic displays are not the ones developing new technologies.

4.2.10 Future Displays

CRTs will probably continue to be the most popular display device for at least several years. Near-term CRT developments should include the availability of high resolution (about 1000 lines) color at moderate cost, improved display hardware for fast and accurate curves, lines and characters, low cost hardware for such functions as edge clipping, windowing and hidden line removal, advanced, low cost scan converters and hardware to generate quality moving-pictorial images from high-level specifications and commands.

The plasma panel is already challenging the CRT in some areas and probably has the greatest potential of current alternatives for advanced graphics in the near future. The next few years should see the availability of competitively priced, high-resolution plasma panels with color and half-tone capability and selective read, write and erase.

4.3 TSPI DISPLAY REQUIREMENTS

It was not the purpose of this study to postulate the configuration of displays for the COR. For analyses and evaluation purposes however, the following probable characteristics were derived from the statement of work and other information.

4.3.1 Continental Operations Range

The COR will most likely be implemented in two parts. The near-term system (3 to 5 years in the future) will be able to track 16 targets. The far-term system (five to ten years in the future) will be able to track about 100 targets, of which approximately 60 would be airborne vehicles and 40 ground vehicles. The near-term system will operate as an independent unit. There will be no range control except for the TSPI system. The far-term system will have command and control functions at a master control center which would have much greater computational and display capabilities available.

Input data to the TSPI system will be from both field elements and information relayed from the airborne vehicles. The basic output of the TSPI system will be very accurate X, Y, and Z coordinates for each vehicle. Additional data which could be available include the velocities and accelerations of several range elements in three dimensions, the attitudes of all aircraft and specific event data from the vehicles, such as the simulated or actual firing of a missile or release of a bomb. Other information could include the type of each aircraft or ground vehicle, the name and rank of each pilot, the amount and type of armament on each vehicle, the maximum acceleration allowable for each aircraft, etc. Other facilities available to the range control computer could include TV cameras located on the range, various air-to-air, air-to-ground, or ground-to-air missile simulations able to be run in real time, remotely controlled ECM equipment, RPVs, etc. The range control computer thus has a continuous high-volume stream of data to process. The use to which this data is put depends primarily on the purpose of the exercise being conducted.

Potential uses of COR could include pilot training in air-to-air combat and ground attack, evaluation of weapon systems, tactics development and similar OT&E functions. It would be possible to control range elements from the range control center either by computer or manually, and to tie in simulations of ECM equipment with real operations.

4.3.2 Displays

As far as information display is concerned, it may be only necessary, for example, to record relevant data during the operation. Later this could be processed, with the final results taking the form of listings summarizing statistics such as weapons miss distances, or individual pilot scores. For various reasons, however, it may be highly desirable to provide facilities for real-time man-machine information transfer if efficient use is to be made of the range.

4.3.2.1 Set-Up and Coordination

If 100 vehicles would have to be maneuvered into position before an exercise could begin, a central controller with easy access to the positions of each element and verbal contact with participating personnel would facilitate the exercise set-up. This would be especially important when aircraft with high fuel-consumption rates were involved.

4.3.2.2 Command and Control

The overall range commander must have fast and efficient access to range data to maintain effective control over activities. The actual information required to be presented is a function of range configuration.

4.3.2.3 Safety

Computer analyses of vehicle trajectories could be used to detect potential collisions while analyses of aircraft maneuvers could detect instances of structural overstress. Many dangerous situations could arise, however, which would require the experience and problem-solving ability of a skilled human operator to detect and correct. This suggests that some form of real-time visual position display is necessary for the safety officer to fulfill his function.

4.3.2.4 Training

If air crew training is to be performed on the COR, some form of performance evaluation would be required. An experienced instructor in intimate contact with the situation would be desirable. In addition, a visual recapitulation of the exercise would add to student understanding. This could be accomplished by recording the necessary data for later redisplay (see Section 4.4.2 for ACMR).

4.3.3 Display Characteristics

Having established a probable need for some form of visual display capability, certain characteristics can be identified and discussed.

4.3.3.1 Discussion

To make effective use of the range, the visual displays would be used in a variety of formats depending on the specific exercise. The nature of the exercises would change with time as new systems and tactics were developed. Many candidate systems are severely limited by hardware. For this reason emphasis should be placed on general-purpose programmable display hardware. This would tend to prevent the early obsolesence of the equipment and extend the potential use of the range. It would be possible to use general-purpose display equipment for additional functions, such as general data reduction and analyses for scenario development.

A TSPI display should present the viewer with enough relevant information in a condensed and simple form so that he can constantly evaluate system operation, quickly isolate problems, and have access to appropriate data for rapid decision making. Control of systems producing large volumes of data, such as TSPI systems, usually implement "management by exception." In a TSPI application, this would mean that only a small amount of the available data or information extracted from the available data would be displayed under normal conditions. When a problem develops or finer detail is required, as determined by the computer and/or the human operator, progressively more specific information could be provided. The display would, in effect, zoom in on the data from a particular area.

There will probably be at least three basic types of information to be displayed: alphanumeric, symbolic, and geographical. The alphanumeric information would include facts and figures about the operation, the participants, and the vehicles. It would be used for reference. Some information, like aircraft type, would remain constant during an exercise, while others, like the remaining fuel for each aircraft, would change. Coding schemes other than alphanumeric could be used to indicate such factors as remaining armament for each aircraft or current G loads.

For a small number of low-performance aircraft, flight data could be continuously displayed in alphanumeric format. When more or higher-performance vehicles are involved, other methods would have to be employed. The amount of data could be reduced or it could be presented on multiple displays. Alternately, the operator could select a subset of the vehicles for display, or the range control computer, with manual override, could be programmed to dynamically determine the information to be displayed.

The graphics displays would be necessary when the volume or rate-of-change of the data was too great for effective alphanumeric presentation, or where a graphical presentation would enhance the viewer's understanding of a particular situation. One application would be computer generation of suitable 3-D line drawings of aircraft engaged in air-to-air combat. A presentation such as this could be produced during the exercise and redisplayed later from recorded data (see Section 4.4.2 for a discussion of ACMR). Desirable options would include three dimensional rotation, zoom, automatic centering of the scene, instant replay with slow motion and stop-action functions and the ability to generate alphanumeric characters at random points on the screen. Hard copy would also be desirable.

The third type of presentation, geographical, is required where the relation of the vehicles and events relative to points on the ground is important. In such a situation, computer generated graphical information would be combined with geographical information.

Several techniques exist to accomplish this. Maps on slides or microfilm could be projected onto a CRT either directly or through a rear port, for example. An excellent display results when pictorial information is projected on the back of a plasma panel. Graphical information can be superimposed on TV images in dual mode CRT displays. This could be used with map images or with remote TV cameras mounted on the ground or in aircraft, missiles or bombs. PPI-type displays could be generated using general purpose display equipment.

4.3.3.2 Large Screen versus Small Screen

The choice between large screen displays and small screen individual consoles can be difficult. Large screen displays are used when a number of people view the same scene, when close cooperation or interaction between the viewers is desirable or where an overall view is required. This is especially true in high level command situations. Large screens are usually difficult to control interactively and individual control of the screen by each viewer is usually undesirable.

Individual consoles provide the viewer with a better view of and superior control through interaction with the display. For general TSPI applications, console displays for the ground controllers would seem advisable.

Large screen displays would probably be required for the effective debriefing of the large numbers of personnel involved in an operation or training exercise. Such screens could also be used for overall range display with the commander directing specific functions through personnel at individual consoles.

Special displays have been developed to optimize performance in specific areas. Air Traffic Control (ATC) consoles for examples, have been produced with special facilities for the display of graphic images combined with true radar data. Many displays have been developed for command and control or monitoring of spacecraft.

The number and types of displays which should be implemented in a TSPI system depends, of course, on the specific requirements. If multiple displays are required, however, certain trade-offs should be considered. Multiple identical or almost identical displays provide redundancy for critical applications, particularly if they can quickly and easily switch functions. It should be noted, however, that failure of a central element such as a display processor could affect all displays that it serves. Multiple, identical displays of a general purpose nature can provide great capability and flexibility. In addition to the easing of installation, maintenance and support problems, the ability to interchange software is certainly desirable. If special requirements such as a need for one or more alphanumeric displays, can be identified, different types of displays may be needed. In all cases compatibility between displays should be sought.

4.3.3.3 Color

The addition of full color capability to a display could be desirable if no degradation of the display occurs in other areas and the additional cost can be justified. The shadow mask tube results in poor line resolution while the penetration-type tube allows only two colors (or their combinations).

Other color techniques are available but the resulting cost and complexity might be hard to justify. The outlook for the future is quite favorable. Full color, high performance displays utilizing high resolution, shadow mask CRTs, plasma panels or laser techniques should be readily available at reasonable cost for TSPI-type applications in a few years.

4.3.3.4 3-D

In most applications pseudo 3-D, as implemented on the more sophisticated CRT displays, provides a good illusion of depth. The results of past efforts to provide a practical system for true 3-D depth perception in order to improve the information transfer or to give a sense of reality have been disappointing. Judging from this, attempts to provide true 3-D displays to TSPI ground controller would probably not improve their operation over properly controlled and formatted pseudo 3-D presentations on two dimensional displays. A possible exception to this would be if the display were to be used to remotely control an air or ground vehicle.

4.3.3.5 Operator Interaction

An integral part of most display systems is the capability for the operator to input commands or information. This input can be generally divided into overlapping layers of control. The first level of control is over the display itself. This includes such things as changing the brightness of the display or rotating the image. The next level would be control of the data processing for display. This includes changing formats, specifying additional processing and so on. The third level of control is over the type and quality of the data being utilized. The operator could select, for example, a subset of the airborne vehicles for which the system would obtain more precise attitude and event data. The last form of control would include direct functional control of vehicles or field elements. This could include direct control of aircraft, ground radar stations, or indirect control through verbal commands to pilots or other personnel.

Various techniques and devices have been developed for input purposes. The most familiar being keyboards, function switches, track balls, light pens and others as described above. In designing the TSPI system, care should be taken to allow for possible future expansion of the control tasks of the ground controllers.

4.3.3.6 Physical Characteristics

Physically the ground controlled displays, at least in the initial system, will be housed in trailers. This provides mobility so that the locations could be changed within a range or the facilities could be utilized on a host range. It does, however, impose restrictions on the hardware. Rugged versions of the equipment would probably be required. Adequate facilities should be planned for large screen displays, if they were to be used. Restrictions would have to be placed on the size, weight and power consumption of the equipment, but given current technology and trends in miniaturization these factors do not appear to present serious technical obstacles.

In all of these factors, the expansion of the initial system into the far-term system should be taken into consideration. Many problems would be averted if the transition were properly planned and coordinated.

4.3.4 Display Design Considerations

The analysis of specific display requirements and the generation of specifications must begin with the planned use of the facilities and the type of end-product information that is required. The purpose and potential applications of the facilities should be compared with possible implementations for return-on-investment analysis. As part of this process, it would be useful to insert display format analysis into the evaluation of proposals. The selection of display formats often determines overall range requirements and specifications. For example, the maximum useful number of aircraft to be simultaneously presented in a particular format with full attitude information determines many other required capabilities of the range. An analysis of suggested format would facilitate system design by providing an opportunity to relate subjective usefulness and benefit factors to technical specifications and required effort factors. Display format analysis should be used as an interface between the personnel who are knowledgeable in the long term range objectives, uses and procedures, with the technical personnel deriving the specifications.

4.3.5 Format Design

The display system format refers to the organization of the data presentation. Because the number of possible formats in any given situation is very large, the selection process has been, in the past, more art than science. Various studies do exist, however, which list the various categories of formats, detail advantages and disadvantages of each and outline design procedures.

The generalized design procedure for a format begins with a high-level information requirement. A detailed statement of format is then derived. This states the answer that the observer should obtain from the format in answer to the information requirement. It defines the variables, items, sets of items and relationships needed. The next step is to generate a format requirement or a short description of the variables, items, relationships, orderings and classifications involved in the format statement. The ability of various types of formats to meet the format requirements is then studied. This is followed by the actual design. The display arrangement is then undertaken to group all the formats according to functional levels and integrate them into a complete display.

4.4 DISPLAYS FOR EXISTING TSPI SYSTEMS

4.4.1 Fighter Air Combat Training

The Fighter Air Combat Training (FACT) system has been proposed by General Dynamics. It was designed for tracking tactical aircraft attacking ground targets through a simulated hostile environment. It could be expanded to include ordnance delivery scoring or air-to-air combat. The display system was planned for PPI-type tracking of aircraft relative to ground targets. Accurate position data would be used to present a track for each aircraft, but attitude information would not be necessary for the basic system. This is in contrast to the ACMR design which emphasizes air-to-air engagements and precise attitude representation and relations. Differences in the intended missions for the two ranges result in basic differences between the display systems.

The functions of the display system during an exercise were defined for the FACT system as real-time mission control, real-time mission critiquing and safety monitoring. The controller's display presents tracks of all aircraft on the range, the status of all threats, both in-the-air (interceptors) and on-the-ground (AAA, SAMS, etc.), and various operating parameters and range events. The parameters would include tabulations of aircraft positions, speeds, headings and altitudes. The events include SAM site discovery and identification by an aircraft, SAM and aircraft radar mode switching, missile arm and launch signals and AAA firing signals for each aircraft and defense site. The operator controls the entire exercise through digital data transmitted through the TSPI system and by direct voice communication with aircraft and the threat sites.

For the real-time display, General Dynamics proposed the use of alphanumeric characters, special symbols and graphics to show the exercise geometry in an augmented PPI radar format. The aircraft position update rate would be approximately once every five seconds. The level of sophistication required for the graphics would be much less than for the ACMR displays.

According to their proposal, the technology evaluated for this display task included CRTs plasma panels, LEDs, TV systems, EL panels, photochromatic systems, and film systems. The parameters investigated were brightness, contrast ratio, resolution, flicker, legibility, color, noise and display size. The results indicated that a CRT display would be the best choice. Since then, however, the Owens-Illinois plasma panel has become available and the opinion has been expressed by some General Dynamics personnel that this might provide a better display. This is probably because of the excellent results obtained when a map is projected on the rear surface of the panel.

It should be emphasized that rather simple graphics are used in FACT, and that the size and resolution are not yet available in plasma panels to generate the complex graphics produced by the ACMR displays.

The FACT designers concluded that, because of a large number of people involved, a large screen display would be required for effective post-flight debriefing. The format would be the same or similar to the real-time display. The approaches considered were projection CRTs, plasma panels, lasers, light values, LEDs, and film systems. According to the proposal, a projection CRT was clearly indicated. A five-foot-square screen was determined to be sufficient.

The debriefing display would be operated in a manner similar to the ACMR display in playback. Raw data recorded on tape could be used to recreate the mission. Functions would include stop action, slow motion, speed up, jump to a specific time, and so on. Interactive controls would include a track ball and function switches. Map overlays would be provided by a slide projector.

A facility proposed for the FACT system which has not been incorporated into the ACMR is an aircraft flight path generator to be used for real-time simulation and post flight debriefing.

Aircraft characteristics such as maximum speed, minimum turn radius and maximum rate of climb would be stored in a data base. The display operator would specify to the system computer the initial aircraft position and velocity. From this information and other data on the real aircraft participating in the exercise, the generator would compute a real-time flight path for an enemy interceptor. This simulated vehicle would appear on the display and real aircraft could be warned to attempt evasive maneuvers in response to the threat.

For debriefing purposes the generator could be used by the instructor to interactively modify the flight path of real or simulated aircraft. This would be helpful in demonstrating or evaluating alternative maneuvers. More extensive simulation could be provided in an advanced system.

Another FACT proposal is for automatic hard copy storage of selected parameters.

4.4.2 Air Combat Maneuvering Range

The Air Combat Maneuvering Range (ACMR) is presently under construction for the Navy at the Marine Air Station, Yuma, Arizona, by the Cubic Corporation of San Diego. The primary purpose of the system is to train air crews in air-to-air and air-to-ground tactics.

The current range configuration tracks up to 16 aircraft and provides attitude data on any subset of four. This information is available to the display subsystem along with accelerations, closing rates between planes and targets, ranges between aircraft, airspeeds and other TSPI-derived variables. Data processing is performed by three XDS Sigma 5 computers. One is used for overall range control, the second for navigational and safety computations and the third for missile simulation (see Section 7.1.1). The display subsystem was developed by Adage, Inc., of Boston.

The usual mode of operation of the ACMR is to have an instructor-pilot seated at a ground console directing the simulated combat engagements of student pilots in real aircraft. Two sets of displays have been implemented, one at the range and the other at the Miramar Air Station near San Diego. The aircraft using the ACMR are based at Miramar. The two sets of displays are connected by a 50 kilobaud microwave link.

The instructor can view three CRTs, two Adage AGT (Adage Graphics Terminal) - 110's for alphanumeric and aircraft parameter display and an AGT-150 for 3-D graphics. An additional AGT-150 is available for independent use by another operator.

Each terminal provides a viewing area of 14" x 14" with a 10" square area for precision viewing. They are able to display 40 lines of 96 characters for a total of 3840 characters. They are generated by a cursive stroke technique. The grid of addressable points is 16K x 16K with a maximum total line length per frame of 11.9K inches. The brightness is 2 foot lamberts and the maximum resolution is 50 lines per inch. The refresh rate is 60 frames per second. Standard data entry features are horizontal and vertical tabulation, formatting, page roll and split screen. Only B and W is available (P-7 phosphor).

The display processor for both is a 30-bit word hybrid computer. It is known as the Adage DBR-4 and is provided with an 8K x 30-bit memory (expandable to 16K or 32K) with a one microsecond cycle time. Up to four independent displays of either type can be served. In the ACMR all four displays are serviced by a single processor. Up to 20 priority interrupt channels are available as options. Magnetic tape and disk units and other peripherals are optional. A 1 Mbps half/full duplex parallel computer interface (RS 232 B) is standard with various options available. Standard are vector and character generators and a hardware coordinate transformation unit allowing automatic scaling, translation and rotation. The AGT-110 has 2-D capability while the AGT-150 has 3-D with Z modulation and can be provided with windowing hardware. An electrostatic hard copy unit is available.

The display processor and one display weighs between 4000 and 8000 lbs. For a standard configuration of a single display and processor the AGT-110 would cost $98,000 and the AGT-150 would cost $167,000. Additional options would, of course, increase the price while multiple displays per processor would reduce the price per display.

Static information is presented to the instructor on the first AGT-110. Data provided includes name and rank of pilot, type of aircraft, name of exercise, hazards, mistakes and evaluation of test results. The second 110 provides a dynamic presentation of altitude, g force, angle of attack, and true air speed for 4 selected aircraft. The AGT-150 display presents a computer-generated real-time graphical representation of the four aircraft. A pseudo 3-D line drawing of each aircraft is presented. A time track variable from 0 to 10 seconds emanates from each wing tip. The left wing track is dotted for identification. Aircraft size and line intensity are controlled to give a realistic display. Line drawings of local mountains are provided to reference ground as an aid to orientation. Crosses are used to illustrate the aircraft ground tracks. The other aircraft (up to 12) on the range are represented by numbered diamonds on the display with no attitude information or time track.

The instructor can interactively change his viewpoint in 3-D and zoom in on the exercise. The center of the display can be automatically set at the centroid of the four aircraft. Other centering schemes including manual adjustment are available. If the point of view is oriented perpendicular to the ground, a PPI-type display results. A computer generated view out the window of any aircraft can be selected. The instructor is in radio communication with the pilots and can give instant advice and criticism.

When a pilot attempts to launch a simulated air-to-air missile, this is reported to the ground where a real-time missile simulation is begun and a hit or miss determined. Hard copy of the screen image can be called for at any time and all relevant data is recorded on magnetic tape. Afterwards the instructor and the pilots can play back the exercise and discuss the results.

The display contract was let to Adage in August 1971 and the hardware delivered in February 1972. The software was delivered and the debugging began in the spring of 1972. By late summer, performance testing and analysis had begun.

The number of aircraft to be presented with attitude information was specified by the Navy. According to the display designers, more aircraft could be presented but the result would be too confusing to an operator, at least for their particular application. Color was not a specified requirement and in their opinion was too expensive and unnecessary.

Debriefing has been found to be difficult with the console CRTs for the number of pilots and other personnel involved. Cubic is currently looking into large screen projection CRT displays to alleviate this problem.

The Navy is reportedly conducting a study to determine optimum use of the ACMR displays.

4.5 CONCLUSIONS AND RECOMMENDATIONS

Because the configuration and uses of the COR have yet to be specified in detail, recommendations concerning specific display implementations cannot be made at this time. Preliminary conclusions and recommendations are as follows.

An organized display design effort should begin in the early stages of overall range design. Display formats and requirements should be important design considerations.

Section 4.3.2 discussed several high-level range functions which would require real-time graphics displays. CRTs and plasma panels appear to be the only practical devices which will be able to provide the required capability within the next few years.

CRT displays currently provide the greatest capability for the detailed, fast moving graphical presentations required for air-to-air combat exercises; plasma panels suffer from lower resolution while providing an excellent display for tracking aircraft and ground vehicles against a very detailed projected map.

Because of flexibility, compatibility, and expandability considerations, general-purpose programmable display hardware is clearly indicated. Many such systems are presently available or under development. New programs for special purpose display hardware development should be avoided unless absolutely required.

The software support to be provided with proposed displays should be studied very carefully. Powerful and versatile high-level languages are a necessity. With the costs of displays continuing to decrease while programming costs rise, the software could easily become the most expensive part of the display system. This is especially true in an environment where the use of the displays is varied and continuously changing.

Hardware capability beyond basic display should be considered. Certain hardware features will no doubt be required so that the displays can perform functions such as 3-D rotation in real time. Features which are likely to prove cost-effective in this application are listed in Section 4.2.10 and described throughout Section 4.2.4.

Within the many functions to be performed by the COR, there will surely be several other than TSPI that require the use of display systems. These functions should be identified early in the development cycle so that total display requirements can be compiled and an integrated set of displays designed.

Section V

EXISTING NAVIGATION SYSTEMS

A brief review of existing navigation systems is provided. DECCA, OMEGA, LORAN, LORAN/Inertial, TACAN, and TRANSIT were evaluated with respect to satisfying TSPI requirements. All of these systems are user orientated and, with the exception of TACAN, passive in the sense that the user does not transmit any signals to determine his position. The TACAN system requires the user to transmit pulses which are replied to by a ground station in order to determine range and bearing. None of the systems have a central location reporting capability which is a prime requirement for a TSPI system.

DECCA, OMEGA, and LORAN are hyperbolic position systems. The user determines position from the intersection of two known hyperbolic lines. These lines are determined by measuring the range difference between the user and land-based stations, properly spaced and normally operated in groups of three.

The LORAN/Inertial system is a hybrid configuration which combines the long term accuracy of LORAN with the short term accuracy of an inertial measuring unit. The overall system is inherently more accurate than either system used independently.

The LORAN/Inertial system can operate day or night and under all weather conditions. The frequencies used are noninterfering with Air Traffic Control signals and known threat equipment.

TACAN is a line-of-sight system with ground-based stations from which users obtain range and bearing. The user must transmit an RF signal to the TACAN station to obtain a range measurement. Bearing is obtained by phase measurement.

TRANSIT is a space-borne navigation system which uses satellites as reference stations. The user measures the doppler frequency of the satellite and translates this into hyperbolic lines of position on the surface of the earth.

5.1 DECCA NAVIGATION SYSTEM

The DECCA navigation system consists of four ground stations, one master and three slaves. Low frequency radio emissions from all stations are phase-locked to and harmonic multiples of the master station signal. A user receiver multiplies the received signals from any two stations to obtain a common comparable frequency. The measured difference in phase between signals determines a hyperbolic line of position for the user.

Typical accuracy is ± 1 n.mi. at 120 n.mi. range from the master station and ± 5 n.mi. at 250 n.mi.

The system is continuous in operation and the user's position is plotted in rectilinear coordinates by a DECCA X-Y type plotter. The time constant associated with this equipment is approximately 0.6 sec.

5.2 OMEGA NAVIGATION SYSTEM

OMEGA is an earth-referenced navigation system operating between 10.2 and 13.6 KHz. At present, four stations are operating although eight stations are planned to provide world-wide coverage. Each station transmits on synchronized frequencies of 10.2, 13.6 and 11.33 KHz in sequence. At each frequency a unique family of hyperbolic lines-of-position (LOPs) is generated by phase difference measurements between two stations of a synchronized pair.

Single frequency OMEGA is the standard configuration. The basic measurement is the phase of the 10.2 KHz signals from each of several stations. Phase differences between two pairs of stations are measured and two LOPs are obtained. Position is then determined at the intersection of the LOPs.

Phase measurement results in multiple ambiguous position possibilities since a phase difference of X degrees cannot be distinguished from a phase difference of X $\pm$360n degrees. At 10.2 KHz, the position uncertainties, called lanes are spaced 16 n.mi. in distance. The position uncertainties can be resolved by starting from a known geographical position and counting lanes or using difference frequency OMEGA. In this mode, the 10.2 and 13.6 KHz signals are used to create a 3.4 KHz difference frequency. The resulting lane width is 24 n.mi. thus decreasing the lane identification problems.

5.3 LORAN NAVIGATION SYSTEM

LORAN is a hyperbolic system of navigation. A measurement of the difference in times of arrival of signals from two points by a receiver provides a measure of the difference in the distance of the propagation paths. Measurement of the time differences and hence the distant differences places the receiver on a hyperbolic line-of-position. Measurements from a minimum of three stations, taken in pairs, are required to obtain a navigation fix. The intersection of the two lines-of-position defines the receiver location.

A LORAN triad consists of one master and two slave stations. The master station initiates RF transmissions at time zero. Each slave station receives these transmissions and phase and frequency locks its receiver to the master station's transmissions. After a prescribed time delay, different for each slave station, each slave station transmits a pulse group. There is no overlap in transmissions from any of the stations.

The receiver synchronizes to the master and slave transmissions and determines the time differences. With knowledge of the slave station time delays, these differences are translated into lines-of-position.

5.4 LORAN-D/INERTIAL NAVIGATION SYSTEM

LORAN-D/Inertial is a hybrid navigation system which integrates data from an inertial measuring unit with position information derived from LORAN/D signals. The inertial dead reckonner has high short term accuracy and is able to follow maneuvers of the user. Long term accuracy, however, is poor due to gyro drifts.

Position data obtained from LORAN-D signals has excellent long term accuracy, thus, the hybrid system which results from combining the two has better overall accuracy characteristics than either subsystem separately. In general, the greater the accuracy of the inertial equipment, the larger the reduction in position error over the unaided LORAN-D system.

Although several integration schemes are possible, the most accurate inertial platforms usually require Kalman filtering techniques to achieve their ultimate accuracy. For a state-of-the-art 0.25-knot inertial system, a reduction in CEP from 300 ft to 78 ft or a factor of 3.85 times is possible neglecting errors due to geometrical dilution of precision and topographical distortion of the earth's magnetic field (warp).

Warp errors, however, may be large enough to make it unnecessary to incorporate an exceptionally precise inertial unit. Overall improvement in position accuracy accounting for warp errors may be typically 12% over an unaided system with little sensitivity to inertial unit accuracy.

5.5 TACAN NAVIGATION SYSTEM

TACAN is a tactical air navigation system which provides an aircraft distance and bearing from a selected ground station within line-of-sight range.

The user sends pulses that are replied to by a ground station. The elapsed time between the user sending and receiving a reply is used to determine the distance to the station. The nominal system accuracy is 0.17 n.mi. The distance-measuring replies from the ground station are amplitude modulated by a rotating directional antenna. This signal is compared with a reference signal sent by the ground station, the phase difference between the two giving the bearing to a nominal accuracy of one degree.

The available frequency band is between 960 and 1215 MHz and is split into 252 channels. Each ground station is assigned one receive and one transmit channel, and can reply to about 100 aircraft simultaneously.

5.6 TRANSIT NAVIGATION SYSTEM

The Transit navigation system uses four orbiting satellites to enable users to calculate position fixes every 110 minutes.

With simple user equipment, position accuracy is 0.5 n.mi. Elaborate equipment will improve accuracy to 0.1 n.mi.

The satellite emits a stable radio frequency signal. The user receives the signal and infers its position with respect to the satellite by measuring the doppler shift in frequency due to the relative velocity between the user and satellite.

To provide the required doppler data, a satellite is equipped with a transmitter containing a very stable oscillator. As the satellite passes within receiving range, its signals provide a doppler curve as well as its orbital parameters and the precise time. The slope of the doppler curve determines the distance between user and satellite. The point of closest approach from satellite to user occurs when the Doppler shift is zero. Thus, knowledge of the time of signal transmission, the position of the satellite in space, the doppler curve and the velocity of the user can provide a navigator with his true position.

Four ground tracking stations monitor satellite emissions and make corrections for atmospheric refraction. One master station also controls satellite clock settings and regulation. All of the above correction information is relayed to a ground injection station. Once every twelve hours, the injection station transmits the correction data to each of the satellites, at which time it is entered into the satellite memory unit.

5.7 COMPARISON OF TSPI SYSTEM REQUIREMENTS WITH EXISTING NAVIGATION SYSTEMS

Table X lists the TSPI member tracking and data rate requirements and compares them to the existing navigation systems described in Sections 5.1 through 5.6. The principle of operation and frequency band are not specified in the Statement of Work. The only restrictions on frequency are that the TSPI system must be compatible with all the emitters and receivers operating on the range. These frequency restrictions are in narrow discrete bands from approximately 100 MHz to 20 GHz so that a wide range of frequencies is available for the TSPI system.

The table shows that the LORAN/Inertial system satisfies more of the TSPI system requirements than any of the other systems. The LORAN/Inertial system also does not have any restrictions that, without further development, prevent it from becoming a candidate TSPI system. The next section discusses the changes and additions required to the LORAN/Inertial to adapt it to the TSPI system requirements.

5.8 MODIFICATIONS REQUIRED FOR LORAN-D/INERTIAL TO BE A CANDIDATE TSPI SYSTEM

The LORAN-D/Inertial navigation system is user-oriented and passive in that the user is not required to emit any RF energy. To adapt it for use as a TSPI system the following additions would be necessary:

1. Capability for range members to identify themselves to a centrally located master station.

2. Capability to report range member's position, attitude, velocity, and discrete event data to a master station.

3. Capability for range members to receive digital data communications from the master station.

4. A centrally located master station to receive range member data, perform necessary processing, display range status and member location, and emit any up-link digital data messages to range members.

If retention of the aircraft navigation, guidance and pilot interface functions of the LORAN-D/Inertial equipment is not required, some simpli-

Table X. Comparison of TSPI Requirements with Existing Navigation Systems

	TSPI SYSTEM REQUIREMENTS			EXISTING NAVIGATION SYSTEMS					
	NEAR TERM	FAR TERM	NEAR-TERM SUBSET	DECCA	OMEGA	LORAN	LORAN/ INERTIAL	TACAN	TRANSIT
PRINCIPLE	NOT SPECIFIED	NOT SPECIFIED	NOT SPECIFIED	PHASE	PHASE	PULSE AND PHASE	PULSE AND PHASE AND INERTIAL	PULSE AND PHASE	PHASE DOPPLER
FREQUENCY BAND	NOT SPECIFIED	NOT SPECIFIED	NOT SPECIFIED	100 kHz	10.20, 11.33, AND 13.60 kHz	100 kHz	100 kHz	960 TO 1215 MHz	150 MHz 400 MHz
NUMBER OF USERS	16 AIR	60 AIR 40 GROUND	4 AIR	UNLIMITED	UNLIMITED	UNLIMITED	UNLIMITED	100	UNLIMITED
RANGE	75-nmi DIAMETER	200-nmi DIAMETER	25-nmi RADIUS	250-nmi RADIUS	WORLDWIDE (1972)	200-nmi RADIUS	200-nmi RADIUS	400-nmi RADIUS	WORLDWIDE
ACCURACY (X AND Y)	150 ft SEP	150 TO 5 ft SEP	20 ft SEP	0.25 nmi	1 TO 2 nmi	300 TO 3000 ft	$\pm$64 ft	$\pm$200 ft $\pm1^\circ$	0.1 nmi
POSITION UPDATE INTERVAL	0.1 s	0.1 TO 0.01 s	0.02 s	0.6 s	NEAR-REAL TIME	NEAR-REAL TIME	NEAR-REAL TIME	NEAR-REAL TIME	6 TO 22 min EVERY 108 min
RESOLUTION	200 ft	200 TO 40 ft	40 ft	50 ft	400 ft	60 TO 300 ft	128 ft	$\pm$50 ft $\pm0.1^\circ$	> 50 ft
AIRCRAFT VELOCITY VECTOR	$\pm3^\circ$ $\pm$10 knots	$\pm3^\circ$ $\pm$10 knots	$\pm3^\circ$ $\pm$10 knots	NO	NO	NO	YES	NO	NO
ATTITUDE	$\pm2^\circ$	$\pm2^\circ$	$\pm2^\circ$	NO	NO	NO	YES	NO	NO
AIRCRAFT MODIFICATIONS	PODS ONLY	PODS ONLY	PODS ONLY	POD	POD	POD	POD	POD	YES
CENTRAL LOCATION REPORTING	REQURIED	REQUIRED	REQUIRED	NO	NO	NO	NO	NO	NO
DISPLAYS	2D	2D EXPAND-ABLE TO 3D	2D	NO	NO	NO	NO	NO	NO

fication of the user equipment is possible. For TSPI use only, the guidance subsystem which interfaces with the autopilot, control indicator panel, and horizontal station indicator could be eliminated.

The simplified LORAN-D/Inertial hardware, together with the LORAN receiver antenna, data link transponder, data link antenna and weapons bus monitor for discrete event data could then be packaged in a pod. This would permit any aircraft qualified to carry that pod to operate on the range with no modifications to the aircraft.

It should be noted that the LORAN-D/Inertial equipment does not compute Z axis (altitude) data. Uniquely specifying altitude requires either:

(a) Three time-of-arrival (TOA) differences obtained from four stations in pairs. These TOA differences will determine three hyperbolic lines-of-position which intersect at a unique point.

(b) A priori knowledge that the range member cannot be located below the plane of the LORAN transmitters. This may be an unreasonable constraint on range member operations for terrain found in the area of the proposed COR.

In the event that three TOA differences would be used to determine Z axis position, changes to the software of the digital processor of the LORAN-D/Inertial equipment would be required. A detailed study would be necessary to determine whether sufficient processor capacity would be made available by deleting pilot and aircraft interface functions to allow Z axis computations to be made.

Unless the LORAN transmitters in the vicinity are dedicated to the TSPI range, they may not be placed in locations which provide optimum user-to-transmitter geometry over the range area. The number of LORAN transmitters required to satisfy the near term system requirements is range dependent. A computer simulation or on-site range evaluation is necessary to determine their number and location. However, contractor analysis of their ranging systems for a typical COR environment indicate that anywhere from seven to 35 transmitters may be required.

With state-of-the-art LORAN-D/Inertial equipment, the gross position accuracy can probably be satisfied over most of the range. It is not obvious, however, that the subset position accuracy can be met and further examination of LORAN-D/Inertial system accuracies for a TSPI-size range would be required to make such a determination.

The proposed system could probably be used to locate ground vehicles as well as aircraft. Use by personnel would depend on the weight of any backpack type unit which might be developed.

Reporting of range member data to the master station could be done using an interrogation-response type data link. A transmitter at the master station would emit interrogation signals bearing the identification code of the next range member to report.

A transponder carried by each range element, upon receiving a properly coded interrogation signal would reply with position, attitude (aircraft only), identification, and discrete event data.

This scheme would not only permit varying the members of the high-interest subset but also make possible up-link digital data communications.

Suitable range member transponders and master station RF equipment can probably be obtained nearly "off-the-shelf." The transponder employed by General Dynamics for their RMS-2/DCS system is very close to what would be needed in its present form.

Several areas should be examined in greater depth to determine the feasibility and cost of adapting the LORAN-D/Inertial system for use as a TSPI system:

1. A detailed examination of the LORAN-D receiver to determine adaptability to extracting Z axis position data from LORAN signals.

2. Study of the feasibility and cost of repackaging a simplified LORAN-D/Inertial system together with a transponder, weapons bus monitor, LORAN receiver antenna, data link antenna, interface electronics and power supply equipment in a pod suitable for mounting to a wide variety of aircraft.

3. Study of LORAN-D/Inertial digital processor to determine adequacy of the present unit to perform Z axis position computations.

4. Determination of LORAN-D/Inertial position accuracy in X, Y, and Z for a specific range area, with a view toward satisfying subset position accuracy. Geometrical dilution of precision (GDOP) errors and warp errors (see Section 5.4) should be carefully examined.

5. Estimate size, weight, transportability, and cost of all subsystems.

SECTION VI

CONTRACTOR SYSTEMS--GENERAL DESCRIPTION

This section provides a brief review of the contractor systems evaluated during the study. They include navigation systems, single target trackers, and central location reporting systems. None of these systems, in their present form, is capable of satisfying the TSPI requirements.

6.1 NAVIGATION SYSTEMS

6.1.1 Hastings-Raydist Radiolocation System

The Hastings-Raydist system is a continuous wave navigation system operating in the 1.6 - 4.0 MHz frequency band. (X,Y) coordinate location is computed by each user based on the phase delay experienced by continuous wave signals propagating through free space. No elevation (Z axis) information is available, however.

In use the Raydist T system has demonstrated position accuracy of 10 ft RMS, with a resolution of 1.5 ft. Usable range is 200 n.mi. during the day and 150 n.mi. at night, and is limited by skywave interference.

Since the system is user oriented, no central location reporting capability exists.

The system has seen little airborne use, having been designed primarily for marine navigation. Consequently, no IMU has been incorporated and the user equipment is not pod-mounted. Lack of IMU data necessarily limits the dynamic performance of airborne range members to minimize position errors due to maneuvering.

No interface with data processing equipment is provided and display equipment consists of user-carried position and track plotters, data printers, line followers, and manual navigators.

The cost to develop the Raydist T concept for use as a TSPI system could be high since large hardware and software development programs would be required. This fact in addition to the known susceptibility of CW ranging systems to multipath errors at low elevation angles convinced Calspan not to consider Raydist T as a primary candidate for a TSPI system.

6.2 SINGLE TARGET TRACKERS

The Calspan TSPI study considered six single target tracking systems. Five of these are precision instrumentation radar systems:

1. RCA - AN/TPQ-27
2. RCA - MPS-36
3. RCA - FPS-105
4. RCA - Digital Instrumentation Radar
5. Tasker Industries - Medium Accuracy Instrumentation Radar (MAIR)

Table XI presents the specifications of interest for the TSPI system.

All of the systems will track only one aircraft in either skin-track or beacon modes. With the beacon-tracking configuration telemetry of data to and from the subject aircraft is possible. However, cost and the complexity of arranging for simultaneous operation of sixteen units to meet the near term system requirements are sufficiently forbidding to rule out consideration of the multiple colocated single target tracking radar scheme of range instrumentation.

The sixth system for tracking a single cooperative aircraft is the Sylvania Precision Automated Tracking System (PATS).

PATS is a laser system which can track one aircraft equipped with a retroflector to a maximum range of 16.5 nmi. with a position accuracy of ±30 ft and a position update rate of 100/second.

Aircraft acquisition is either accomplished manually or from initial position coordinates supplied by an outside source.

No communication with the aircraft is possible using the PATS system.

The system is transportable with a 1 hour set-up time.

PATS can operate day or night but only when visibility is greater than 10 n.mi. and there is no precipitation.

The TSPI requirements for multiple target tracking, range capability of 37.5 n.mi., and target attitude information eliminate PATS from further consideration as a candidate TSPI system.

6.3 CENTRAL LOCATION REPORTING SYSTEMS

6.3.1 Inertial Tactical Navigation System (ITNS) Singer Company

The Singer ITNS is a cooperative ranging system which employs clocks and frequency sources at all user and ground station locations which are precisely synchronized in relative frequency and time with those of a master control station. One way RF transmissions from the master station are received by each range member. Since the master station and range member clocks are synchronized the time difference from the ranging message initiation time to the time of receipt of the message is known by the range member and slant range can be computed. This range data together with information from an on-board dead reckoning inertial system is processed by the range member to obtain an optimal estimate of position.

All range members report their position, in a predetermined sequence, to all other range members and the master station. The additional information obtained by each range member in this procedure is used to further refine the position estimate to be reported during the next cycle.

Table XI. Comparative Specifications of Single Target Trackers

SINGLE TARGET TRACKERS	RANGE SIZE-RADIUS (nmi)	ACCURACY-RANGE (ft)	ACCURACY-ANGULAR (mils)	POSITON UPDATE RATE (Hz)	RESOLUTION RANGE (ft)	RESOLUTION AZIMUTH (°)	OPERATE 24 hours/day	COMPATIBLE WITH USATC	TRANSPORTABLE	SETUP TIME	CHECK OUT TIME	COST	AIRCRAFT MODIFICATION REQUIRED	SYSTEM DISPLAYS	DISPLAY TYPE	DATA PROCESSING COMPUTER
RCA AN/TPQ-27	300	CLASSI-FIED	CLASSI-FIED	250	6	1	YES	YES	YES	30 min	10 min	$1.25M	NONE	YES	NS	AN/UYK-7
RCA AN/MPS-36	32,000	<3	0.15	640	375	NS	YES	YES	YES	8 h 4 MEN	8 h	$2.1M	NONE	YES	"A" SCOPE CCTV	DDP-124
RCA AN/FPS-105	32,000	15	0.35	640	375	NS	YES	YES	NO	N/A	N/A	$1.6M	NONE	YES	"A" SCOPE CCTV	NOVA 800
RCA DIGITAL INSTRUMENTATION RADAR	125	15	0.5	640	750	NS	YES	YES	YES	2 MEN 1 h	1/2-1 h	$500K	NONE	YES	A-N CRT	NOVA 800
TASKER-MAIR	240	15	0.25	320 640 1280	105	~ 1	YES	YES	YES	8 h 2 MEN	2 h	$700K	NONE	YES	TWO DUAL TRACE CRT's	TASKER DIGITAL EQUIPMENT

NS – NOT SPECIFIED

N/A – NOT APPLICABLE

Information reported to the master station can include estimated position, inertial parameter values, and digital communications information on discrete events.

In addition to clock synchronization and identification the ITNS system provides 1024 slots per second during each of which up to 300 bits of digital data may be transmitted from range members to the master station. This scheme provides more than adequate capacity to permit obtaining position, attitude and 100 bits of discrete event data on twelve aircraft ten times per second and four aircraft fifty times per second, (the near-term TSPI requirements).

Since the reporting scheme is preset before the mission a selection of four subset members would have to be made prior to an exercise and could not be changed at will.

The equipment carried by an ITNS range member consists of a ranging system, a computer system, an integrated inertial navigation system, appropriate interface electronic units and power supply equipment. These units are mounted in 1/2 ATR cases and must be carried on-board as sufficient miniaturization to enable pod mounting of the airborne equipment has not been accomplished at this writing.

The inertial navigation system is in the mockup stage and is expected to be flight tested during 1973. It is also designed to be contained within a 1 ATR instrument case and consequently does not lend itself to pod mounting.

No real time data analysis or display capability has been developed for the ITNS master station. Data is currently recorded on magnetic tape for later analysis.

If the master station is provided with equipment to interface with a Loran navigation system (or other commercial navigation system) the system could provide georeferenced position coordinates on all range members and would thus be more compatible with Air Traffic Control, enhancing range safety.

A considerable amount of redesign and development would be required to adapt the ITNS system to the TSPI specifications. The most significant of the areas in which additional work is necessary are:

1. Airborne range member equipment currently carried on-board must be redesigned and repackaged to fit inside a suitable size pod.

2. The ranging system hardware must be optimized for the TSPI function since many modes of operation which are not required for TSPI are possible with existing hardware. Optimization will probably reduce the equipment payload carried by range members and the size of the van required to house the master station.

3. Development and testing of the inertial navigation system must be completed.

4. Real-time display and debriefing hardware and software must be acquired and developed.

6.3.2 Task 4 - International Business Machines Corporation

The Task 4 system was designed to provide guidance information for up to seven cooperative aircraft.

For the aircraft tracking and guidance function, a sequential interrogation, pulse type ranging technique enables computation of aircraft position in accordance with a multilateration algorithm.

An interrogation command signal is originated by the Ground Command Station (GCS). Digitally encoded identification information specifies the aircraft of interest and the GRS to be used for that interrogation. All aircraft carry a pod-mounted transponder which will transmit a ranging reply upon receiving a properly addressed interrogation signal. The ranging reply passes through the same GRS and is retransmitted to the GCS station. The transponder time delays are known and the GCS to GRS range is known either from a geodetic survey or by interrogation of a calibration transponder at a known location, therefore, slant range from the GRS to the subject aircraft can be computed. Calculating three ranges from the GRS stations to the subject aircraft in this manner, it is possible to uniquely determine the three axis position coordinates of the aircraft.

As presently configured, the airborne transponder is mounted within a pod for which the Task 4 system provides guidance information. The transponder is physically small enough that repackaging within a smaller pod (like an AIM-9D) is feasible.

Since the Task 4 system does not incorporate an Inertial Measuring Unit (IMU), no aircraft attitude data is available. Also, since no IMU data is available to minimize errors due to aircraft maneuvering, the member aircraft are limited to level flying at slowly changing altitudes. There is no data available, however, on the dynamic limits of the system in its present form.

Three GRS stations are employed in addition to the GCS station. Position updates can be obtained at a 70/second rate on one aircraft or approximately 10/second on seven aircraft.

Present range size is in excess of 80 n.mi. with good geography.

Display of data in real-time is available on a CRT console in either PPI-type range situation, or alphanumeric range status modes. Mode selection is operator-controlled.

In summary, the Task 4 system fails to meet the Near-Term System TSPI requirements in a number of areas.

1. The system can only track seven aircraft simultaneously.
2. The position update rate on seven aircraft is approximately 10/second.
3. Resolution is not specified.
4. No attitude data is available.
5. Member aircraft limited to level flying and slowly changing altitudes.
6. No subset of aircraft at higher update rate and position accuracy available together with remaining range members at gross data rate and position accuracy.
7. Not all aircraft can carry pods in which transponder is presently mounted. Size of pod limits aircraft performance characteristics.

Since the primary objective of the Task 4 system is vehicle guidance the system has not been optimized for the aircraft tracking function. It is anticipated that much development work and many software and hardware modifications would be required to meet the TSPI requirements.

Note: The IBM Task 4 system has an updated variant, the ALSS (Advanced Location and Strike System). The ALSS demonstrates a considerable TSPI capability in its present IOT&E stage. The ALSS was available during the time of the Calspan TSPI study, but could not be included in the study due to its classification. Appendix C (Secret) of this report, prepared for RADC and published separately, will discuss ALSS technology and its relationship to TSPI requirements.

6.3.3 Air Force Weapons Effectiveness Testing - Weapons Effectiveness System Test Environment (AFWET-WESTE) - Raytheon Company

The AFWET-WESTE system can obtain position, attitude and identification information on 15 cooperative aircraft and position and identification information on up to 11 ground units of which 10 are fixed and one is mobile. Both coarse and fine position locating subsystems are carried on-board each member.

Coarse position is obtained passively from a DECCA navigation set with an accuracy of approximately 400 ft (1σ). Fine position of the member with respect to the ground master station, other range members, or any fixed, instrumented ground element is obtained from a precision Position Reference Radar/Transponder (PRRT). The aircraft is active during fine position measurement in that RF energy must be emitted. The fine position accuracy is $\pm$ 5 ft in range and 2 milliradians in azimuth and elevation angles.

The DECCA navigation system is a CW-type operating on 100 KHz and employs one master and three slave stations each requiring a large (300 ft high) tower. CW systems suffer degraded position accuracy at low aircraft operating altitudes. Attitude information is obtained from the aircraft's own instrumentation and a modification kit is necessary for each different type of aircraft using the range.

All range elements report their position to the master station. Time multiplex UHF radio transmission enables down-link reporting for airborne range members. Ground units report on individual UHF frequencies. Up-link communications from the master station to range members use the same techniques.

In addition to a transmitting and receiving antenna at the master station, a 1200-ft tower located at one side of the range is employed to minimize data loss from antenna shadowing due to aircraft maneuvering. A second radar transponder is mounted through the top of the aircraft fuselage to further minimize this data loss.

The position and attitude update rate for all range members is 10 per second and is hardware controlled. Therefore, no higher data rate on a subset of aircraft can be obtained with present system components.

Data analysis and display is performed in essentially real-time. An IBM 360-65 handles data processing for the system. Alphanumeric read-out and major event annotation are provided in addition to the basic two dimensional display capability.

Beside TSPI information the AFWET-WESTE system also provides trajectory simulation for bombs, bullets, rockets, and missiles as well as kill/no kill assessment and miss distance calculations.

The inertial data obtained from the instruments on-board each aircraft is used for presentation of aircraft attitude and is not used to improve short-term bad-geometry or maneuvering position accuracy as is done in a true hybrid-integrated system.

The ultimate position accuracy of the DECCA system has not been achieved and further development will enable an improvement in position accuracy. However, it should be noted that unaided DECCA navigation system data degrades with aircraft maneuvering and the aircraft performance limitations necessary to achieve TSPI position accuracy requirements would undoubtedly restrict the range elements in their activities. The integration of inertial navigator data would provide the required short term position accuracy.

In summary, the principal reasons for not considering the AFWET-WESTE system to be a primary candidate for TSPI are:

1. Measurement of inertial data requires either modifications to each aircraft used on the range or development of an inertial measuring unit which could be incorporated into the AFWET-WESTE pod.

2. Integration of inertial data with DECCA information will be necessary to achieve the required position accuracy at all range locations.

3. The DECCA navigation system requires 300 ft towers and the auxiliary telemetry tower is 1200 ft high. These structures cannot be considered to be "transportable" in any common usage of the word.

4. The central processor computer is an IBM 360-65 the size and transportability of which preclude its use for a TSPI system. The AFWET-WESTE system could probably be adapted to provide only TSPI information with a much smaller computer unit but software development costs would probably be high.

6.3.4 Multiple Target Tracking and Identification System (MTTIS) - General Dynamics

The General Dynamics MTTIS is a proposed system for which the ranging system hardware has been built and tested. A three baseline interferometer is used to measure two angles (azimuth and elevation) plus range to uniquely determine the position coordinates of a cooperative aircraft.

A coded ranging interrogation signal is transmitted from the ground station. The aircraft whose identification code matches that of the ranging signal retransmits the signal to the ground. The difference in phase of the signal as received at two locations on the ground is proportional to the angle between the receiver baseline and a radial vector to the aircraft. This can be seen more clearly in Figure 8.

Slant range to the aircraft is determined by measuring the difference in phase between the ranging transmission and the reply signal as received at the master station ranging receiver. This phase difference is proportional to the two-way ranging distance to the aircraft, since the transmitter and ranging receiver antennas are colocated.

Simulation based on an error model of the three baseline interferometer predicted position errors of less than 50 ft in X,Y, and Z (Reference 4). Tests with a vertical baseline interferometer confirmed the value assumed for worst-case multipath errors which is the largest error term for a CW ranging system (Reference 5).

A pod mounted Airborne Instrumentation System (AIS) was proposed. The pod would contain an Inertial Measuring Unit (IMU) and preprocessor, encoder/decoder, transponder, power supply, and I/O interface equipment. Development of this pod for MTTIS never progressed beyond the concept stage.

Several factors rule MTTIS unsuitable as a primary candidate for a TSPI system:

1. The MTTIS system hardware has not been sufficiently developed. Only the AIS transponder exists. Ground station hardware has not been fabricated in its entirety and the real-time data analysis and display capability has not been developed.

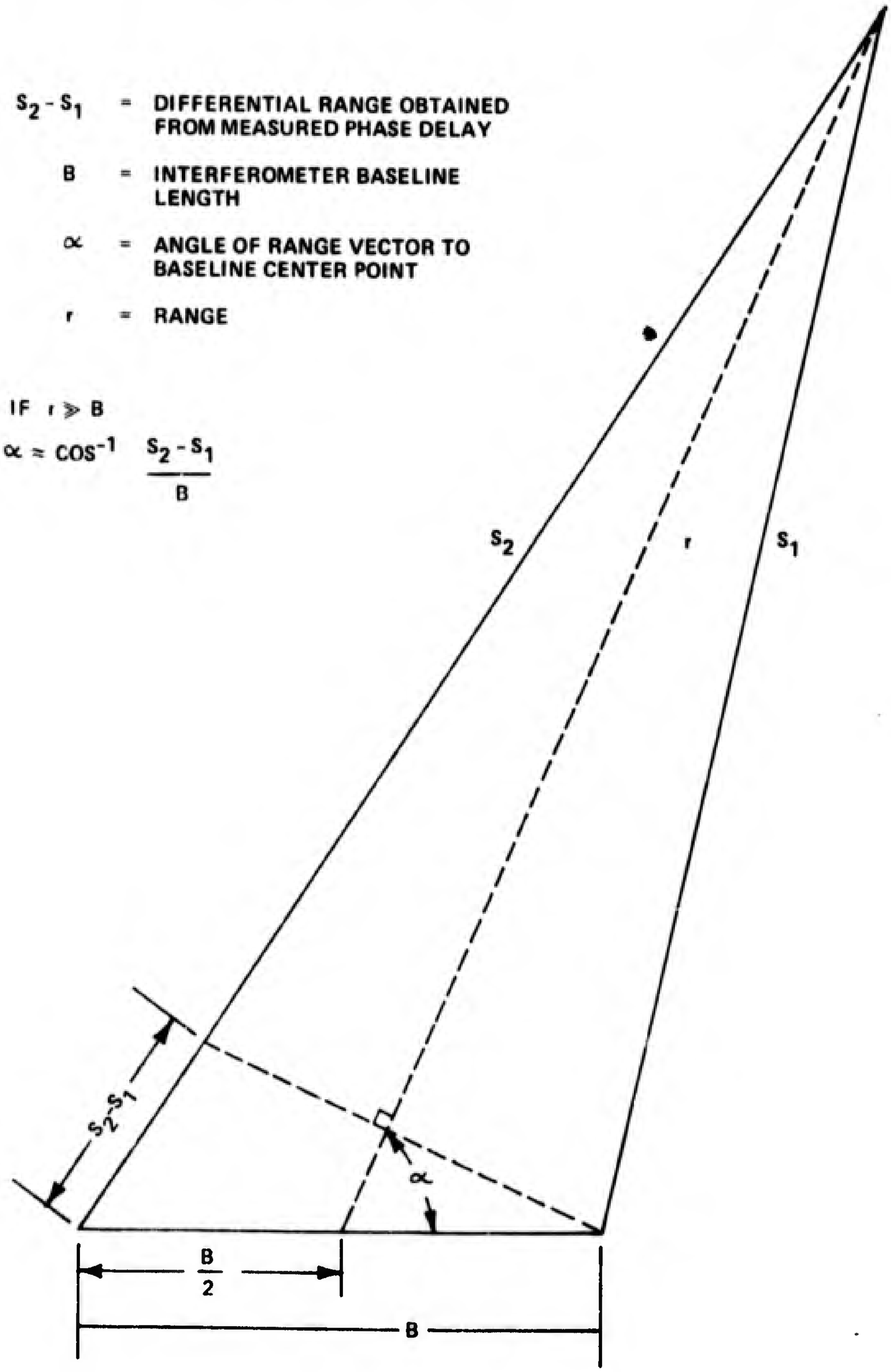


Figure 8. Baseline Interferometer Geometry

2. Obtaining position information on a subset of aircraft at a higher update rate would require a reduced data rate on the remaining aircraft. The maximum aircraft interrogation rate is limited by the time required to phase-lock the ranging receiver at the ground station ot the reply signal from the aircraft.

3. The position accuracy requirement of 20 ft SEP on a subset of aircraft probably could not be satisfied at low elevation angles unless inertial-aiding of the position data was incorporated. The system as proposed is not of the hybrid/inertial type.

4. The minimum tracking altitude is governed by the minimum usable elevation angle of the interferometer. Below 1.5° the tracking system cannot achieve adequate multipath discrimination, thus, the 2000 ft minimum altitude specification can only be met inside a range of 24.6 n.mi. diameter.

5. No digital data communications capability beyond that required for attitude (IMU) data is available.

6. General-Dynamics representatives feel that the severe terrain of the Nellis AFB area will increase multipath errors significantly over those measured in Reference 5. For this reason they feel that a pulse-type multilateration system such as the RMS-2/DCS would be a more suitable system for the TSPI task. They also feel it would be simpler to expand the RMS-2/DCS system to meet the far-term system requirements than it would to achieve the same capability with the MTTIS concept.

6.3.5 Phased Array Ranging Trilateration System (PARTS) - Radio Corporation of America

PARTS is an RCA proposed system which would employ multiple phased array radar stations to obtain range and range rate data on aircraft. A multilateration algorithm would be used to compute aircraft position and velocity.

Each phased array radar would have a 60 degree electronic scan in elevation/azimuth and a 60 degree mechanical scan in azimuth/elevation.

The basic range would be an equilateral triangle 43 n.mi. on a side. Adding a fourth station would produce a parallelogram-shaped range as shown in Figure 9. The long diagonal of this range is 75 n.mi.

It should be noted that aircraft in Area 1 of the range are "visible" to all four phased array radar stations, assuming favorable topography. In Area 2 of the range, however, only stations A and D can "see" the aircraft. This is due to the 60 degree azimuth scan limit on stations B and C.

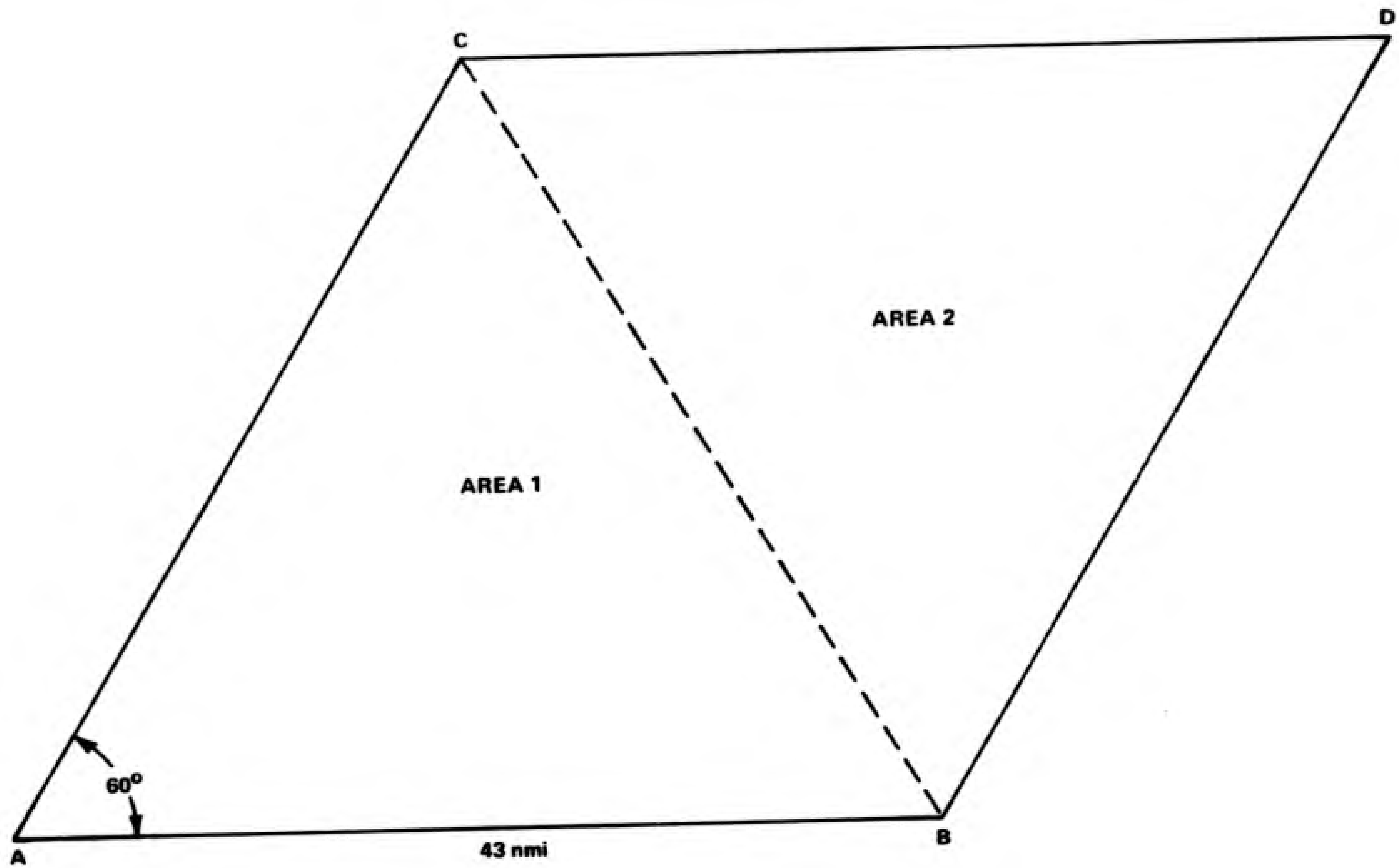


Figure 9. Parts Range Configuration

Each phased array radar can track a target having a 1 square meter cross section at a maximum range of 75 n.mi. Data from the preliminary accuracy study done by RCA applies to the skin tracking model of operation. Unambiguous identification of aircraft, as required for TSPI would probably require the use of a beacon on range aircraft.

No provision was made for obtaining inertial parameter data from the aircraft. If a pod-mounted IMU were attached to the aircraft a separate data link could be used to obtain this information for use at the range control station. Attempting to communicate this data via the radar links would necessitate increasing the dwell time on each aircraft and correspondingly reducing the position update rate.

Basic accuracy of the radar is predicted to be 1 ft in range and .05 mil in azimuth and elevation. Using these figures, RCA predicted a position accuracy of 1.73 ft in X and Y for aircraft between 1000 and 50,000 ft altitude. Z accuracy was predicted to be 8.7 ft for aircraft between 10,000 and 50,000 ft AGL, 19 ft for aircraft between 5,000 and 10,000 ft AGL and 43 ft for aircraft in the 2000-5000 ft AGL region.

The RCA PARTS system was not considered to be a primary candidate for the TSPI task for the reasons which are summarized below:

1. Little hardware actually exists and the phased array antenna in a configuration suitable for TSPI range instrumentation has not been built.

2. RCA has not devised a scheme for obtaining IMU data from the aircraft. Additionally, since skin tracking mode has been proposed, no method for uniquely identifying aircraft under all conditions exists. Except for the case of two aircraft flying in close formation, however, previous trajectory and velocity information could be used to keep track of aircraft identities.

3. A significant amount of software development would be required to synchronize and direct the operation of four phased array radar stations and process the resultant data for display and debriefing in real time.

4. The radar units have a minimum elevation angle of 0.3° and thus would not be able to track ground elements as required for the far term system.

5. Based on RCA computations, the minimum separation distance between two aircraft which can be resolved by the phased array radar at 15 GHz is 1000 ft at 40 n.mi. The 200 ft TSPI requirement can only be met at ranges less than 5 n.mi.

SECTION VII

TSPI CANDIDATE SYSTEMS

7.1 AIR COMBAT MANEUVERING RANGE (ACMR)- CUBIC CORPORATION

This section details the characteristics of the Cubic Corporation Air Combat Maneuvering Range (ACMR) and the General Dynamics Measuring System - Data Collection System (RMS-2/DCS) and compares the system performance specifications to the Continental Operating Range (COR) requirements.

Both of these systems use a multilateration technique to determine range member location from multiple slant ranges. They differ, though, in range measurement technique with Cubic employing continuous-wave phase comparison and General Dynamics using leading edge pulse.

Both systems can operate day or night and under all weather conditions in which range aircraft can operate. The frequencies used for the r.f. ranging signals and digital data transmission are noninterfering with Air Traffic Control signals and known threat equipment.

It is possible, with either system, to self-survey the location of ground reference stations within system accuracy. It should be noted that the overall accuracy of the computed location of range members will be degraded accordingly. Normally, a second order geodetic survey is used to establish reference station locations.

7.1.1 Type of System

The Cubic Corporation ACMR can be characterized as a multilateration, CW-FM, simultaneous-ranging tracking system for location and identification of cooperative aircraft. By simultaneously measuring the ranges from multiple ground stations to a subject aircraft, it is possible to perform a multilateration computation to uniquely determine the position of the aircraft with respect to the ground reference network.

Range from a ground station to the aircraft is computed by measuring the phase delay experienced by sinusoidal modulation on a continuous-wave carrier. Since the phase delay is directly proportional to the distance the signal propagates through free space, knowing the velocity of propagation enables computation of the corresponding range distance.

The ground reference network is composed of a master station and several remote interrogator-responder stations. This network communicates with an airborne transponder contained in a pod, mounted to the member aircraft.

The master station selects a remote interrogator-responder and sends a ranging command to it. The interrogator-responder interrogates the transponder of the desired aircraft which replies to all of the stations in the reference network simultaneously. The remote interrogator-responders receiving the aircraft ranging reply transmit the signal back to the master station where the phase delays are measured and the corresponding ranges are computed.

The range data are fed to a central computer which smoothes the data and computes the relative position of the aircraft by a multilateration algorithm. Relative position data for all aircraft on the range is displayed for real-time monitor and command and control functions and/or may be recorded on magnetic tape for post-mission debriefing.

Aircraft attitude is measured by an inertial measuring unit (IMU) located in the aircraft pod. Attitude data is reported to the ground network along with the ranging information and is employed by the central computer to minimize errors in computed aircraft position due to maneuvering of the aircraft and less-than-optimal aircraft-to-ground network geometry. This latter effect is the familiar geometrical dilution of precision (GDOP) experienced by all multilateration systems.

7.1.2 Description of Subsystems and Their Components

ACMR is comprised of four principal subsystems:

AIS - Airborne Instrumentation Subsystem
TIS - Tracking Instrumentation Subsystem
CCS - Computation and Control Subsystem
DDS - Display and Debriefing Subsystem

7.1.2.1 Airborne Instrumentation Subsystem

The components of the AIS are contained in a AIM-9D pod having the same external dimensions and center of mass as a Sidewinder missile. This pod can be mounted to any aircraft equipped with an LAU-7A missile rack and contains the inertial measuring unit, data encoder, ranging transponder and weapons bus monitor.

The inertial measuring unit (IMU) is a strapdown Lear-Siegler Industries package. Three orthogonal angular rate gyros and three orthogonal linear accelerometers with analog feedback electronics and a six-channel analog-to-frequency converter make up this unit. A small, hard-wired preprocessor is also included to integrate the accelerometer outputs to determine velocities. This unit is also manufactured by LSI and is their model LS-50. Cubic Corporation repackages the computer to fit inside the pod. Modifications to the LSI design to adapt the unit to ACMR needs are in the input-output section and the programmed instruction read-only memory.

The input-output section provides an interface with the data sensors and includes discrete data inputs used for system checkout.

The read-only memory is electrically programmable to enable modifications which may be required by flight testing requirements.

The range transponder serves as a data-link terminal in addition to its range measurement function. A square-law receiver and low-power output transmitter are the principal components of this unit. Since range measurement is performed on the modulation frequencies no high-stability oscillator is required in the AIS transponder.

The weapons bus monitor senses signals at the aircraft launcher to determine weapons status, time of fire, and the type of weapon selected. A radar lock-on indication is also provided.

7.1.2.2 Tracking Instrumentation Subsystem

A master station and several remote interrogator-responder stations form a high-speed, phase-lock-loop ranging system and two-way data link. Additional equipment at the master station included a controller-processor computer for ranging functions, data link equipment for microwave communications with the CCS, voice communications equipment for ground-to-aircraft two-way communications and a precise time-of-day clock.

The master station equipment is housed in two 10 ft x 20 ft vans and contains the following electronic equipment:

1. The range measuring equipment occupies two equipment racks and includes the following:

    a. Range Measuring Assembly
    b. Master Station to Interrogator Transmitter
    c. Interrogator-Responder #1
    d. Interrogator to Master Station Receiver
    e. Calibration Interrogator-Responder
    f. Data Link Assembly
    g. Power Supplies

2. Three additonal racks are used to mount the master station computer.

3. The magnetic tape recorder is mounted adjacent to the computer.

4. A teletype with stand and chair is mounted in a corner of the trailer.

5. Two additional racks contain the equipment required for the microwave data link between the TIS master station and the CCS equipment.

6. The equipment required for voice communications with range members is mounted in one rack.

A 25 ft high tubular steel tower supports the seven antennas required for the TIS master station functions. An omnidirectional antenna serves the interrogator-responder located at the master station and the calibration transponder receiver.

Two sectorial horns are the transmit and receive antennas for the master station-to-interrogator-responder communications.

A third sectorial horn, which is identical to the other two, is the transmitting antenna for the calibration transponder.

The microwave (E/F band) data link is served by an 8 ft diameter parabolic reflector.

VHF communications capability between range elements is provided by two omnidirectional monopole antennas.

The remote interrogator-responders consist of the electronics package, containing receiving and transmitting circuitry for ground-to-ground and ground-to-air ranging signal transmission, an omnidirectional antenna for the ground-to-air link, a parabolic reflector fed by a dipole for line-of-sight communications with the master site, and the battery power supply with a solar cell module to extend the useful unattended service interval.

7.1.2.3 Computation and Control Subsystem

The CCS requires three vans and a tower to support the necessary antennas. One trailer houses the XDS Sigma 5 computers and related equipment; the second trailer is equipped for display and debriefing capability; and the third trailer provided maintenance and support functions for the computer and display vans as well as creature comforts for the operating personnel.

Three Xerox Data Systems Sigma 5 computers are arranged in a multiprocessor configuration. The master Central Processing Unit (CPU) performs all input/output data handling and scheduling. The first slave CPU processes the pod data; and the third unit executes the missile simulation program. The third CPU is optional and in the event of a malfunction in a CPU during an exercise, the missile simulation could be deleted, retaining all other system functions since the three CPU's are effectively operating in parallel. Using the multiprocessor configuration enables each CPU to perform a nearly equal proportion of the processing load.

7.1.2.4 Display and Debriefing Subsystem

Two display and debriefing trailers are currently incorporated into the ACMR system. The Operations Control and Display Van is located adjacent to the CCS van as mentioned previously. A second trailer, the Remote DDS is identical to the Control CCS van except for communications equipment. Its function is to provide a remote monitor and debriefing capability, although, in the event of failure at the Control CCS, the remote DDS can assume complete system control as well as provide range monitor and debriefing capability.

Each DDS has 2 identical consoles, one at each end of the trailer, separated by an equipment area. From left to right the consoles contain a Status Board CRT with subsystem data entry and control keyboard, the main system control panel, the Range Situation Display CRT which provides simulated 3-D graphic presentation, and Aircraft Parameters Display CRT which provides aircraft and range safety data. Operating positions for the system operator, the ground instructor pilot, and the range control officer are provided at the console.

A raised floor area behind the console area can accomodate four observers or students and the desk-chairs they require. Additional personnel can be accomodated if necessary.

The equipment room contains the following:

1. Display processors
2. Data recorders
3. Voice recording and playback equipment
4. Voice/Data synchronizer
5. Hard copy printer
6. UHF voice communications control units

Complete provisions for communications exist at each console. The following facilities are provided:

1. The control keyboard can be used to transmit and receive information from other consoles. Communications are displayed on the Status Board CRT in alphanumeric form.

2. An open-line intercom between all manned locations within the ACMR system is provided through an operator headset/microphone.

3. An outside dial telephone is installed.

4. A speaker intercom system enables communications with mission support organizations.

5. UHF communications between aircraft and ground through the headset intercom may be interfaced with this system to provide two-way communications between any pilot and all range personnel.

6. A communications monitor speaker may selectively monitor any or all of the range voice communications.

7.1.3 Present System Operational Description

7.1.3.1 Tracking Instrumentation Subsystem

The ACMR system is capable of tracking and identifying up to 16 cooperative aircraft. Tracking is accomplished by measuring the slant range from the aircraft to the interrogator responder ground stations using CW-FM phase comparison ranging. Every 50 milliseconds a set of range measurements is made to four high interest aircraft. The ranging slot to each aircraft is 10 milliseconds long. The fifth time slot per ranging cycle is devoted alternately to calibration of the master station-to-interrogator-responder links and ranging to the 12 low interest aircraft. Thus, the position update interval is 1.2 seconds for low-interest aircraft.

Figure 10 details the ranging system interrogation-response signal flow path. A coded ranging interrogation command is emitted by the master station transmitter. All interrogator-responders receive this signal but only the interrogator-responder designated by the identification code in the command signal will enable its ground-to-air interrogation transmitter.

The interrogation signal is received by all airborne receivers. Only the transmitter of the subject aircraft is enabled, causing an air-to-ground ranging response signal to be emitted. This response signal is received by all ground interrogator-responder receivers. Each ground interrogator-responder then transmits the ranging reply signal to the master station receiver on the responder transmitter frequency unique to each ground station in the reference network.

All of the links in the TIS ranging path operate on distinct single frequencies except the remote responder transmitter-to-master station receiver link. Each responder transmitter has its own unique carrier frequency since all responders must be capable of transmitting range signals to the master station receivers at each range measurement time slot.

The signal flow during ranging and calibration intervals is shown in Figure 11. The calibration transponder is colocated with the TIS master station and receives and transmits on the aircraft transponder frequencies. A unique identification code is assigned to the calibration transponder which allows each ground station to master station link to be calibrated. This is accomplished when the master station transmitter commands the interrogator-responder to interrogate the calibration transponder. Each interrogator-responder is calibrated in a simple numerical rotation every tenth ranging time slot (assuming 16 member aircraft).

The slant range from the interrogator-responder to the aircraft can be extracted from the total loop link range by the method which follows. Reference can be made to Figure 12.

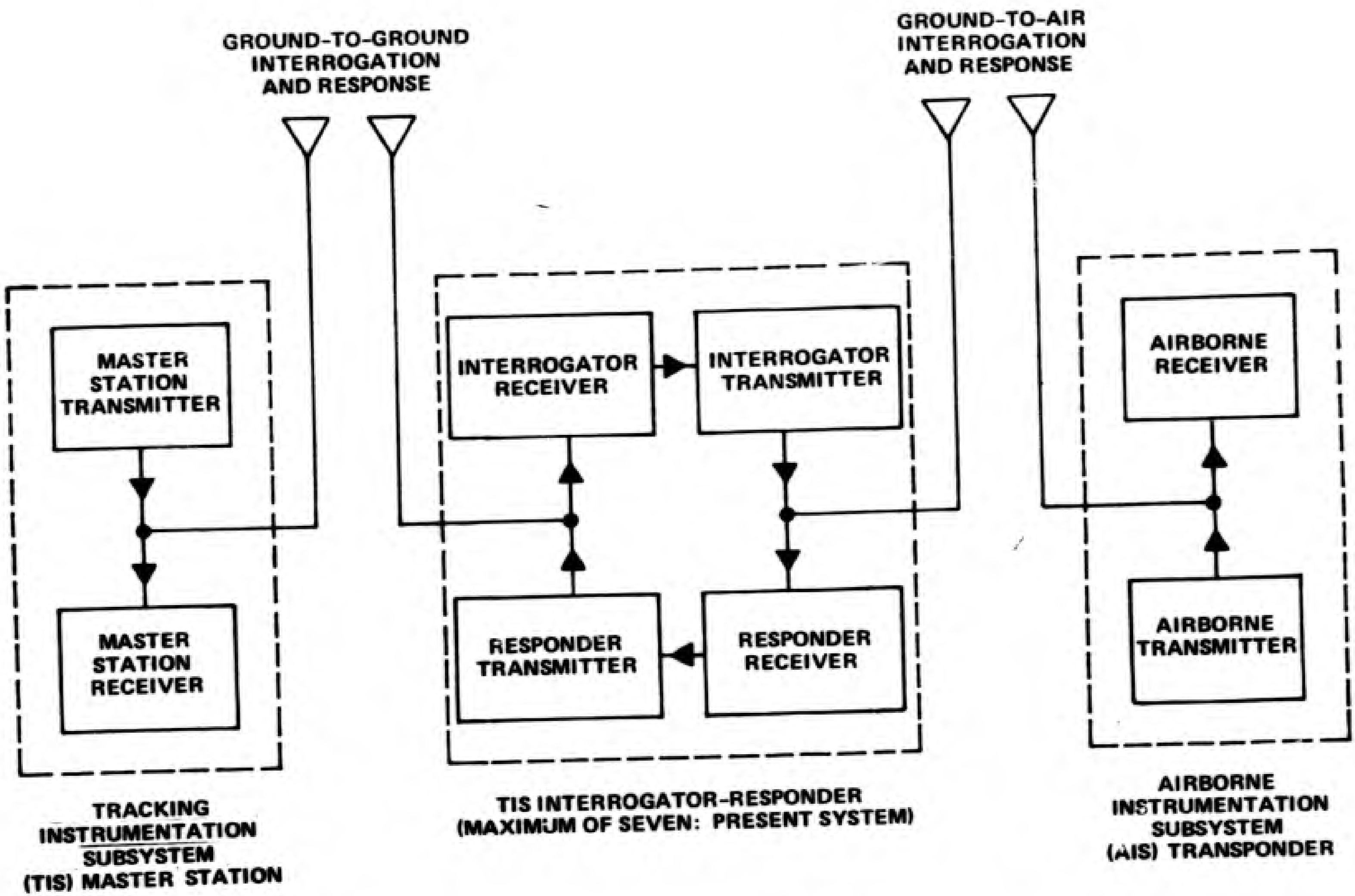


Figure 10. TIS-AIS Ranging System

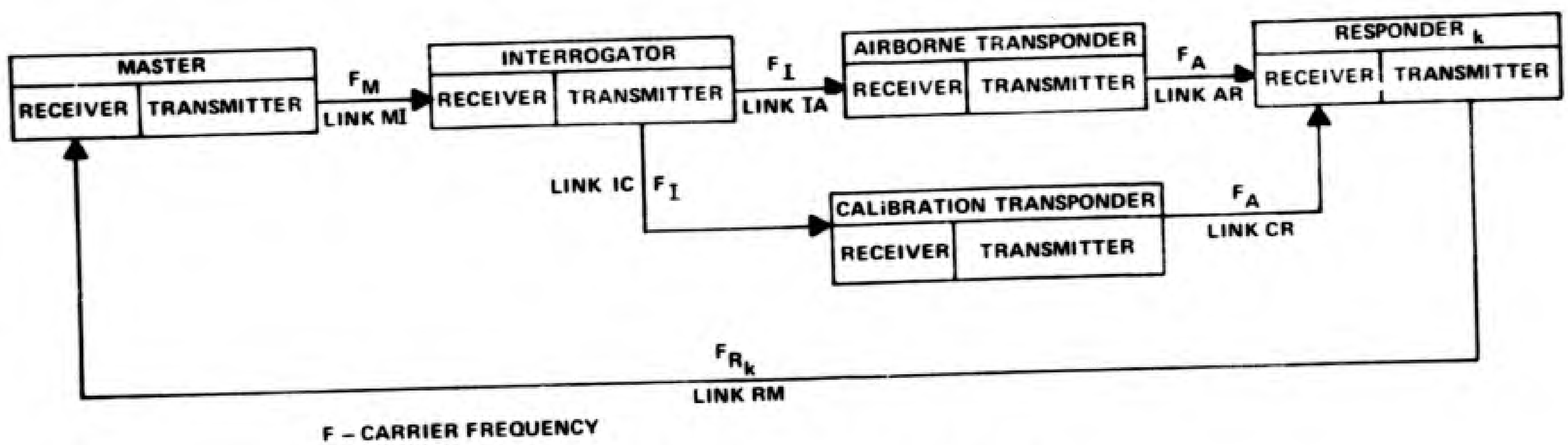


Figure 11. TIS Ranging System Links

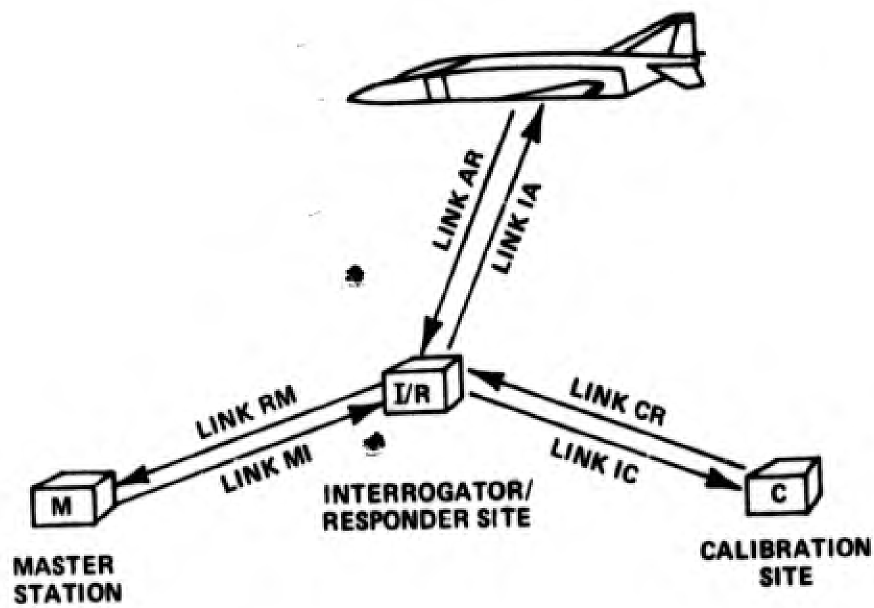


Figure 12. Tracking Instrumentation Subsystem (TIS) Ranging and Calibration Signal Flow

The aircraft ranging loop (ARL) can be represented as a sum of the four range links or

$$ARL = MI + IA + AR + RM$$

since $IA = AR$ and $MI = RM$

$$ARL = 2MI + 2IA$$

similarly the calibration range loop (CRL) can be expressed as:

$$CRL = 2MI + 2IC$$

forming the difference: $[ARL - CRL] = 2IA - 2IC$

Since the interrogator-responder and calibration transponder sites are fixed surveyed ground locations the slant range to the subject aircraft (IA) can be expressed as:

$$IA = 1/2\ [ARL - CRL + 2S_{IRC}]$$

where S_{IRC} is the distance from the interrogator-responder to the calibration transponder.

As discussed in Section 7.1.1, the loop range is computed from the measured phase delay experienced by sine wave modulation in propagating through free space, knowing the velocity of propagation. Figure 13 is a block diagram depicting the master station equipment range computation scheme.

The output of a reference oscillator is sent to the modulation generator where three harmonically-related ranging tones are generated. Three tones are required to resolve range unambiguously to 21.5 nmi. Since the phase digitizers can divide one full wavelength into 2^{12} parts (4096), the least significant bit of the digitized range tone is equal to 1 ft. This is the minimum resolvable difference in range.

The modulation tones are then linearly combined, forming a composite modulation signal which is then used to phase modulate the master transmitter. The master transmitter signal is received and coherently retransmitted on the ground-to-air interrogator frequency. In the airborne transponder the interrogator signal is demodulated and retransmitted coherently back to all of the responder receivers. The ranging signal is again coherently retransmitted by the responder transmitters to the six channels of the master receiver. Since the seventh interrogator-responder is located at the master site no air transmission link is required.

In the master receivers the range signals are demodulated, filtered, and converted back to the original three ranging tones. The phase of each tone is compared with the phase of the signal as emitted and the phase difference is measured. From the measured differences in the phase of the coarse, medium and fine ranging tones a digital range word is composed.

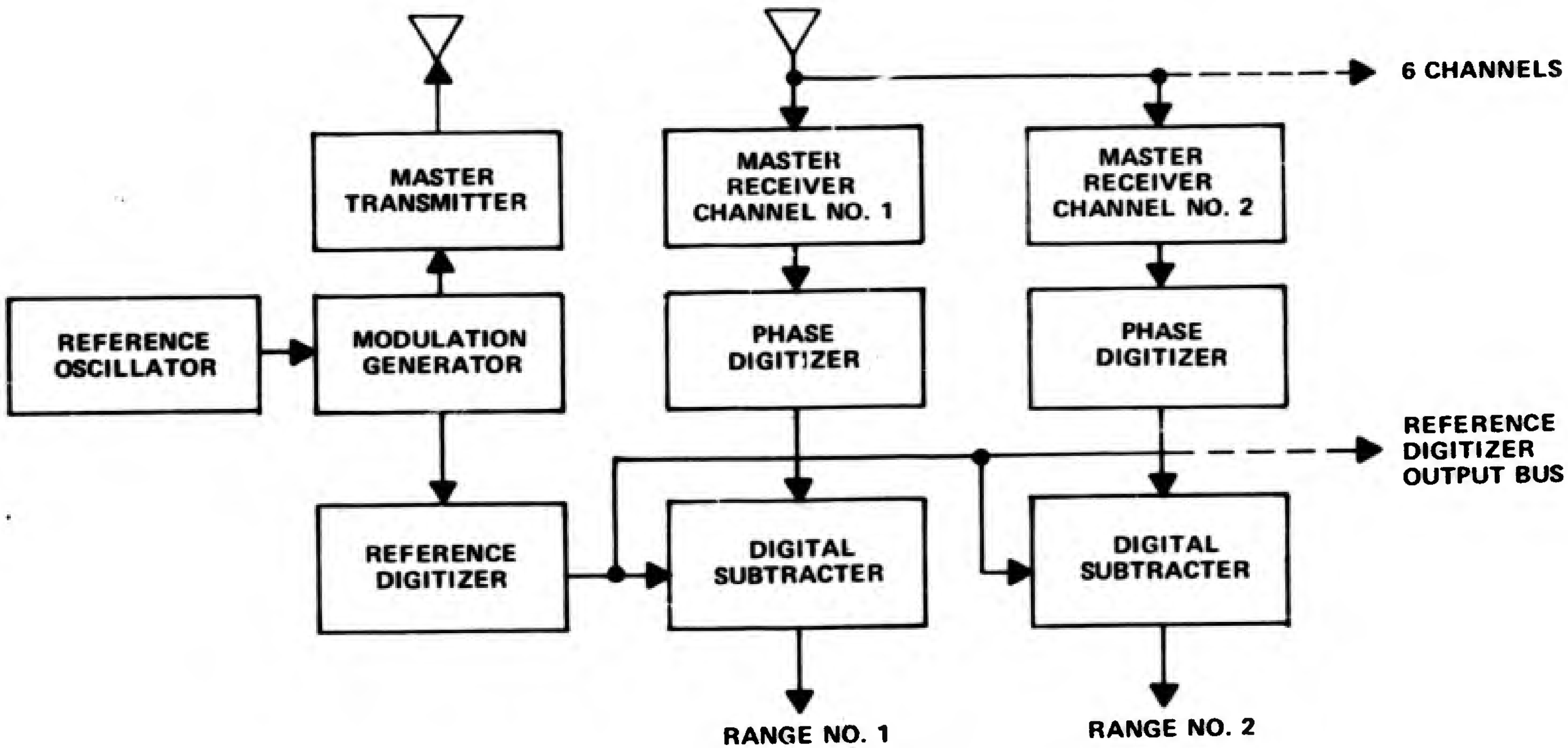


Figure 13. Master Station Range-Measuring Equipment

The aircraft-to-master site range can be unambigously resolved out to approximately 173 nmi. by measuring the time elapsed between transmission and reception of a signal at the master station using a chronograph. This time difference can be considered as an extended range signal and combined with the other range-word-partials in the formatting of the 20-bit range word. The seven range words are then time tagged and used by the TIS Master Station computer to compute aircraft position.

The Master Site computer is a Xerox Data Systems Sigma-3 which performs the controlling and data compression functions in advance of the TIS-CCS data relay.

The utilization of an on-range computer has several advantages:

1. The processing load of the CCS computers is reduced by performing independent functions such as calibration and interrogator selection on-range.

2. Having a preprocessing capability on-range reduces the data rate necessary for the data link from 160k bits/sec (inputs to the TIS computer) to 50k bits/sec (microwave data link information rate).

3. Immediate notification of system malfunction is provided to range personnel and the CCS, thus enhancing air safety.

4. Off-the-shelf interface equipment is provided and the cost of developing custom-built TIS-CCS data relay equipment is avoided.

5. Since software already available for the XDS Sigma-5 is compatible with the Sigma-3, the need for special peripheral devices is eliminated.

6. Expansion of internal capacity and peripheral equipment can be accomplished with relatively low cost.

7. Test and calibration of the TIS during maintenance periods can be provided independent of the CCS.

7.1.3.2 Aircraft Instrumentation Subsystem

Shown in Figure 14 is a block diagram of the equipment contained in the AIS pod. The interrogation signal transmitted by the ground reference network is received by all airborne transponders. The receiver demodulates the incoming signal and feeds the composite ranging signal to the range signal filter and the decoder. If the digital identification codes of the ranging signal and the transponder match, the output of the decoder enables the transmitter.

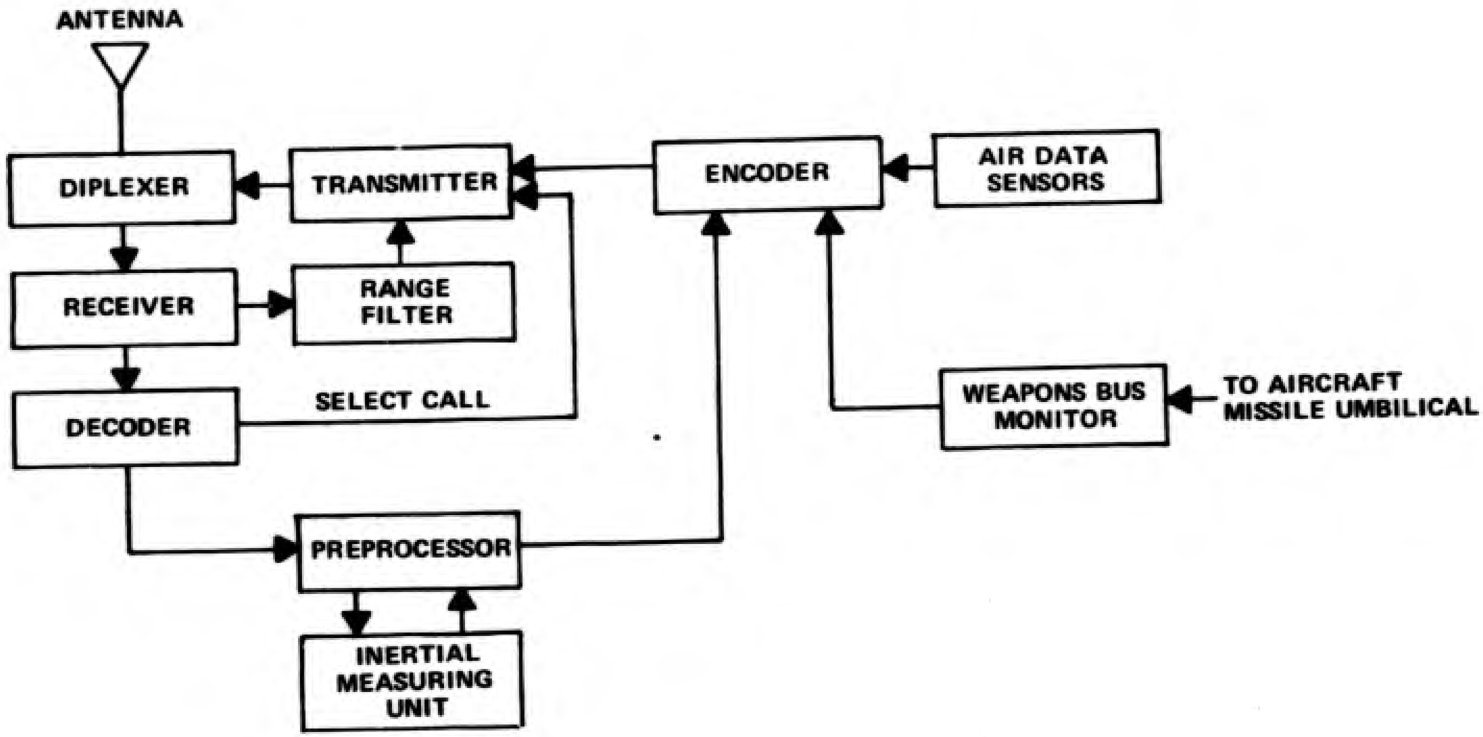


Figure 14. Airc-aft Instrumentation Subsystem

The filtered ranging signal is then used to modulate the transmitter such that the retransmitted signal is phase coherent with the received interrogation signal.

Digital information to correct errors in the inertial measuring unit is also present in the up-link command as pulse-code modulation of the carrier frequency.

The decoder converts this information to digital form, whereafter, the preprocessor does the computations necessary to convert the data to a form suitable for use as IMU correction inputs.

Outputs from the IMU are fed to the preprocessor where the angular rates and accelerations are integrated to obtain angular position and velocity information.

The Euler parameters from the preprocessor together with the air sensor data and weapons bus monitor outputs are sent to the encoder, the output of which is used to pulse code modulate the transmitter.

7.1.3.3 Computation and Control Subsystem

Each Central Processing Unit (CPU) in the CCS multiprocessor system is provided with the required processing time plus a 25% surplus capacity as a safety factor.

Using one CPU for all I/O scheduling avoids duplication of peripheral equipment, thus reducing system cost. An input device is provided for each CPU, however, enabling their off-line use for special purposes, and permitting rapid loading of hardware diagnostics, improving system maintainability.

Multiport memory access eliminates the need for transferring data from one portion of the memory to another, thus providing immediate access to all memory by all CPU's.

A modular program employing a combination of FORTRAN and assembly language code is used for the CCS. The CCS is responsible for integrating the operation of the subsystems and performing the major mathematical computations for the ACMR system functions, namely:

1. processing range and attitude data transmitted from the TIS.
2. computing IMU update corrections for the AIS pods.
3. computing aircraft performance parameters as required to present a complete and accurate picture of range activities.

Those executive functions and data handling tasks where bit and byte operations are common are programmed in XDS Sigma-5 assembly language.

Mathematical computation routines subject to changes due to system task modifications are coded in FORTRAN language because of the speed and reliability with which such programs can be developed.

As presently configured the CCS program is capable of two modes of operation. The normal range data processing functions are performed in the Active Mode. The Monitor Mode uses exercise environment data from the DDS to initialize the program. The exercise is terminated by providing pilot performance information summaries to the DDS.

The mode of operation is controlled by the CCS executive function. In addition the executive handles I/O and interrupt scheduling, timing and sequencing of subprograms, and real-time operability testing and calibration (RTOT/C) functions.

Using a distributed executive function enables the scheduling task to be accomplished by several simple subprograms instead of a large complex centralized program.

Five tasks are supervised by the executive program. These subprograms perform the following functions:

1. AIS-TIS Data Processing - Using ranging and attitude inputs from the AIS and TIS subsystems a track prediction and smoothing algorithm is employed to compute position, velocity, attitude and IMU update parameters for all range elements.

2. Display Support - Parameters relating range aircraft to each other are computed for use by the DDS. Such parameters as angle of attack, mach number, closing velocity, normal acceleration, etc. are of interest here.

3. Hazard Monitoring - The aircraft performance parameters developed above are policed to determine if safety factors for individual aircraft or pairs of aircraft have been exceeded.

4. Pilot Monitoring - Discrete event data on pilot weapons selection, armament, and release are coordinated with launch envelopes and launch opportunities and a statistical summary is presented to the DDS for display.

5. Weapons Simulation - Missile and aircraft performance are simulated in real time and used to determine weapon boundary compliance.

7.1.3.4 Display and Debriefing Subsystem

Each DDS van can be used independent of the other range subsystems for playback and debriefing. Capabilities for start, stop, backup, zoom, and coordinate rotation are incorporated and can be used in the real-time or play back situation.

The simulated 3-D display of the range situation uses size and brightness scaling to provide depth perception. The range display presents the location and attitude of the aircraft on the range and range terrain. A variable length time history ribbon for the wing tip traces eases visualization of aircraft maneuvers.

The alphanumeric display CRT presents pertinent aircraft performance parameters. Upon detection of a safety hazard both audible and visual alarms are provided to enable notification of the pilot(s) of the maneuvering aircraft.

7.1.4 Comparison of ACMR System to TSPI Requirements

7.1.4.1 Near Term Requirements

The Cubic Corporation ACMR System is capable of satisfying many of the TSPI requirements in its present form. Three specific areas require further discussion:

1. Position and attitude update rates
2. Range size vs position accuracy trade-offs
3. Discrete event data transmission capability

7.1.4.1.1 Position and Attitude Update Rates

The ACMR system uses a high-speed phase-lock-loop for its DME function. The minimum time required for one interrogation-response cycle is limited by the time required for the master station receivers to phase-lock to the ranging reply signals. The 10 millisecond ranging slot presently required permits a maximum of 100 ranging cycles (aircraft interrogations plus calibrations) per second.

ACMR requirements were initially for tracking and identification of four high-performance aircraft. One hundred ranging slots are adequate to provide 20 position and attitude updates per second per aircraft with a calibration interrogation every fifth ranging command.

To track and identify 16 aircraft, the scheme proposed by Cubic Corporation for TSPI would retain the same basic data gathering capacity. The frequency of interrogation for the four high-interest aircraft will remain the same, i.e., 20/second. The remaining twelve aircraft will be updated in position and attitude by interrogating one aircraft every other calibration interval, thus providing a 0.83/second update rate.

Using this scheme, any of the 16 aircraft could be members of the subset of 4, and the members of the subset could be changed during an exercise by appropriate TIS computer inputs.

In summary, the ACMR system can track and identify 16 cooperative aircraft. A subset of four can be selected from these 16 and the data on these aircraft will be obtained more frequently. The aircraft in the subset may be located anywhere over the range. The required update rates of 10/second (gross) and 50/sec (subset) cannot be satisfied.

Cubic's proposed interrogation scheme effectively provides for a subset of 4 high-interest aircraft at all times and, consequently, no provision for a uniform data rate for all 16 aircraft would exist. Obtaining this capability would require modifications to existing software and, probably, a larger computer for the TIS function.

7.1.4.1.2 Range Size vs Position Accuracy Tradeoffs

Range size is limited by the requirement for line-of-sight between the remote interrogator-responders and the TIS master station. At present no relay transponders have been developed to extend the range to areas where line-of-sight is impossible due to geographical constraints.

Additionally, an increased range diameter would probably require a larger number of ground stations to insure reception of an adequate number of ranging replies by the interrogator-responders at all aircraft positions over the range, and to avoid geometrical-dilution-of-precision (GDOP) due to poor aircraft-to-ground station geometry. Increasing the number of interrogator-responders would require a larger address capacity in the TIS computer, additional frequencies for the new responder-to-master station reply links, and a corresponding increase in the number of channels in the master station receiver.

Using the seven station reference network for which the ACMR system is presently configured, Cubic Corporation performed a simulation study to determine position accuracies possible with a 40 nmi. diameter range situated at the Nellis AFB site. The accuracies generated by this simulation do not reflect the augmentation possible with inertially aided data and, consequently, are not completely representative of the achievable accuracy for the ACMR system.

The results of this study, [Reference 6] are included herein as Figures 16 through 21. The location of the ground interrogator-responders used for the simulation are shown in Figure 15 and their geographical coordinates are given in Table XII.

It should be noted that the altitudes referred to in the captions of the simulation accuracy contour plots (Figures 16 through 21) are mean sea level (MSL) values. Thus, the altitude of the aircraft above the reference network is then within the range of 5,600-8,700 ft for the 15,000 ft MSL curves and 25,600-28,700 ft for the 35,000 ft MSL curves.

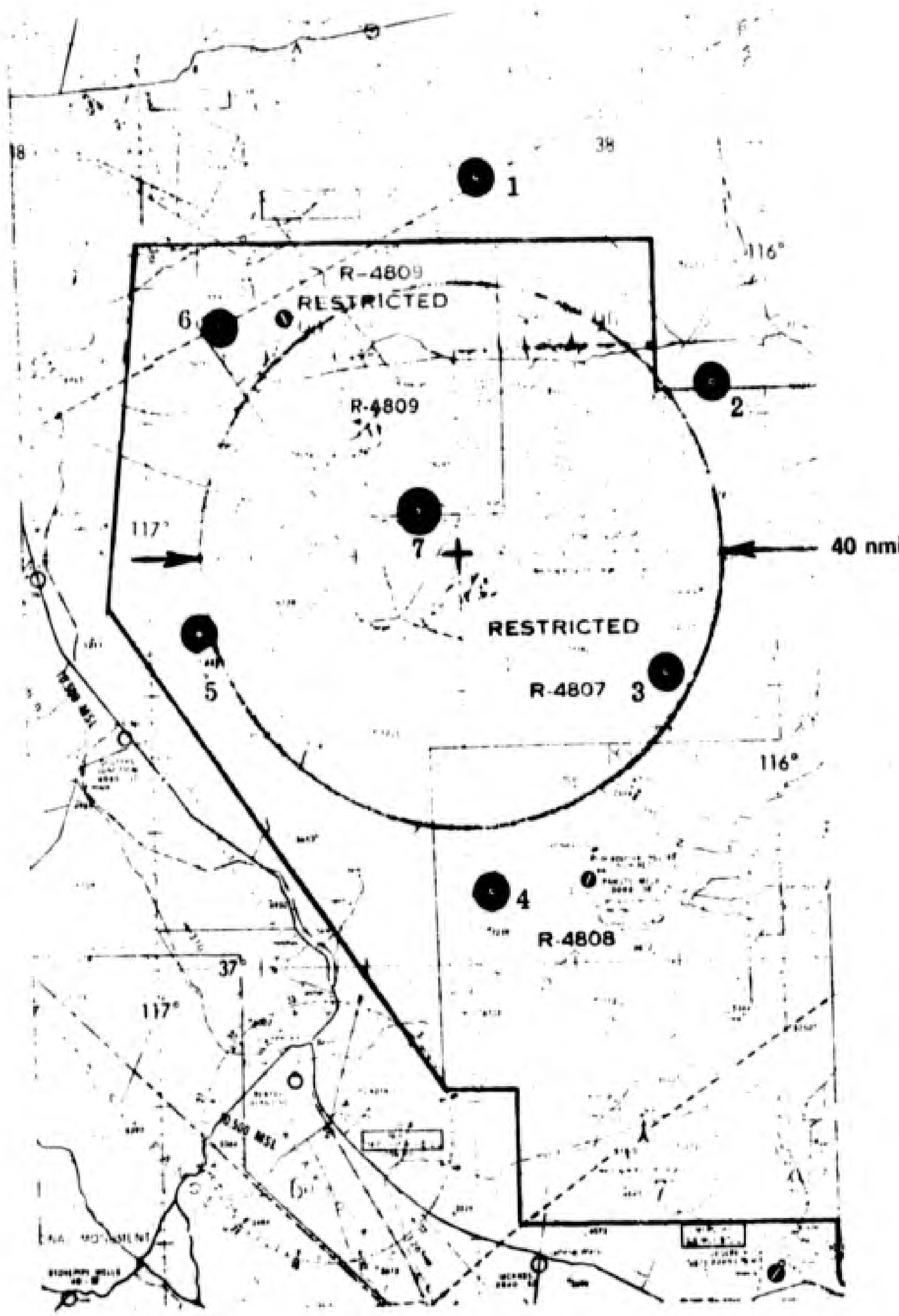


Figure 15. Potential Site for Nellis AFB Air Combat Maneuvering Range

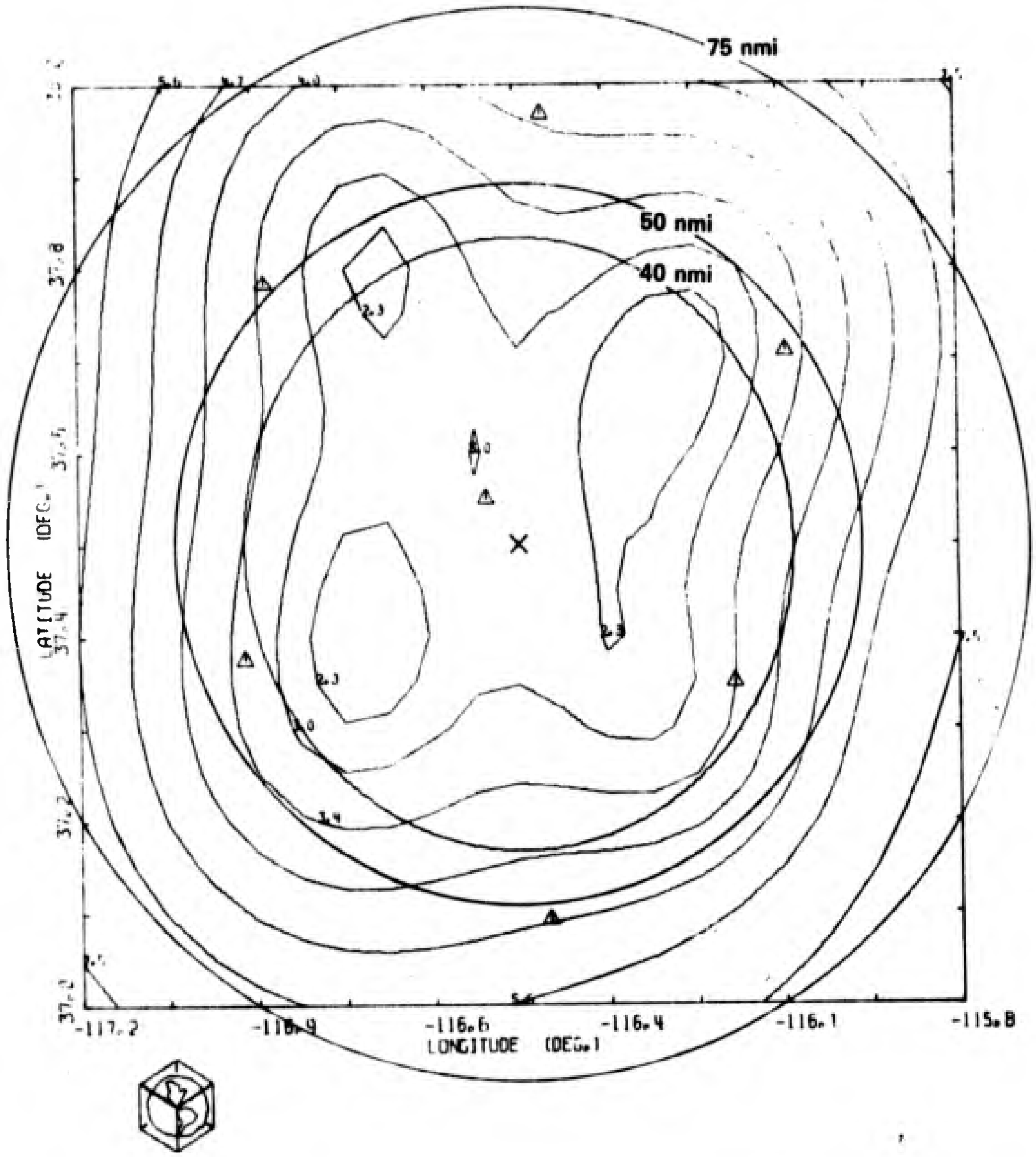


Figure 16. X-Errors, Altitude = 15000 ft, System Error = 4 ft, Nellis West ACMR

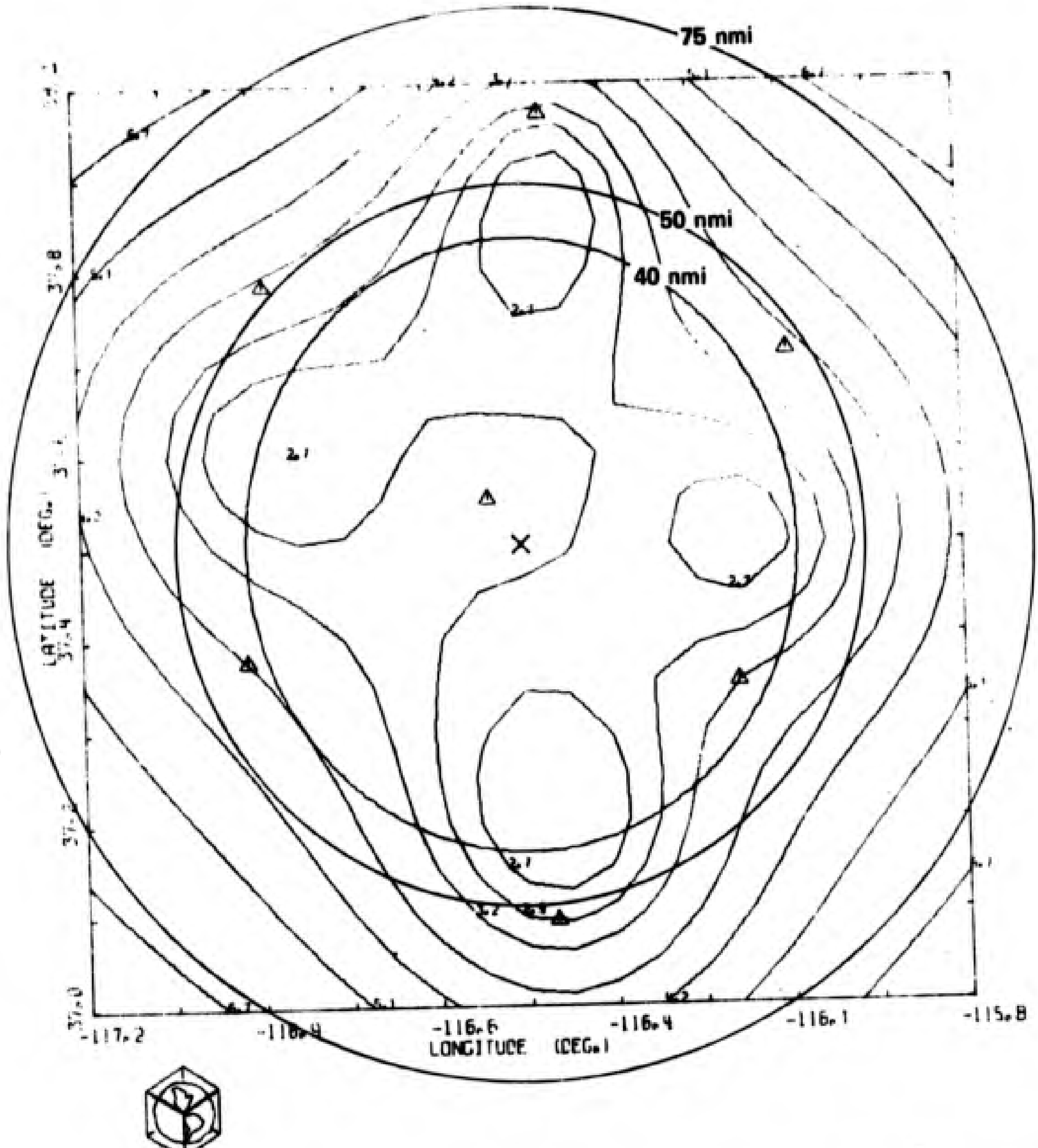


Figure 17. Y-Errors, Altitude = 15000 ft, System Error = 4 ft, Nellis West ACMR

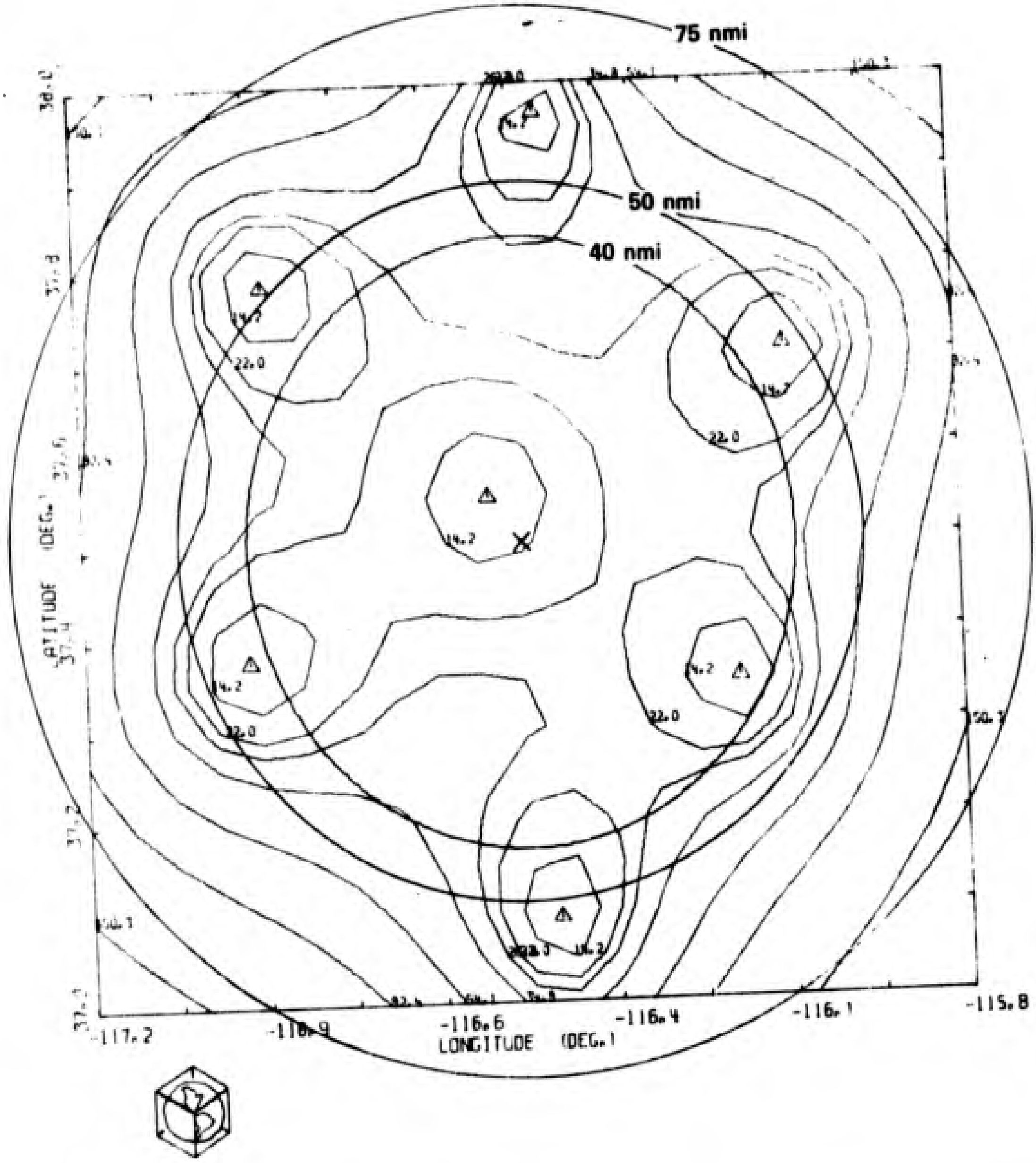


Figure 18. Z-Errors, Altitude = 15000 ft, System Error = 4 ft, Nellis West ACMR

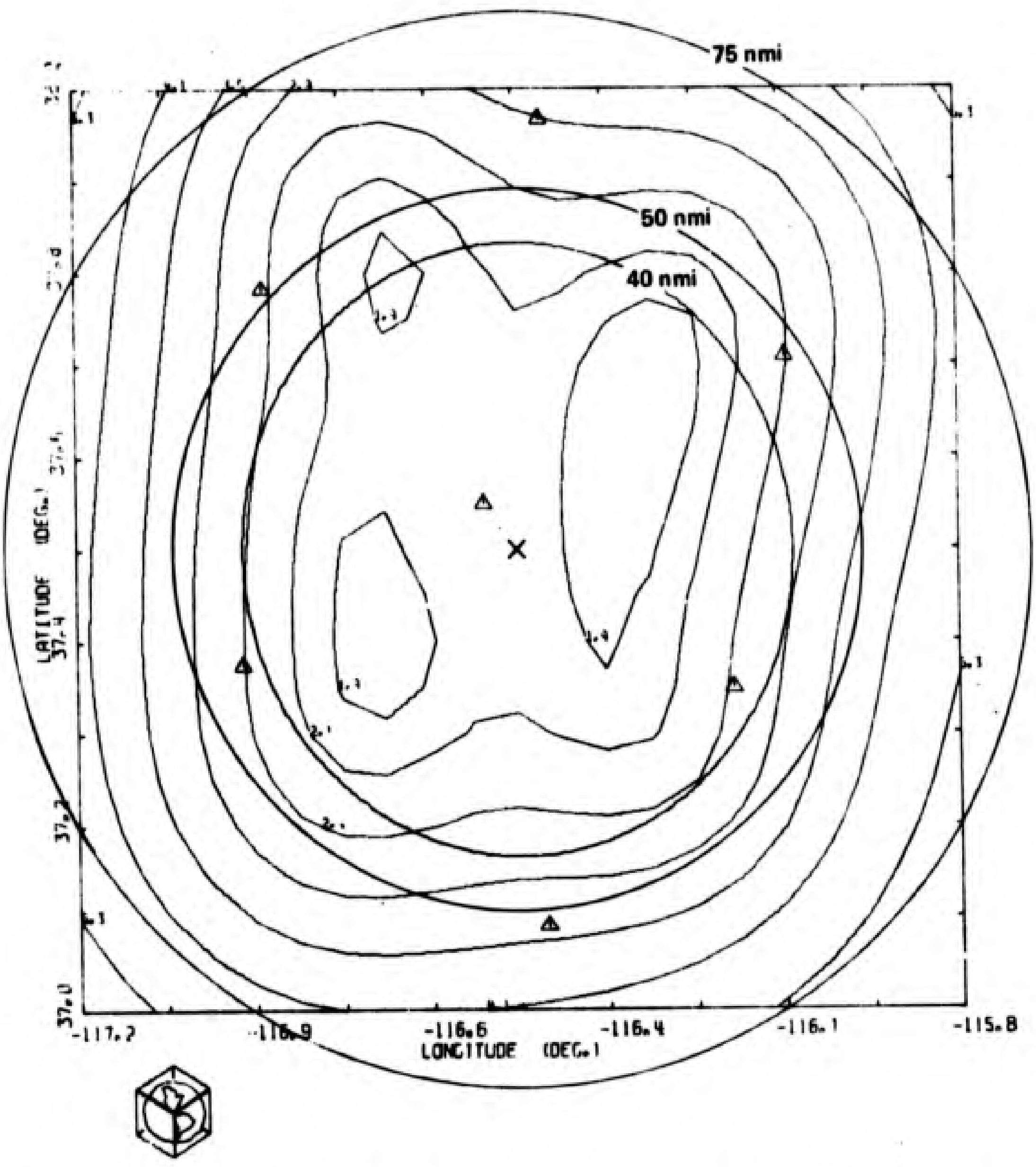


Figure 19. X-Errors, Altitude = 35000 ft, System Error = 2 ft, Nellis West ACMR

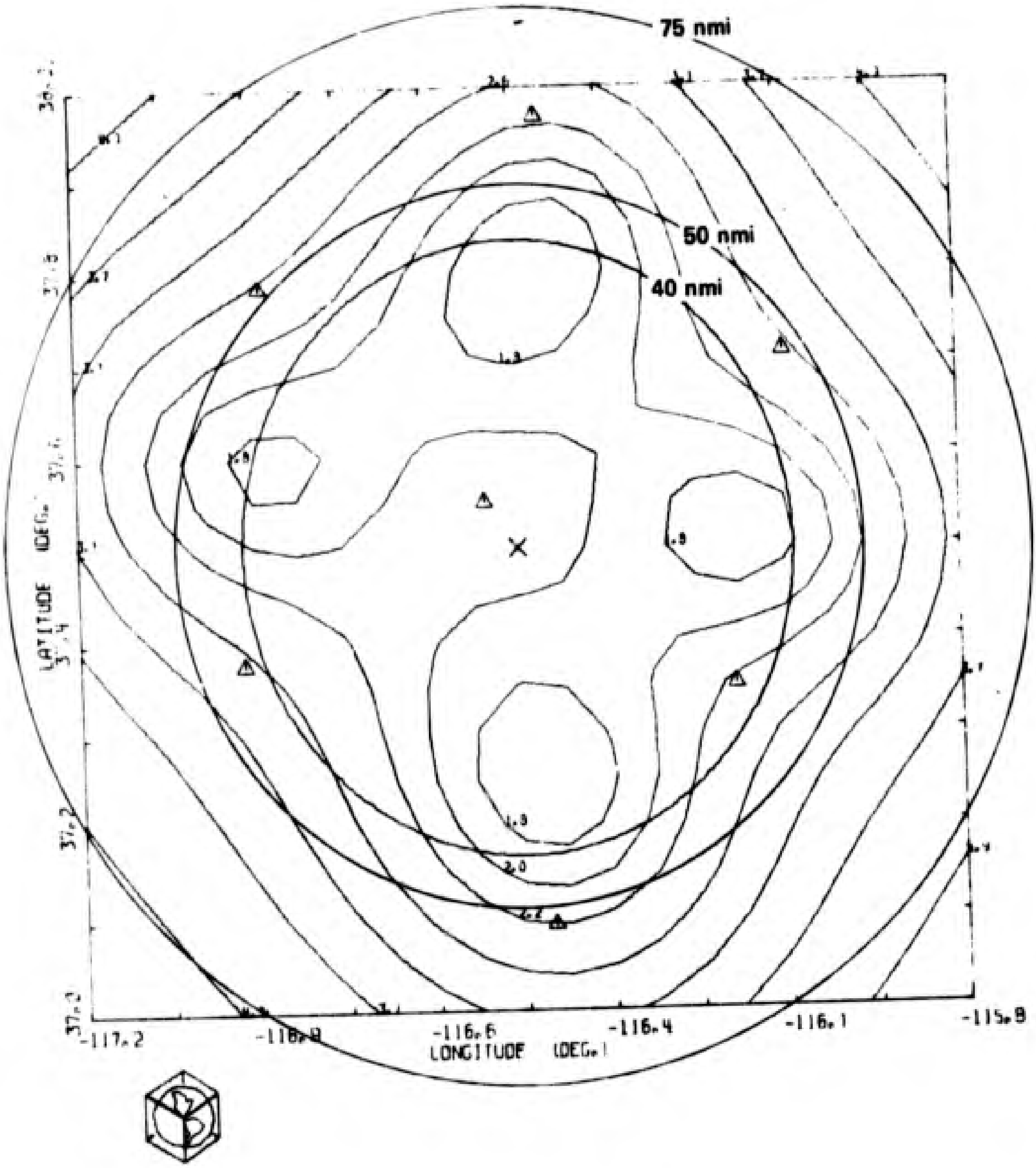


Figure 20. Y-Errors, Altitude = 35000 ft, System Error = 2 ft, Nellis West ACMR

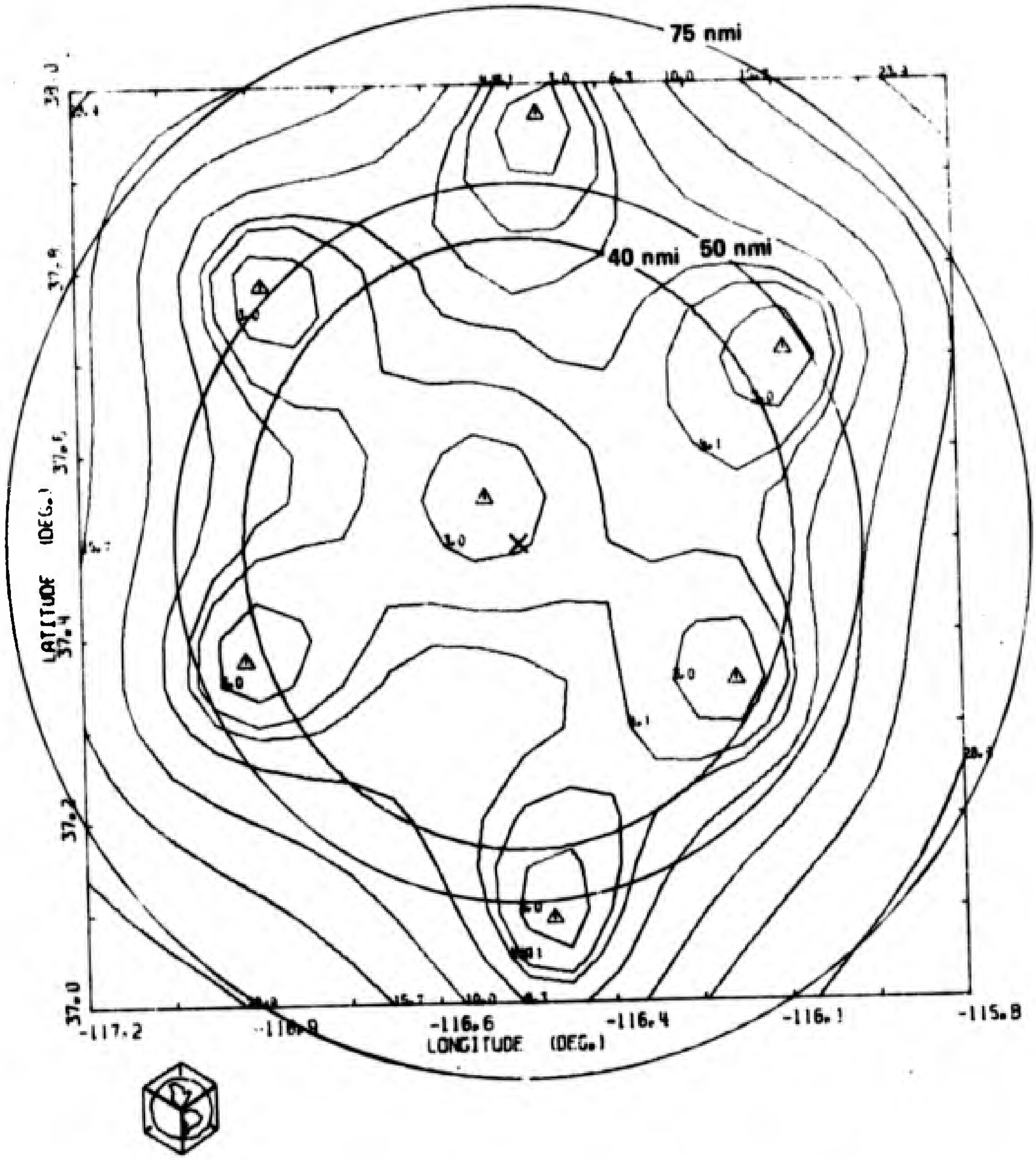


Figure 21. Z-Errors, Altitude = 35000 ft, System Error = 2 ft, Nellis West ACMR

Table XII. Nellis ACMR Station Data

STATION	LATITUDE (° ' N)	LONGITUDE (° ' W)	ALTITUDE, MSL (ft)
1	37 58	116 27.5	9425
2	37 42.5	116 05.5	7070
3	37 21	116 10.5	7820
4	37 05.5	116 27.5	7470
5	37 22.5	116 55	6375
6	37 47	116 53	7500
7 ((MASTER)	37 33	116 33	6285

75 nmi. diameter and 50 nmi. diameter range circles have been added to the simulation accuracy contour plots (Figures 16 through 21) by Calspan. These circles correspond to the near-term system overall range and subset range sizes respectively.

The X and Y coordinate accuracies for both altitudes are within 10 ft for even the 75 nmi. diameter range and with inertial aiding these figures will improve slightly.

As with any multilateration system, the Z axis errors are the largest. Since Z axis precision degrades with decreasing altitude it is not surprising that the 15,000 ft MSL accuracies are 55 ft and 160 ft vs 10 ft and 30 ft at 35,000 ft MSL for the subset and overall range respectively. This degradation is due to the geometrical dilution of precision (GDOP).

As has been shown in Section 2.3 the standard deviation of the measurement can be given by:

$$\sigma_{Z_o}^2 = \left[\left(\frac{R_{OA}}{Z_o}\right)^2 \sigma_R^2 + \left(\frac{X_o}{Z_o}\right)^2 \sigma_{X_o}^2 + \left(\frac{Y_o}{Z_o}\right)^2 \sigma_{Y_o}^2\right]$$

Assuming three ground stations with equal baseline lengths is a reasonable simplifying assumption. Assume also that the aircraft lies on a line which bisects the baseline between the two remote ground stations and is flying at an altitude $H = Z_o$.

From Figure 22 it can be seen that:

$$R_{OA} = \sqrt{X_o^2 + Y_o^2} \approx \sqrt{X_o^2} = X_o$$

for altitudes which are small compared with range radius X_o.

$Y_o = 0$ by geometry.

It will also be convenient and reasonable to allow: $\sigma_{RA}^2 = \sigma_{X_o}^2$

For altitudes H_1 and H_2 we can write:

$$\sigma_{H_1}^2 = \left[\left(\frac{R_{OA}}{H_1}\right)^2 \sigma_{RA}^2 + \left(\frac{X_o}{H_1}\right)^2 \sigma_{X_o}^2\right] \approx 2\left(\frac{R_{OA}}{H_1}\right)^2 \sigma_{RA}^2$$

$$\sigma_{H_2}^2 = 2\left[\frac{R_{OA}}{H_2}\right]^2 \sigma_{RA}^2$$

since ROA will not change appreciably for small changes in altitude.

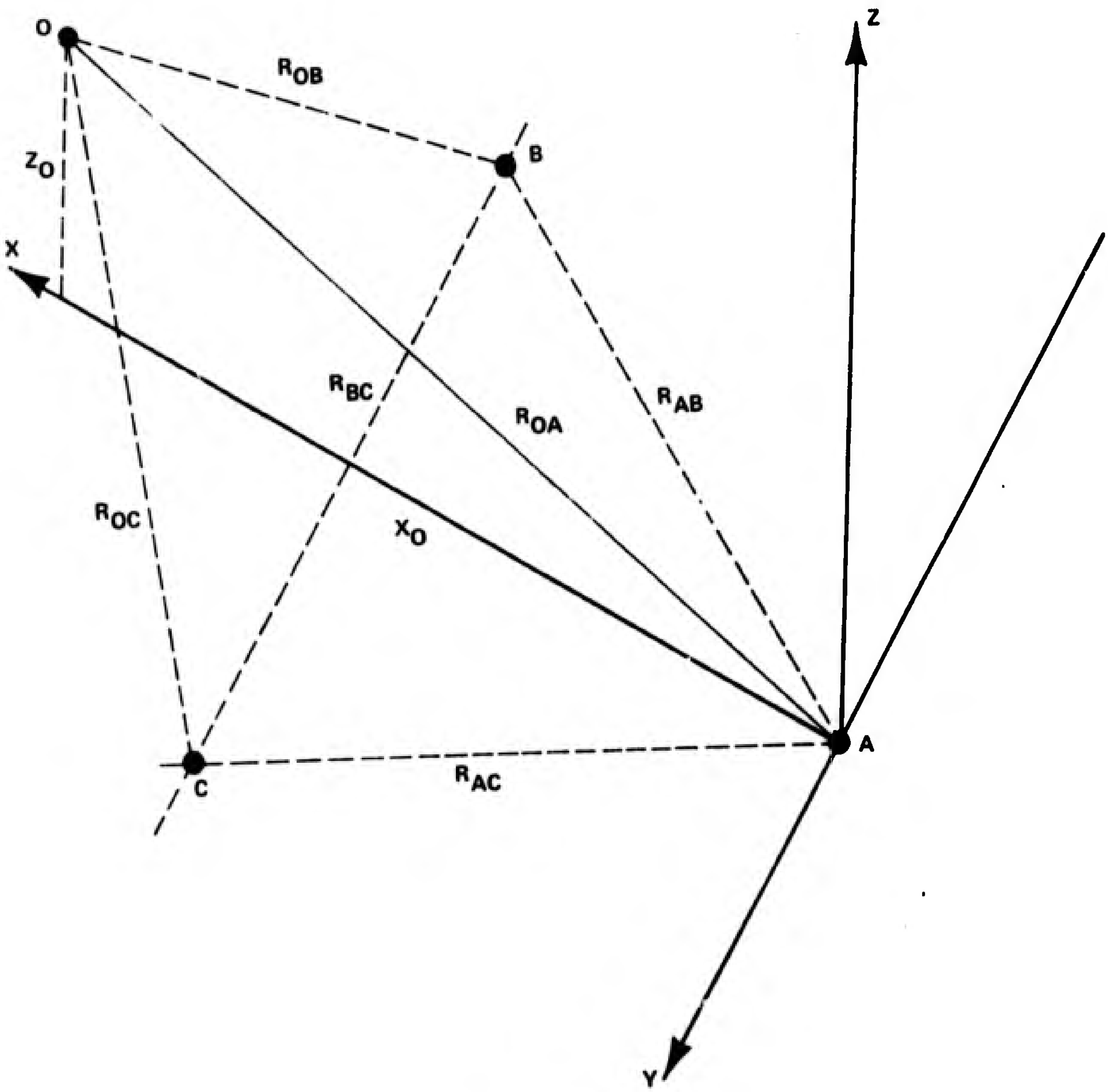


Figure 22. Trilateration Geometry

We can now form the quotient:

$$\frac{\sigma_{H_1}^2}{\sigma_{H_2}^2} = \frac{2\left(\frac{R_{OA}}{H_1}\right)^2 \sigma_{RA}^2}{2\left(\frac{R_{OA}}{H_2}\right)^2 \sigma_{RA}^2} = \left(\frac{H_2}{H_1}\right)^2$$

$$|\sigma_{H_1}| = \frac{H_2}{H_1} |\sigma_{H_2}|$$

The above relationship applies to the special geometry assumed in its derivation but the standard deviation computed using these assumptions is probably more optimistic than would be computed for an exact solution.

Using the data from Figure 18 as being representative of Z accuracy for an average altitude of 7150 ft $\approx$ 7000 ft above the reference network, it is now possible to compute numbers for Z accuracy at 2000 ft (TSPI minimum altitude spec.).

These computations assume the geometry of Figure 22, no change in ranging accuracy [σ_{RA}] with altitude and negligible variation of R_{OA} for altitudes which are small compared to the range of interest.

The Z axis accuracy is computed to be 560 ft for the 75 nmi. diameter range and 190 ft for the 50 nmi. diameter range at 2000 ft altitude above the reference network.

It should be noted that the assumption of no change in ranging accuracy (σ_{RA}) with altitude neglects the increase in multipath errors at lower elevation angles.

Sollenberger in Reference 7 demonstrates that at low elevation angles the maximum error in phase angle measurement due to multipath in an FM-CW ranging system is given by:

$$\alpha = \arctan \frac{2}{\beta} \approx \frac{2}{\beta} \quad \text{for large } \beta$$

where α is the phase error in radians
β is the deviation ratio

$$\text{If} \quad \beta = \frac{\Delta f}{f_m}$$

where f_m is the modulation frequency, Sollenberger also shows that the maximum range error due to multipath can be given by

$$\sigma_{RM(max)} = \frac{c}{\pi \Delta f} \quad \text{meters.}$$

A further approximation will still yield an upper bound for the range error which is accurate enough for purposes of discussion. Since C is the speed of light and is approximately equal to 3 x 10^8 meters/second:

$$\sigma_{RM(max)} = \frac{100}{\Delta f} \quad \text{meters}$$

The ACMR system uses a high deviation ratio of 10 to reduce multipath errors and modulation frequencies on the order of 240 KHz to achieve the desired resolution and simplify filtering of the received ranging replies. Thus, Δf = 2.4 MHz and $\sigma_{RM(max)}$ = 42 ft. This is the maximum value which may be encountered. The actual error at any instant is a complicated function of antenna height, elevation angle to the aircraft, reflection coefficient, and the phase lag upon reflection, and is usually less than the above figure.

For the ACMR installation at Yuma MCAS Cubic Corporation was able to assume, based on terrain considerations and a minimum operating altitude of 5000 ft above the reference network, that single path reflection from the desert floor constituted the most significant source of multipath error.

The terrain in the Nellis AFB area is quite different from the Yuma site, hence, the multipath errors for a range located in the Nellis area will be larger and more difficult to model for simulation purposes. The modelling of multipath effects require the specification of reflection coefficient and phase lag at reflection. Three options are available for inputting these parameters for the Cubic Corporation simulation program:

1. As a constant value - Assuming these parameters to be constant is an unreasonable assumption for severe terrain variation over the range.

2. As a tabular input of predetermined values - These parameters are subject to large variations with small changes in elevation angle, antenna location, etc. and an accurate tabulation is exceedingly difficult to achieve.

3. As values computed from the appropriate equations assuming smooth earth - The smooth-earth approximation is only valid for diffuse reflections under the following conditions:

   a) the antennas are not too directional
   b) the slopes of the surface irregularities are small
   c) the surface is statistically rough
   d) the distribution of irregularities is isotropic
   e) the angle of incidence is not near the pseudo-Brewster angle ($\approx 17°$)
   f. the transmitting and receiving antennas are directed toward each other

It is apparent that b,d, and e will not be satisfied for a very substantial portion of the proposed COR range area and consequently this type data input will not be useful in predicting multipath errors at the low elevation angles of interest.

Errors due to multipath effects can be minimized at a particular elevation angle by optimizing the antenna height above ground. By optimizing antenna heights for low elevation angles it may be possible to achieve lower overall multipath errors because of the decrease of errors with increasing elevation angle.

Range geometry, i.e. the placement of ground interrogator-responder stations, may be varied to achieve greater low altitude position accuracy in an area of particular interest, say, for weapons delivery scoring. For the ACMR-type range activities, (pilot training, dogfighting, etc.) operation below 5000 ft (above the reference network) should not occur too frequently. Thus, range use at low altitudes should be predictable in nature and frequency, and some optimization of position accuracy with use is possible.

Some improvement in position accuracy at low altitudes is possible with inertially-aided data. Based upon the extrapolated accuracies computed for the overall range (75 nmi. - 560 ft Z accuracy) and the subset range (50 nmi. 190 ft Z accuracy). The inertial aiding would have to provide factors of improvement of 5.5 and 14.6 respectively to meet the near-term TSPI system requirements. The amount of improvement possible is dependent upon the accuracy of the IMU equipment, the update rate of IMU information, the type of computational algorithm used to integrate ranging and IMU information, the accuracy of the ranging system, etc. and Calspan has not been able to determine the amount of improvement attained by the Cubic ACMR system.

All of the accuracies quoted for the Cubic Corporation ACMR system are based on simulation accuracy data. Comparison of demonstrated system accuracies with simulation data should be made as soon as the acceptance testing of ACMR at Yuma has been completed. A Cubic Corporation simulation report [Reference 8] containing simulation results for the inertially-aided ACMR system at the Yuma site is available and will facilitate this comparison.

7.1.4.1.3 Discrete Event Data Transmission Capability

Discrete event data from the aircraft weapons bus monitor is available each interrogation in addition to the attitude update information. The downlink message has 71 bits available for discrete event data on aircraft weapons. The uplink data message carries 112 bits of IMU correction data. Since no pilot-to-pod interface exists no further uplink message requirements can be envisioned by Calspan.

7.1.4.2 Far Term Requirements

7.1.4.2.1 Range Site

The 200 nmi. diameter range requirement for the far term system could possibly be met in either of two ways.

a) Multiple Subsystems - If multiple ACMR TIS subsystems were colocated over the range area. The basic ACMR coverage could be obtained for sixteen aircraft. Some software problems can be envisioned when an aircraft flies from the surveillance of one subsystem to another since each subsystem, although controlled by a common CCS, would have its own TIS computer and the same frequencies of operation (except the responder-to-master station r.f. links).

Because of the necessity for a separate frequency for each responder to-master station link the total portion of the r.f. spectrum occupied by the system will be larger.

The CCS computer would also be required to be larger to handle the increased computational load associated with directing two TIS computers.

b) Relay Transponders - If the range extremities to 200 nmi. diameter were to be covered by one expanded ACMR system, relay transponders would be required to communicate with remote interrogator-responders located beyond line-of-sight of the master station. An additional r.f. channel per interrogator-responder would be required for the responder-to-master station links, as with the multiple subsystem scheme above.

A larger TIS computer would probably be required due to the larger address capability needed. For a sixteen aircraft capacity the CCS computer probably would not need to be changed, although software changes would be necessary.

7.1.4.2.2 Number of Range Members

Cubic Corporation does not believe that the ACMR system can be adapted to track and identify ground members due to the large multipath and GDOP errors associated with low elevation angle tracking.

The number of airborne members may be increased by:

a) decreasing the position update rate on each aircraft.
b) colocating multiple ACMR systems under direction of a large central CCS.

Since the ACMR system is limited by design to 100 interrogation intervals per second maximum, additional aircraft could only be accomodated on the range by reducing the position update rate on each aircraft. This method will be feasible for either scheme of range size expansion elected (see 7.1.4.2.1 above). No increase in the number of frequencies will be required since all aircraft receive and transmit on the same frequency. The address capability of the TIS computer will have to be larger to uniquely address all aircraft.

Colocating multiple ACMR systems is an extremely costly plan both in terms of dollars and number of r.f. channels needed. To maintain the present ACMR data rates on 60 aircraft would require four complete ACMR systems. Bearing in mind the 100 interrogations per second data rate limitations of the ACMR system any number of update rate vs number of systems tradeoffs are possible.

The question of what position update rates are required to specify aircraft location with the desired accuracy is discussed elsewhere in this report. Specifying data rates higher than actually needed can be extremely costly in light of the above considerations.

7.1.4.2.3 Aircraft Operating Altitudes

The minimum aircraft operating altitude of 200 ft above the reference network is not likely to be achieved considering the dramatic increase in multipath and GDOP errors at low elevation angles.

For specific range locations it may be possible to optimize the placement of the interrogator-responders to obtain improved low altitude position accuracy, but the errors under these conditions are not easily predictable.

The maximum altitude of 80,000 ft AGL does not pose any particular problems.

7.1.4.2.4 Aircraft Maximum Velocity

Aircraft operation for extended periods at 4000 feet per second can result in pod cooling difficulties. Any aircraft operating within the MIL-E-5400 specifications should experience no difficulties.

7.1.4.2.5 Subset Aircraft Position Accuracy

The required position accuracy for the X and Y axes can probably be approached for all aircraft within a 5 nmi. radius of several predetermined ground coordinates.

It is unlikely that the location of these subset areas will be variable during a mission but given the desired coordinates prior to a mission some optimization of system accuracy (by relocating remote interrogator-responders) is possible.

The requirement for 5 ft (1σ) Z axis accuracy is not likely to be satisfied at the lower altitudes. The altitude at which errors exceed this limit is difficult to determine since it is a function of range geography, interrogator-responder placement, IMU-aiding improvement ratio, and many additional factors.

7.1.4.2.6 Position Update Rates

Due to the 10 millisecond minimum interrogation interval length imposed by the master station receiver phase-locking time no more than 100 interrogations per second are possible with the present ACMR hardware. Consequently, the 100 position/second update rate on each subset aircraft is not achieveable. See also remarks on update rates for the near-term system (Section 7.1.4.1.1).

7.1.5 Cost of System Components

Cost data for ACMR, system components in their present state of development have been supplied to Calspan by Cubic Corporation. These figures are summarized in Table XIII.

The cost of components meeting the TSPI requirements will likely be higher since some modifications to AIS and TIS components will be necessary and the data processing requirements for the CCS and DDS equipment will be greater. For this reason direct comparison of these data with the figures presented for the General Dynamics RMS-2/DCS system is not invited.

7.1.6 Reliability and Maintainability

Estimated reliability figures for the ACMR airborne and ground subsystems have been computed by Cubic Corporation. A separate analysis for the airborne equipment was deemed necessary due to the vastly different temperature and vibration environments experienced by the pod-mounted hardware. The study results appear in Table XIV.

A Mean-Time-To-Repair (MTTR) figure has not been either estimated or observed for the ACMR system.

Several design features will reduce repair time, namely:

1. redundant ground stations
2. redundant displays with integral software
3. modular components in AIS pod

These features would probably be common to both ACMR and RMS-2/DCS systems in TSPI configuration.

7.2 RANGE MEASURING SYSTEM - DATA COLLECTION SYSTEM (RMS-2/DCS) GENERAL DYNAMICS

7.2.1 Type of System

The RMS-2/DCS system by General Dynamics is a multilateration, sequential ranging system which employs a pulse-type, leading edge ranging technique to obtain position and identification information on cooperative range members. Both aircraft and ground units can be tracked.

Multiple ranges obtained in sequence from several ground transponders to the range member of interest are used as inputs to a Kalman filtering algorithm which predicts the position of the member based on past information.

Measuring the elapsed time between transmission and reception of a ranging pulse signal by the reference network and knowing the velocity of propagation it is possible to compute the slant range to the subject element.

Table XIII Summary of Costs - Cubic Corporation
ACMR

	UNIT PRICE ($)	ESTIMATED FOR ACMR	
		QUANTITY	PRICE ($)
AIRBORNE TRANSPONDERS	80,000	12	960,000
INTERROGATOR STATIONS	70,000	6	420,000
DISPLAY VAN*	870,000	2	1,740,000
MASTER STATION	500,000	1	500,000
MAIN COMPUTER VAN	1,500,000	1	1,500,000
SPARES**	800,000	-	800,000
TEST EQUIPMENT	115,000	-	115,000
DEPOT MAINTENANCE	700,000	-	700,000
			6,735,000

*A DISPLAY VAN CONSISTS OF TWO SETS OF DISPLAYS. A SET OF DISPLAYS CONTAINS TWO ADAGE 110's FOR ALPHANUMERIC DATA AND ONE ADAGE 150 FOR 3-D GRAPHICS.

**SPARES ESTIMATED AT 10 TO 20% OF INITIAL EQUIPMENT COSTS.

Table XIV Maintainability of ACMR System

	FAILURE RATE (10^6 HOURS)*
AIRBORNE EQUIPMENT-AIS	733
GROUND EQUIPMENT -DDS	1250
-CCS	3518
-TIS	1690
TOTAL	7191 F 10^6 HOURS

ACMR SYSTEM MTBF 139 HOURS

*CALCULATED BY CUBIC CORPORATION

The ground reference network is composed of remote transponders and relay stations arranged in a configuration determined by range terrain and accuracy requirements. This network transmits to and receives from the transponders carried by range members.

The master station emits a coded ranging signal which contains, in digital form, the address codes of the remote transponder and range member to be used for that ranging interrogation. The link path extends from the master station to the remote transponder, to the aircraft and back again through the same system elements. At the master station the total two-way transit time is measured and the slant range from the remote transponder to the range member is computed.

Relay stations have also been developed which extend the range to areas where line-of-sight communication with the master station is not possible.

The master station computer does the slant range computations and applies these data to the algorithm which produces range member position information. The output of the computer is recorded on magnetic tape for post-mission data analysis.

7.2.2 Description of Subsystems and Their Components

For convenience and uniformity the subsystems will be referred to using the same nomenclature employed in the description of the Cubic Corp. ACMR system (section 7.1).

7.2.2.1 Airborne Instrumentation Subsystem

General Dynamics has developed a transponder which can be mounted on aircraft and ground vehicles as well as carried by personnel in the field. The principal components of the transponder are the receiver, transmitter, digital storage and control logic unit, and power supply.

The receiver assembly hardware does transmit/receive rf switching, filters, amplifies and detects the received interrogation signal, and provides automatic gain control.

A linearly amplitude modulated transmitter having a peak power of 16 watts at 2 percent duty cycle is used. Since the RMS-2/DCS system uses a pulse-type ranging technique, the crystal-controlled oscillator is not required to be a high-stability unit.

The digital storage and control logic unit provides an interface with input/output accessories and serves as a data terminal for two-way digital data communication with the master station. The address recognition and error sensing functions are also handled in this unit.

The transponder will be referred to as a B-unit.

7.2.2.2 Tracking Instrumentation Subsystem

The TIS for a typical range installation can be composed of the following elements:

a. Master Station (C station)
b. Remote Transponders (A stations)
c. Remote Relays (D stations)

With a single central master station, a maximum of 127 remote transponders and 7 remote relays may be employed.

Figure 23 shows the C-site facility and ancillary equipment. A 40 foot air-conditioned semi-trailer houses the C station and Varian 620/f computing system. An operations office area and latrine are also provided. The van may be transported by air or ground, and the undercarriage is removable to enable transportation via C-141 aircraft. The entire van can be accommodated by a C-5 aircraft.

The antenna support is a 30 ft. walk-up tower consisting of five portable sections which are bolted together. An omnidirectional antenna 4.5 inches in diameter by 120 inches high serves as the primary transmitting and receiving antenna for the C station. A four foot diameter parabolic dish may also be used for directive communications, usually with a D station situated at a long distance from the master site.

Finally, a spring mounted whip antenna is attached to the rear of the van. This antenna serves the timing receiver which monitors WWV transmissions.

The computing system generates the appropriate ranging commands for the C station, receives range data or digital messages from the C station, performs all ranging calculations, and records all range and communications data on magnetic tape for post-real-time display and/or printout.

Two equipment bays are provided to house the computer, computer interface electronics, computing system controls, two magnetic tape transports, and related optional accessories. Four peripheral units are separately mounted in the van and the computing system is diagrammatically represented in Figure 24.

Figure 25 shows a remote transponder as it would appear in a typical installation. The remote relay units employ the same hardware and, therefore, appear identical. Mounted at the top of the 24 ft. high support tower may be either a low-angle omnidirectional antenna or a high-angle shaped-beam antenna depending on whether ground or airborne units are being tracked. The electronic module is also mounted to the tower; A propane-fueled power supply is used, providing an unattended service interval of 7 days.

Both A and D stations may be mounted in vehicles to enhance the mobility of the reference network.

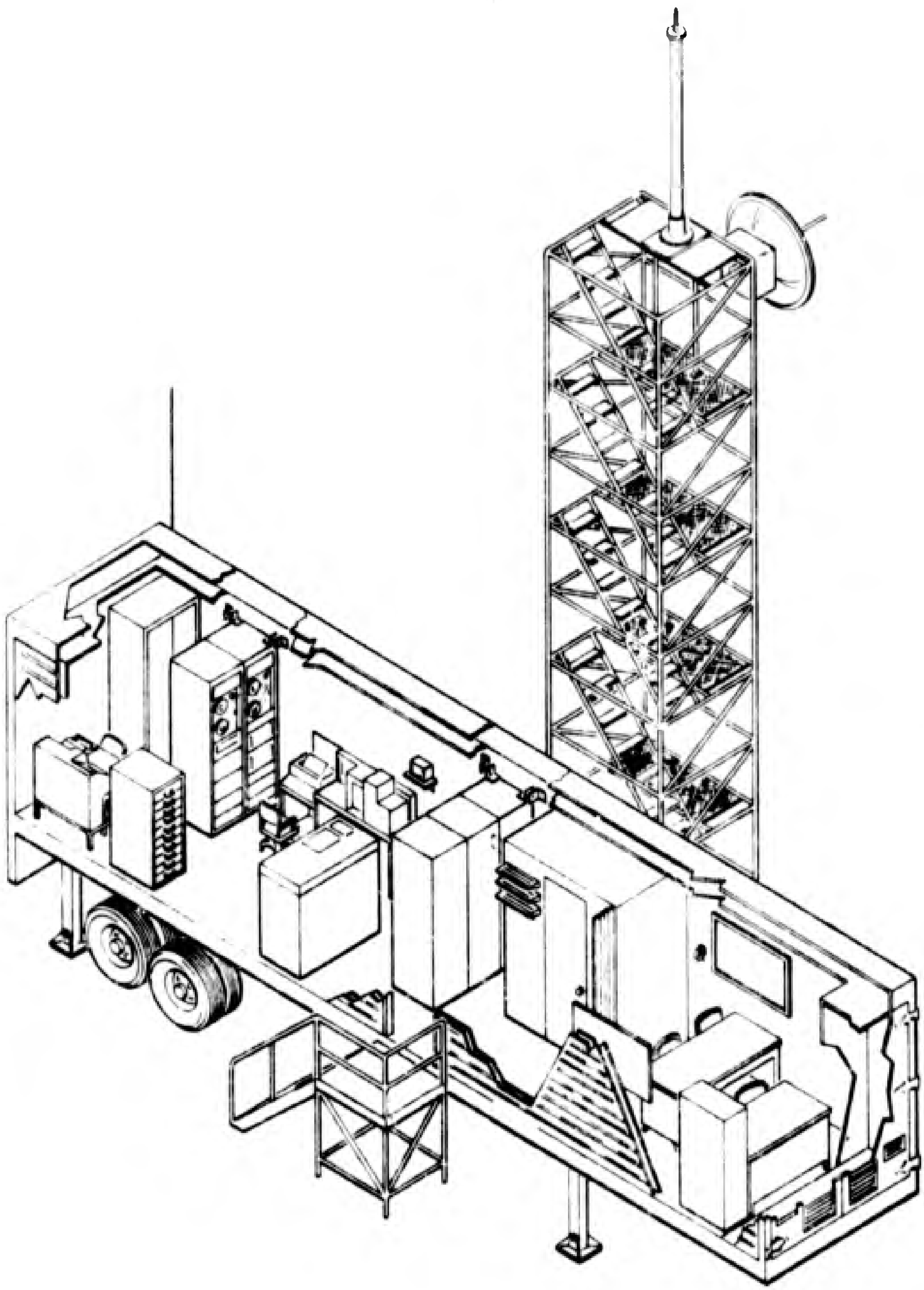


Figure 23. Typical Installation, RMS-2/DCS C Site Facility

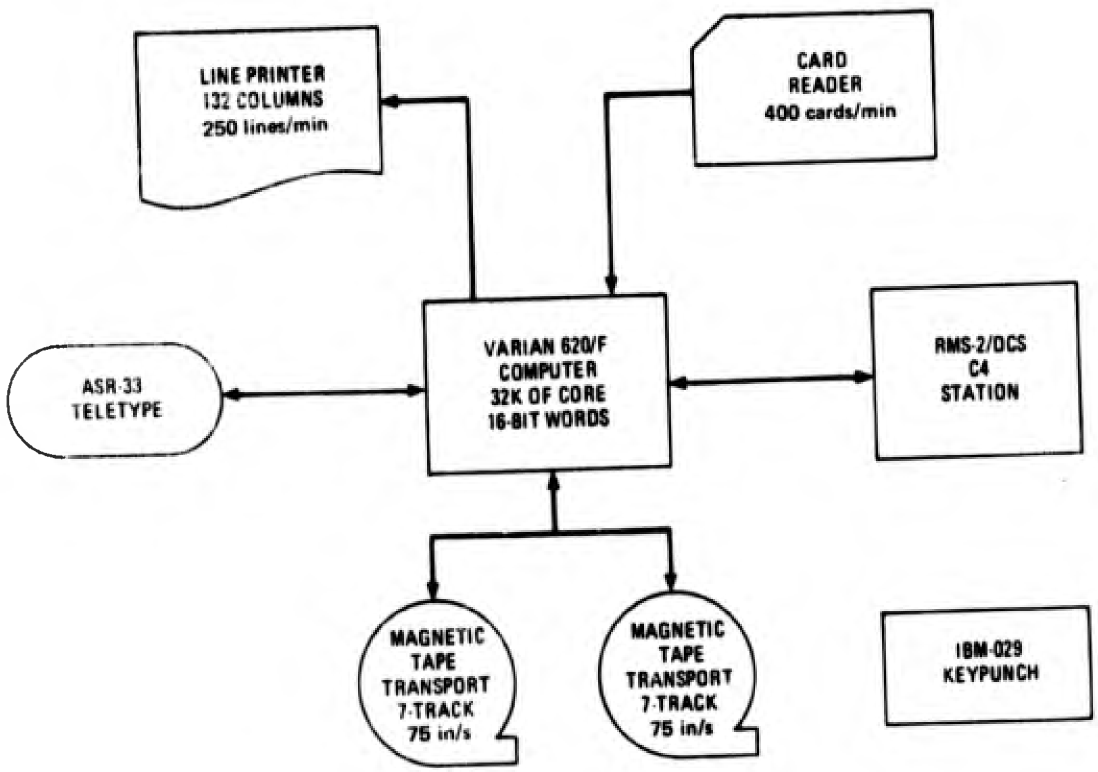


Figure 24. RMS-2/DCS Computer System, Functional Diagram

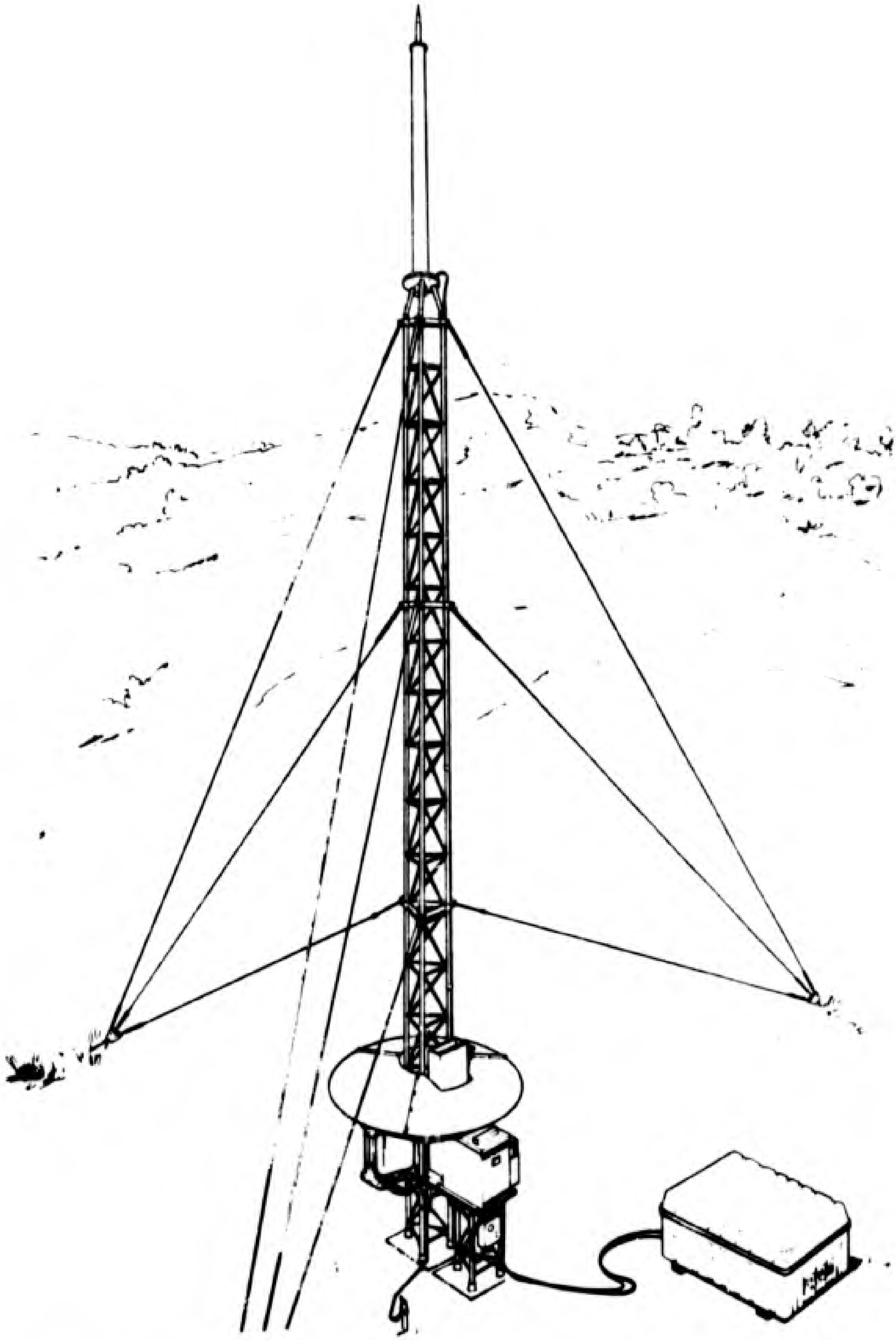


Figure 25. Typical Installation, A (or D) Station Erected in the Field

7.2.2.3 Computation and Control Subsystem

Although the RMS-2/DCS system has no separate CCS computer, at least two functions normally associated with the CCS are performed by the Varian 620f computer system.

a. The range data are used to compute position in accordance with a Kalman filtering algorithm.
b. Every 30 seconds, a system performance summary printout is initiated on the line printer. This procedure enables determination of any system malfunctions or unit failures in real-time.

7.2.2.4 Display and Debriefing Subsystem

The RMS-2/DCS system has no provision for real-time display of range data.

7.2.3 Present System Operational Description

7.2.3.1 Tracking Instrumentation Subsystem

Figure 26 depicts a typical operational configuration for the RMS-2/DCS system. The Varian 620f computer sends out ranging commands in parallel form to the C station where they are converted to serial form for transmission to the ground reference network. The commands contain digital coding information which specify the path to be followed by the signal. A designated A station will be instructed to obtain a range to a specific B unit. The B unit response returns to the C station through the same ground link. Where a relay transponder is employed, the ranging command will contain the digital address code for that station as well.

Digital communications messages also contain coded digital path specification data and are usually relayed over a link known to have recently produced valid ranging responses from the desired range member.

The interrogation scheme used is governed by the software routine employed for a given range exercise. For example, the C station may be directed to range on each member through all remote transponders in sequence. This scheme may be followed for several cycles and then selected transponders may be used to range to those B units from which valid range responses have been obtained. There are a large number of possible variations of these and other schemes which may be used depending on exercise requirements.

The digital address code includes four fields (groups of bits) of information:

Field 1 - D station address
Field 2 - A station address
Field 3 - B unit address
Field 4 - Mode

The four possible modes are ranging, short communication (SCOM), extended communication from A station to B unit (EAB), and extended communi-

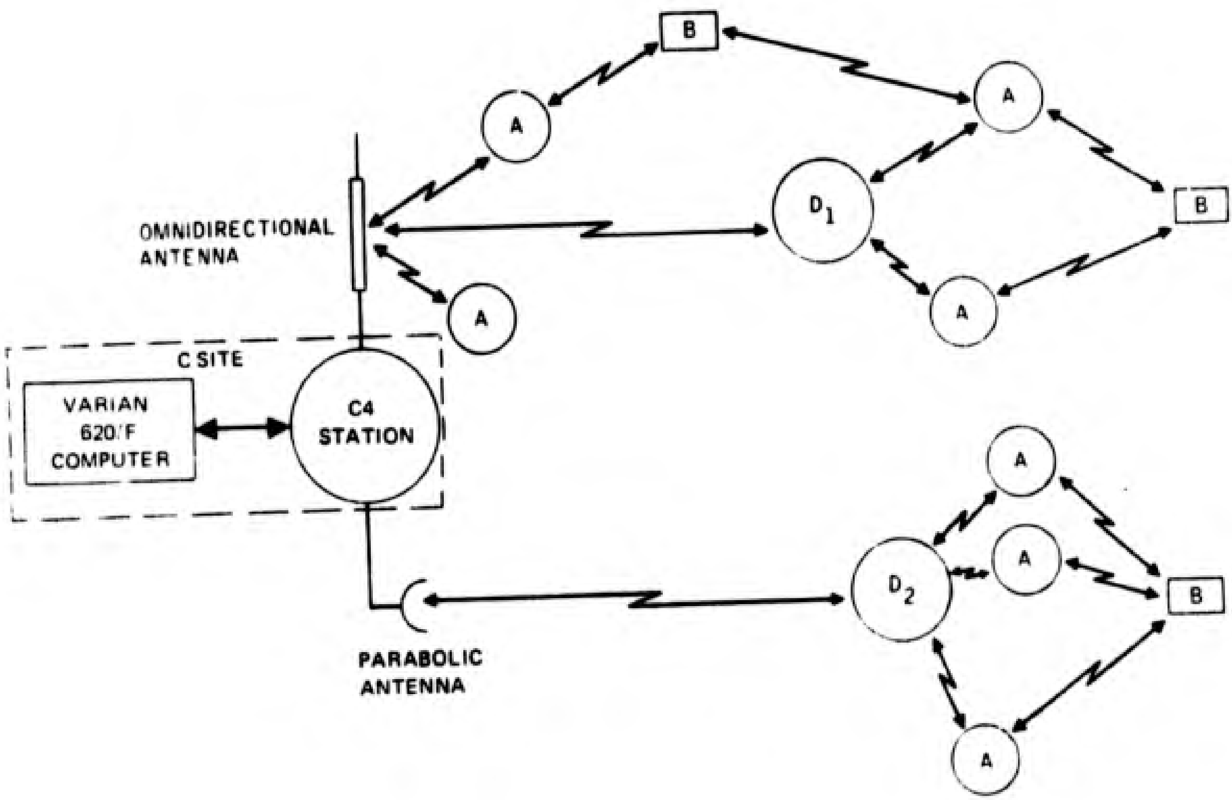


Figure 26. RMS-2/DCS Operation

cation from B unit to A station (EBA).

1. Range - A designated A station is directed to send a ranging pulse to a given B unit. If the first field of the digital address code contains all zeros no relay transponder will be used for the interrogation. Only the remote transponder designated by the second field will enable its transmitter to send the ranging command to the selected B-unit. The return path from the B-unit to the master station will include the same reference network elements as the up-link path.

2. Short Communication - A four bit message is sent via the selected A-station to the B-unit and a down-link message of 13 bits is returned from the B-unit.

3. Extended Communication A-to-B (EAB) - A specific A station transmits a 42-bit message to the desired B unit. The only reply from the range member is a single validity bit to indicate that the message has been received.

4. Extended Communication B-to-A (EBA) - The designated A station obtains a 42-bit message from a specific B unit.

The maximum range between C and A (or C and D) stations is 4.8 nmi. and the maximum range between an A station and a B-unit to the C station is approximately 44 nmi., providing a range diameter of 88 nmi. maximum.

The rate at which data can be obtained is dependent on the type of command (mode) and the distance between stations in the ground reference network. For each of the four types of command it is possible to have a signal path which includes a D station or a direct C to A link. The total message times for these eight cases are summarized in Table XV. Propagation time is not included in these figures.

As an example of system capability assume the following parameter values:

C to D station distance	4.8 nmi
Average D to A station distance	2.4 nmi
Average C to A station distance	2.4 nmi
Average A station to B-unit distance	1.6 nmi

If half of the commands are routed through a D station and the remainder are sent through direct C to A links the RMS-2/DCS system is capable of executing 4100 commands within 3.4 seconds. These commands are distributed by type as follows:

Range	1800
SCOM	2000
EAB	150
EBA	150

The specific requirements of TSPI are addressed in Section 7.2.4.

Table XV RMS-2/DCS, Total Message Time
(Less Propagation Time)

TYPE COMMAND	LINK PATH ELEMENTS	
	C-D-A-B (μs)	C-A-B (μs)
RANGING	812	493
SCOM	884	555
EAB	1421	857
EBA	1250	801

The carrier frequency for all stations in the RMS-2/DCS system is 930 MHz. Four subcarrier frequencies are used for unique transmission channels in each link of the signal path. Four channels are necessary to prevent mutual interference between similar units. The upper and lower sidebands of each channel are used as the digital "1" and "0" states to enable transmission of digital information with minimal multipath interference. The channel and sideband assignments are shown in Figure 27.

The start of a message is defined by an initializing pulse followed by a blank space. The location of the initiating pulse determines which type of station is being addressed in the command. The channel initialization for all possible link paths is shown in Figure 28.

The slant range can be extracted from the round-trip propagation time in a manner similar to that discussed in Section 7.1.3.1 for the Cubic Corporation ACMR system. Since the transponder delays, distances between stations in the reference network, and propagation velocity are all known, slant range computation is straightforward.

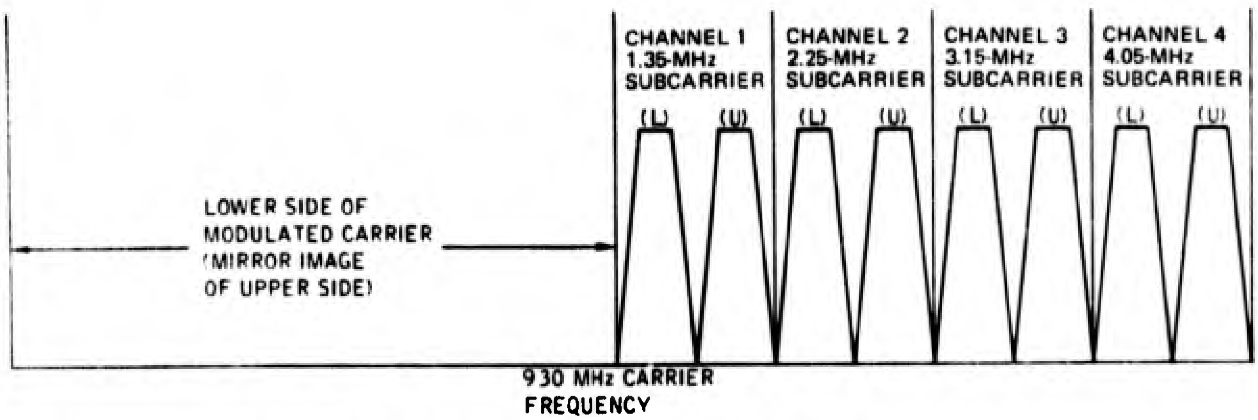
The Varian 620f computing system implements the desired interrogation routine, time tags all ranges received from the C station, performs ranging calculations and records system data output on magnetic tape for post-exercise analysis.

Varian software includes a Master Operating System (MOS), AID II Programmer's Debugging Aid, BASIC Interpreter, and a complete set of input diagnostics for the Central Processing Unit, memory, optional mainframe equipment, and peripherals.

The following system programs are included in the Master Operating System:

a. FORTRAN IV Compiler
b. DAS Macro Assembler
c. Loader
d. Source File Editor
e. System Maintenance Program
f. System Preparation Program
g. Debug Package
h. FORTRAN Run-Time Input/Output (I/O) and Mathematical Library

General Dynamics has developed an operational system test program (LOGT) which verifies that all A and D stations and all B-units are capable of transmitting and receiving in all four message modes. The LOGT program is written in DAS assembly language and is modular to enable specific modules to be exercised as the user requires.



TRANSMISSION, C TO A OR D TO A:

CHANNEL 1	CHANNEL 1U - LOGIC 1 CHANNEL 1L - LOGIC 0
CHANNEL 4	CHANNEL 4U - LOGIC 1 CHANNEL 4L - LOGIC 0

TRANSMISSION, A TO C OR D:

CHANNEL 2	CHANNEL 2U - LOGIC 1 CHANNEL 2L - LOGIC 0
CHANNEL 3	CHANNEL 3U - LOGIC 1 CHANNEL 3L - LOGIC 0

TRANSMISSION, C TO D:

CHANNEL 2	CHANNEL 2U - LOGIC 1 CHANNEL 2L - LOGIC 0
CHANNEL 3	CHANNEL 3U - LOGIC 1 CHANNEL 3L - LOGIC 0

TRANSMISSION, D TO C:

CHANNEL 1	CHANNEL 1U - LOGIC 1 CHANNEL 1L - LOGIC 0
CHANNEL 4	CHANNEL 4U - LOGIC 1 CHANNEL 4L - LOGIC 0

TRANSMISSION, A TO B:

CHANNEL 2	CHANNEL 2U - LOGIC 1 CHANNEL 2L - LOGIC 0
CHANNEL 3	CHANNEL 3U - LOGIC 1 CHANNEL 3L - LOGIC 0

TRANSMISSION, B TO A:

CHANNEL 1	CHANNEL 1U - LOGIC 1 CHANNEL 1L - LOGIC 0
CHANNEL 4	CHANNEL 4U - LOGIC 1 CHANNEL 4L - LOGIC 0

Figure 27. RMS-2/DCS RF Transmission Spectrum

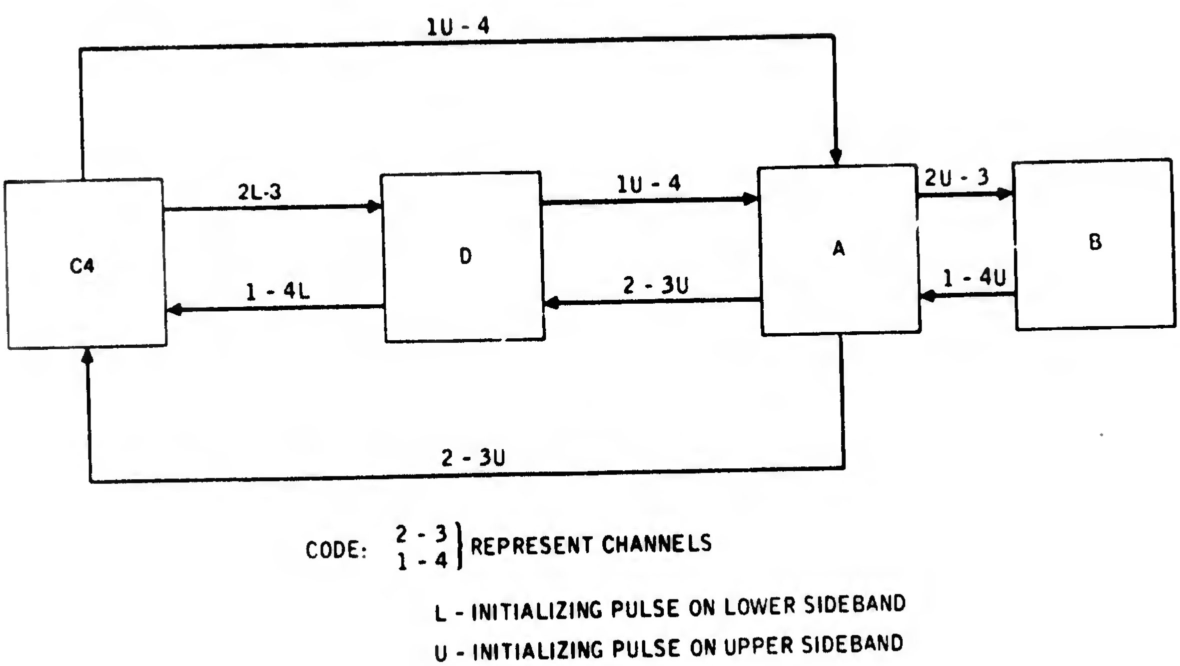


Figure 28. RMS-2/DCS Channel Utilization

7.2.3.2 Aircraft Instrumentation Subsystem

A block diagram of the B-unit transponder appears in Figure 29. The output of the receiver is monitored by the digital storage and control logic. If the initializing bit and digital address code agree with those required by the control logic unit the transmitter is turned on and the appropriate reply message is sent.

For the ranging mode the ranging pulse is retransmitted on the reply channel.

In the case of a short communication (SCOM) the four bit up-link message is stored and a 13 bit message is returned to the ground reference network.

An extended communication from an A station to a B unit (EAB) consists of a 42 bit up-link message which is stored. A single "validity bit" acknowledging receipt of the message is the only reply transmission.

When a request for an extended communication from a B-unit to an A-station is received a 42 bit message is transmitted to the A-station.

Typical input/output accessories for use with the transponder may be an inertial measuring unit and preprocessor assembly, weapons bus monitor, vehicle systems/armament monitor, manpack data unit, etc.

7.2.4 Comparison of RMS-2/DCS System with TSPI Requirements

7.2.4.1 Near Term Requirements

The General Dynamics RMS-2/DCS is an existing system designed specifically to meet U.S. Army requirements for determining and recording the locations of tactical units during field exercises. Consequently, some development will be necessary to develop the hardware and software capabilities dictated by the TSPI system requirements.

There are five areas at present in which the RMS 2/DCS system do not fully meet the requirements set forth in the TSPI statement of work:

1. The airborne transponder is not pod mounted and no inertial measuring unit has been incorporated. G-D is developing a pod to contain the transponder and plans to incorporate the Lear-Siegler Industries IMU and preprocessor to obtain attitude data on airborne members. This pod assembly is anticipated to be ready for test by the first quarter of 1973. It is reasonable to expect the attitude data accuracy to be on the order of that attained by the Cubic Corporation ACMR system since the IMU's are identical.

   The pod components will be arranged as shown in the sketch of Figure 30. The IMU is positioned at the extreme rear of the pod to place it closer to the center of gravity of the aircraft

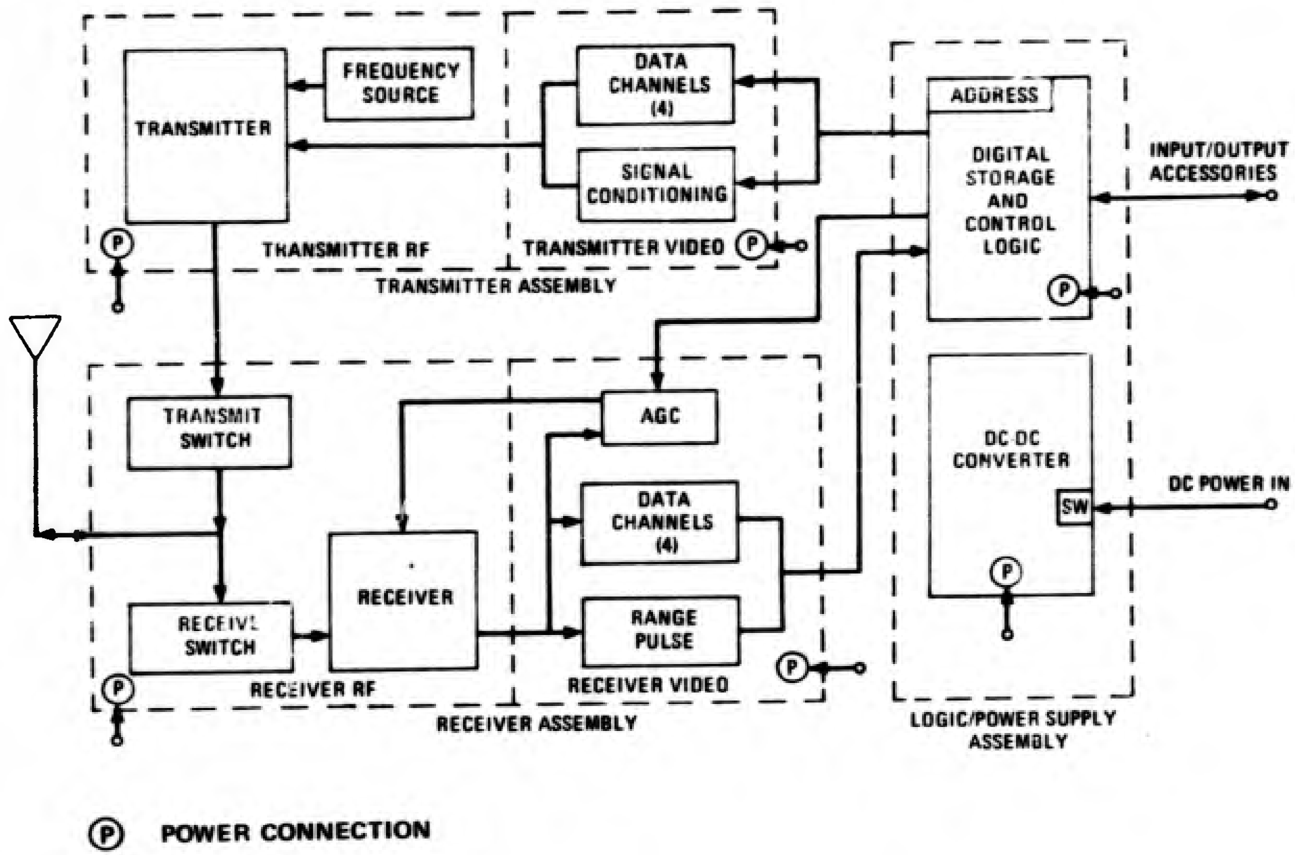


Figure 29. Micro-B Unit Functional Block Diagram

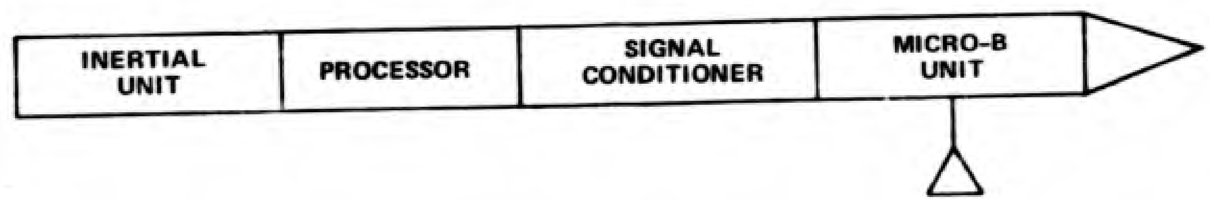


Figure 30. RMS-2/DCS Pod Component Placement

and reduce cross-coupling effects, e.g., displacement (velocity and acceleration) with pitch and roll inputs.

Placing the transponder at the front of the pod provides minimum shadowing of the antenna by the aircraft wings.

2. No real-time data analysis or display capability exists. Much of the software required to do the range safety, display support and related data processing tasks is available from similar systems developed for DOD. Thus, acquiring real-time data analysis capability (the CCS function) would not entail massive software development costs. This aspect of the data processing problem is addressed in more detail in Section 9.1.2.

   General Dynamics is experienced in the design and construction of display equipment, particularly large screen projection type units as shown in Figure 31. Both this unit and an interactive console display have been used by G-D for post-real-time display of RMS-2/DCS data, consequently display software development costs should be minimal.

3. Position accuracy for a subset of four aircraft is not known for the proposed system with inertial aiding. The X and Y axis accuracies measured during the Combat-Hunter Maverick missile trials [Reference 10] without inertial equipment are $\pm$ 6 ft (1σ) which is within the $\pm$ 20 ft requirement. The Z axis accuracy for the Combat Hunter exercises at low altitudes is $\pm$ 48 ft. If inertial aiding will produce a factor of improvement of 3.7 then the near term position accuracy specification can be met completely. The minimum altitude at which the 20 ft SEP specification can be met is highly dependent on the amount of improvement possible by integrating IMU data into the position computation algorithm.

4. Although the RMS-2/DCS system provides digital communications capability, the message size for an extended A to B or B to A communication is only 42 bits. This is not sufficient to allow complete attitude updates each interrogation. Four successive interrogations are required to update all of the IMU state variables, i.e., obtain a complete set of pod data, thus no surplus capability for discrete event data exists coincident with position data interrogations. Discrete event data is time-tagged as it occurs and can be down-linked within two interrogations of its occurrence (typically several milliseconds).

5. The RMS-2/DCS cannot meet the position and attitude update rates required for TSPI in its present configuration. The scheme proposed by G-D for the TSPI task provides for tracking 16 aircraft - four at a high update rate and the remaining twelve at a low update rate.

Figure 31. Large Screen Display Projector

For the four high interest aircraft a total of 32 ranges per second per aircraft are obtained. 40 EBA messages per second per aircraft provide 10 attitude updates per second per aircraft. These data are used to compute an updated position estimate 4 times per second per aircraft.

The twelve low-interest aircraft are interrogated for range data 8 times per second per aircraft. 4 EBA messages per second per aircraft are obtained to provide 1 attitude update per second per aircraft. A new position estimate is computed once per second on each aircraft using these data.

The members of the group of four high interest aircraft can be changed through appropriate software inputs in real time, in effect providing a subset arrangement at all times. This is not the only scheme which is possible and the system hardware is not constrained to this implementation. The update rates for this scheme represent the maximum capability of the RMS-2/DCS system.

Some increase in data rate could be obtained by changing from a sequential ranging to a simultaneous ranging scheme. An increased number of subcarrier channels on the A to C station link would be necessary to permit all A-station transponders to reply to the master station simultaneously. In implementing this change care must be exercised to prevent exceeding the maximum duty cycle of the transponder transmitters.

The duty cycle is defined as the ratio of total transmitter "on" time to the time interval between message starts. It may be possible to increase the maximum duty cycle by reducing maximum power output but the effect on signal/noise ratio at maximum B unit-to-A station range must be evaluated.

Adding power amplification to maintain the same power output at a higher duty cycle will require increased physical size, heat dissipation capability, and input power consumption from the transmitters.

Any changes in system configuration for increased data rate must be scrutinized closely to determine the impact on other system parameters and should be the subject of a separate design study. The data rates required by the TSPI statement of work are discussed further in Section 10.3.

7.2.4.2 Far Term Requirements

7.2.4.2.1 Range Size

The far term system has a required range diameter of 200 nmi. Two possible schemes for meeting this specification are envisioned.

Given adequate line-of-sight distances between the master station and relay transponders it would be possible to increase range size by adding power amplification to the C and D station transmitters. Higher towers may be required to achieve the required line-of-sight distances, and the D-station power supply and reserve capacities would need to be increased.

Since the RMS-2/DCS system can be operated with a maximum of 7 D stations and 127 A stations, all having the same carrier frequency, no increase in the portion of the r.f. spectrum used would be experienced.

The second scheme would employ multiple colocated RMS-2/DCS subsystems having all C site computers interfaced with a master CCS computer. A larger address code may be required to insure that all D and A stations of all subsystems will be discretely addressable; however, only one carrier frequency would be required. This arrangement would enable any aircraft to operate within the surveillance of any subsystem.

7.2.4.2.2 60 Airborne and 40 Ground Members

The RMS-2/DCS system is currently capable of discretely addressing up to 1023 range members, any number of which may be airborne or ground units. The rate at which position updates on these members may be obtained is limited by the maximum interrogation rate as determined by message size and propagation time, the duty cycle restrictions on the various transponder transmitters, and the number of airborne units carrying IMU equipment.

Increasing the rate at which data is available may be accomplished by converting from sequential to simultaneous ranging techniques as discussed previously in Section 7.2.3.1.

A further increase in data rate may be effected by colocating multiple subsystems each with a different carrier frequency. Each subsystem would be dedicated to specific range members and would also be required to track those units anywhere on the range.

Instead of providing redundant hardware over the entire range a multiple frequency transponder could be developed for the A and D stations. The C-station would also require multiple carrier frequency transmitting and receiving equipment.

It may be necessary to provide a separate antenna for each subsystem carrier frequency since simultaneous transmission from the same antenna at several frequencies could result in the generation of undesirable harmonics.

B-unit transponder changes for each additional subsystem would be confined to modifying transmitters and receivers for operation on a frequency other than the present 930 MHz carrier frequency.

7.2.4.2.3 Operating Altitude of Range Members

The RMS-2/DCS system is presently capable of tracking line-of-sight ground members.

The 200 ft minimum aircraft operating altitude requirement can probably be met but not without some sacrifice in position accuracy.

7.2.4.2.4 Velocity of Range Members

The 0-100 FPS velocity specification on ground members does not present any difficulty and is within the current capability of the RMS-2/DCS system.

The 0-4000 FPS velocity specification for aircraft poses no problems with the tracking system capability, however, pod cooling difficulties may arise from prolonged operation at maximum velocity.

7.2.4.2.5 Subset Position Accuracy

The X and Y axis position accuracies are ± 6 ft (1σ); however, it is not likely that Z axis position accuracy on this order of magnitude can be obtained due to multipath and GDOP errors. The 5 ft SEP specification requires the 1σ position accuracy in each axis be ± 3.25 ft. This figure is less than the basic ranging system accuracy (as computed in Section 8) which can be considered to be a limiting case accuracy. Even with aiding of position accuracy due to integration of IMU data, it seems unlikely that state-of-the-art ranging equipment can economically meet the 5 ft SEP specification stated as a far-term system requirement.

7.2.4.2.6 Position Update Rates

The RMS-2/DCS system probably cannot be modified to obtain data rates high enough to satisfy the far term system subset requirements with economic feasibility. See additional comments on data rates in Sections 3.4, 7.2.4.1, and 7.2.4.2.2.

7.2.5 Cost of System Components*

The cost data summarized in Table XVI apply to the General Dynamics - RMS-2/DCS system as configured for the Combat Hunter experiments. It should be noted that no IMU equipment was used, the airborne transponders were not pod mounted, and no real-time display and debriefing capability existed.

Since the proposed airborne pod will incoporate the same LSI inertial package and preprocessor, the total pod costs will probably be similar in magnitude, exclusive of development costs.

Production quantities on some items (e.g. the micro-B transponder) should lower the per unit cost significantly,

The data presented for the RMS-2/DCS system and the Cubic Corporation ACMR should not be compared unit-for-unit since both systems are not configured to accomplish the same task.

* See Section X for cost estimates of a near-term system configuration.

Table XVI Summary of Costs for RMS-2/DCS

	QUANTITY	UNIT PRICE ($)
MICRO "B" TRANSPONDERS	30	22,000
INTERROGATOR STATIONS ("A") COMPLETE	15	51,245
MICRO "B" ANTENNAE	30	1,243
"C" STATION (INCLUDES TRAILER/ AIR CONDITIONER)	1	525,764
COMPUTER PERIPHERALS SOFTWARE		
"D" UNIT (RELAY STATION) COMPLETE	1	52,438
TEST EQUIPMENT STATION (INCLUDES TRAILER/AIR CONDITIONER)	1	477,103
MODULE AND BLACK BOX TESTERS, SPARE PARTS STORAGE		
SPARE PARTS	1 LOT	179,577
DOCUMENTATION, OPERATIONS MANUALS	1 LOT	30,153
OPERATION AND SUPPORT (DIFFICULT TO DETERMINE WITHOUT SPECIFICS)		

7.2.6 Reliability and Maintainability

Based on continuous operation at Hunter-Liggett Military Reservation, an observed A and D station Mean Time Between Failures (MTBF) of 23,000 hours with 60-70% confidence has been observed.

No data is available on B-unit transponders or the C-station equipment.

No maintainability information is available on the RMS-2/DCS system.

SECTION VIII

CONTRACTOR SYSTEMS--ANALYSIS OF RANGING TECHNIQUES

8.1 RANGE ACCURACY ASSESSMENT OF A LEADING EDGE RANGE TRACKING AND CW/DME TECHNIQUE

8.1.1 Introduction

The following paragraphs delineate various causes of errors in a leading edge range tracking and CW/DME technique. Results are summarized in Table XVII with the assumptions made.

8.1.2 Atmospheric Propagation Error

Cooperative target of interest will be operating in the troposphere (i.e., below 50 kft) where the propagation errors are well known and data corrections are available [Reference 11]. This range error consists of two parts, a bias error and a random error, which are dependent upon the elevation angle and the range to the target as well as the refractive index. Work at the National Bureau of Standards (NBS) and others has shown that a large portion of the range error can be eliminated by measuring the surface refractivity in the regions near a radar site and applying corrections derived from simple algorithms [References 12, 13]. It is assumed that the bias error can be adequately compensated for and, therefore, will cause no uncertainty in the range measurement.

The random error caused by irregular refractivity fluctuations of the troposphere has been studied [Reference 14]. Experimental data gathered by the NBS has been statistically treated by Barton [Reference 15] to obtain the standard deviation of the total fluctuations and arrived at the following simple expression relating the standard deviation (σ_{R_A}) and path length (L).

$$\sigma_{R_A}/L = 15 \times 10^{-6}$$

Since the total path length L involved is equal to twice the range (R) to the target, the above equation becomes:

$$\sigma_{R_A} = 30 \times 10^{-6} R$$

For a twenty nautical mile target range, an error of 3.6 feet could be expected. This error can be reduced by recognizing the fact that daily changes as well as seasonal changes cause the largest contribution to the fluctuations. If corrections to the refractive index model are made on a daily basis, then the standard deviation is approximately:

$$\sigma_{R_A} = 10 \times 10^{-6} R$$

or approximately 1.2 feet of uncertainty for a 20 n.mi. range [Reference 16].

Table XVII Summary of Range Errors

ERROR SOURCE	σ_R^2 (ft^2)		CONDITIONS
	LEADING EDGE	CW/DME	
(1) PROPAGATION	1.4	1.4	R = 20 nmi
(2) SIGNAL TO NOISE	1.1	8.3	$(SNR)_L$ = 35 dB CW/DME S/N = 20-dB LEADING EDGE $B_L = B_{iopt}$ FOR CW/DME
(3) RANGE OSCILLATOR OR VOLTAGE-CONTROLLED OSCILLATOR INSTABILITY	1.6	8.3	R = 20 nmi FOR LEADING EDGE $B_L = B_{iopt}$ FOR CW/DME
(4) THRESHOLD LEVEL INSTABILITY	20.0	NA	$\Delta V_T/V_T = \pm 0.75$ dB
(5) INSTRUMENT ERROR	3.0	3.0	ASSUMED
(6) AIRBORNE TRANSPONDER ERROR	3.0	3.0	ASSUMED
(7) MULTIPATH	NA	21.0	β = 20 FOR CW/DME. ASSUMED GATED OUT FOR LEADING EDGE
(8) QUANTIZATION	0.1	0.1	Δ = 1 ft
(9) DATA PROCESSING	2.0	2.0	ASSUMED
TOTAL	32.2	47.1	(LEADING EDGE) = 5.7 ft (CW/DME) = 6.9 ft

8.1.3 Precision Ranging System of Interest

Two types of precision ranging systems (i.e., leading edge and CW-DME) are of current interest. In a leading edge range tracking technique, a determination of the range is made by observing when a given point on the leading edge of the received pulse signal crosses a preset threshold. In the CW-DME ranging technique, a CW received signal is compared to a given CW reference signal, where the range is expressed as the difference in phase between the reference signal and received signal.

In modern range tracking, the time difference is usually measured with a counting technique. In the leading edge technique a range counter is started by the leading edge of the transmitted signal and stopped by the leading edge of the received signal. Similarly, in a CW-DME implementation a "zero crossing" of the reference signal starts the range counter and the phase shifted "zero crossing" of the received signal stops the counter.

8.1.4 Signal to Noise Effect on Leading Edge Ranging Systems

The effect of thermal noise on the position uncertainty of the leading edge of a pulse has been analyzed [Reference 17] and an expression derived for the standard deviation in the threshold crossing level. To evaluate the expressions given in Reference 17, the standard deviation of the noise σ_N, the standard deviation of the derivative with respect to time of the noise $\sigma_{N'}$, the slope of the leading edge M and the threshold voltage V_T must be known. For a large signal to noise ratio, the pertinent expression from Reference 17 (i.e., Equation 31, Reference 17) can be approximated as:

$$\sigma_{R_c}^{2} \doteq erf\left(\frac{M}{\sigma_{n'}}\right) \cdot erf\left(\frac{V_T}{\sigma_n}\right) \cdot \frac{\sigma_n^{2}}{M^{2}}$$

To evaluate $\sigma_{n'}$, the standard deviation of the derivative of the noise associated with the detection process, the following model is assumed. The received signal is passed through an IF amplifier, detected in a linear detector and filtered by a video amplifier of bandwidth B_V. This video bandwidth is sufficient to pass a pulse rise time of t_R seconds. Then for an ideal intermediate frequency passband characteristic, the video spectrum in the region from 0 to B_V, after detection by a linear detector is given [Reference 18] as:

$$S(f) = \frac{N_0}{4\pi}\left\{1 - \frac{|f|}{B_V}\right\} \qquad 0 < f \leq B_V$$

where N_0 is the noise power per unit bandwidth in the intermediate frequency amplifier. The variance of this spectrum can be computed as:

$$\sigma_n^{2} = 2\int_0^{B_V} \frac{N_0}{4\pi}\left\{1 - \frac{|f|}{B_V}\right\} \cdot |H(f)|^2 \, df = \frac{N_0 B_V}{4\pi}$$

where $H(f)$ is the network transfer function of the video amplifier. For simplicity we have assumed that $|H(f)|^2$ is unity for $0 < f \leq B_V$, and zero elsewhere.

The variance of the derivative of the noise ($\sigma_{n'}^2$) can be determined from the following relationship:

$$\sigma_{n'}^2 = 2 \int_0^{B_V} S(f) \cdot f^2 \cdot |H(f)|^2 \, df$$

since the derivative of the noise can be obtained by passing the spectrum of the noise, $S(f) \, |H(f)|^2$ through an ideal differentiation (i.e., $H_D(f) = j \, f$). Therefore, the expression for $\sigma_{n'}^2$ becomes:

$$\sigma_{n'}^2 = \frac{\sigma_n^2 B_V^2}{6}.$$

The expression for the variance in the crossing level can be related to signal to noise ratios and pulse rise time as follows. Let

$$\frac{S}{N} = \frac{V_T^2}{2 \sigma_n^2}$$

$$M^2 = \frac{4 V_T^2}{t_R^2}$$

Then

$$\frac{M}{\sigma_n'} = \frac{2 V_T \sqrt{6}}{t_R \sigma_n B_V} = \frac{4\sqrt{3}}{t_R B_V} \cdot \sqrt{\frac{S}{N}}$$

Substituting into the expression for $\sigma_{R_c}^2$ yields:

$$\sigma_{R_c}^2 \doteq erf\left(\frac{4\sqrt{3}}{t_R B_V} \cdot \sqrt{\frac{S}{N}}\right) \cdot erf\left(\sqrt{\frac{2S}{N}}\right) \cdot \frac{t_R^2}{8\left(\frac{S}{N}\right)}$$

Since the optimum relationship between rise time and bandwidth is given as

$$t_R B_V = 0.35$$

and the error function (erf) can be approximated as unity for values of the argument greater than two, the expression for σ_{R_c} can be approximated as:

$$\sigma_{R_c} = \frac{t_R}{\sqrt{8} \sqrt{S/N}}$$

Assuming an effective signal to noise ratio of at least 20 dB and a rise time of 65×10^{-9} sec, the resultant error would be:

$$\sigma_{R_c} = 2.3 \times 10^{-9} \text{ sec}$$

or approximately one foot of range error would be incurred.

8.1.5 Oscillator Instability (Leading Edge Ranging)

In a pulse ranging system or a CW-DME, precision oscillators are used as a reference to determine range. Their contribution to system error is

8.1.3 Precision Ranging System of Interest

Two types of precision ranging systems (i.e., leading edge and CW-DME) are of current interest. In a leading edge range tracking technique, a determination of the range is made by observing when a given point on the leading edge of the received pulse signal crosses a preset threshold. In the CW-DME ranging technique, a CW received signal is compared to a given CW reference signal, where the range is expressed as the difference in phase between the reference signal and received signal.

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$$\sigma_{R_C}^2 \doteq erf\left(\frac{M}{\sigma_{n'}}\right) \cdot erf\left(\frac{V_T}{\sigma_n}\right) \cdot \frac{\sigma_n^2}{M^2}$$

To evaluate $\sigma_{n'}$, the standard deviation of the derivative of the noise associated with the detection process, the following model is assumed. The received signal is passed through an IF amplifier, detected in a linear detector and filtered by a video amplifier of bandwidth B_V. This video bandwidth is sufficient to pass a pulse rise time of t_R seconds. Then for an ideal intermediate frequency passband characteristic, the video spectrum in the region from 0 to B_V, after detection by a linear detector is given [Reference 18] as:

$$S(f) = \frac{N_0}{4\pi}\left\{1 - \frac{|f|}{B_V}\right\} \qquad 0 < f \leq B_V$$

where N_0 is the noise power per unit bandwidth in the intermediate frequency amplifier. The variance of this spectrum can be computed as:

$$\sigma_n^2 = 2\int_0^{B_V} \frac{N_0}{4\pi}\left\{1 - \frac{|f|}{B_V}\right\} \cdot |H(f)|^2 \, df = \frac{N_0 B_V}{4\pi}$$

where $H(f)$ is the network transfer function of the video amplifier. For simplicity we have assumed that $|H(f)|^2$ is unity for $0 < f \leq B_V$, and zero elsewhere.

The variance of the derivative of the noise ($\sigma_{n'}^2$) can be determined from the following relationship:

$$\sigma_{n'}^2 = 2 \int_0^{B_V} S(f) \cdot f^2 \cdot |H(f)|^2 \, df$$

since the derivative of the noise can be obtained by passing the spectrum of the noise, $S(f)\,|H(f)|^2$ through an ideal differentiation (i.e., $H_D(f) = j f$). Therefore, the expression for $\sigma_{n'}^2$ becomes:

$$\sigma_{n'}^2 = \frac{\sigma_n^2 B_V^2}{6}$$

The expression for the variance in the crossing level can be related to signal to noise ratios and pulse rise time as follows. Let

$$\frac{S}{N} = \frac{V_T^2}{2\sigma_n^2}$$

$$M^2 = \frac{4V_T^2}{t_R^2}$$

Then

$$\frac{M}{\sigma_n'} = \frac{2V_T\sqrt{6}}{t_R \sigma_n B_V} = \frac{4\sqrt{3}}{t_R B_V} \cdot \sqrt{\frac{S}{N}}$$

Substituting into the expression for $\sigma_{R_C}^2$ yields:

$$\sigma_{R_C}^2 \doteq erf\left(\frac{4\sqrt{3}}{t_R B_V} \cdot \sqrt{\frac{S}{N}}\right) \cdot erf\left(\sqrt{\frac{2S}{N}}\right) \cdot \frac{t_R^2}{8\left(\frac{S}{N}\right)}$$

Since the optimum relationship between rise time and bandwidth is given as

$$t_R B_V = 0.35$$

and the error function (erf) can be approximated as unity for values of the argument greater than two, the expression for σ_{R_C} can be approximated as:

$$\sigma_{R_C} = \frac{t_R}{\sqrt{8}\,\sqrt{S/N}}$$

Assuming an effective signal to noise ratio of at least 20 dB and a rise time of 65×10^{-9} sec, the resultant error would be:

$$\sigma_{R_C} = 2.3 \times 10^{-9} \text{ sec}$$

or approximately one foot of range error would be incurred.

8.1.5 Oscillator Instability (Leading Edge Ranging)

In a pulse ranging system or a CW-DME, precision oscillators are used as a reference to determine range. Their contribution to system error is different depending upon the technique used. Usually in a pulse system, a precision oscillator is used to determine range, i.e., a given number of zero crossings of the oscillator are counted to determine range. In the CW-DME the phase shift between two precision oscillators are used to determine range. For the pulse ranging system, where the number of zero crossings are counted to determine range, it can be shown that the error in range σ_{R_0} is equal to:

$$\sigma_{R_0} = R \frac{\sigma_f}{f_0}$$

Hence, the error is range (R) dependent and is proportional to the frequency stability of the oscillator (σ_f / f_0). Factors that contribute to oscillator instability [Reference 19] are:

(1) thermal noise
(2) aging
(3) variation in drive level
(4) temperature
(5) power supply variation
(6) loading
(7) vibration

Taking into account all these factors, precision crystal oscillators, which are economically feasible for field type of equipment, exhibit stabilities between 1 part per million to 100 parts per million, i.e.,

$$1 \times 10^{-6} \leq \sigma_f / f_0 \leq 100 \times 10^{-6}$$

To obtain a higher stability oscillator means to compensate items (3) to (7) above must be employed.

Assuming in field equipment that a frequency stability (including aging) of 10×10^{-6} is reasonable, the following error in ranging will be incurred for a range of 20 n.mi.

$$\sigma_{R_0} = 20 \times 6080 \times 10^{-5} = 1.22 \text{ ft}.$$

8.1.6 CW-DME Ranging

In this ranging technique, it is assumed that a phase locked loop (PLL) is utilized. The error in the output signal is caused by two sources; namely, (1) the input noise, which perturbs the phase of the input signal and causes the output signal of the PLL to "jitter" in phase, which when compared to the reference signal will result in a random phase (range) error, (2) the instability of the Voltage Controlled Oscillator (VCO) in the PLL which causes phase jitter on the output. The amount of this jitter is related to the inherent stability of the VCO used.

Total error due to random noise and VCO instability has been assessed [Reference 20] and is given as:

$$\sigma_\theta^2 = \frac{N_o B_L}{P_c} + \frac{1 + \frac{1}{4}\delta^2}{8 \tau_c B_L}$$

where:

P_c	=	power in carrier signal
N_o	=	noise/unit bandwidth
B_L	=	effective loop bandwidth
δ	=	loop damping factor
τ_c	=	oscillator coherence time

It is apparent from the above expression that an optimum bandwidth ($B_{L_{OPT}}$) exists which will minimize the total phase error. Taking the derivative of the above expression and equating it to zero, yields:

$$B_{L_{OPT}}^2 = \frac{P_c}{N_o} \cdot \frac{1 + \frac{1}{4}\delta^2}{8 \tau_c}$$

Defining $(SNR)_L$ as $\frac{P_c}{N_o B_{L_{OPT}}}$ we have:

$$\sigma_{\theta_{min}}^2 = \frac{2}{(SNR)_L}$$

Phase locked loops are seldom operated with signal to noise ratio within the loop [$(SNR)_L$] of less than 30 to 40 dB. It is difficult to maintain $(SNR)_L$ greater than 40 dB under all system conditions; hence, for the purpose of assessing this error, an average $(SNR)_L$ of 35 dB will be assumed. The resulting phase error is:

$$\sigma_{\theta_{min}} = \frac{1.414}{56} \text{ radians } (1.43 \text{ degrees})$$

This is equivalent to a range error of 1024/360 x 1.43 or 4.1 feet if a ranging tone (approximately 960 kc) is selected such that 2π radians is equal to 1024 feet which is convenient for digital calculations (i.e., $2^{10} = 1024$).

Selecting the loop bandwidth (B_L) to optimize the phase error may not be possible in all cases since acquisition time (lock up time) is also dependent upon loop bandwidth. An approximate expression is available [Reference 21] for lock up time in terms of the loop parameter for a second order loop. The expression is:

$$T_L \doteq \frac{(\Delta\omega)^2}{2\delta\omega_n^3}$$

where:

T_L	=	lock up time
δ	=	loop damping factor
ω_n	=	loop natural frequency

ω_n is related to the effective loop bandwidth B_L for a second order loop [Reference 22] as follows:

$$B_L = \frac{\omega_n \delta}{2}\left(1 + \frac{1}{4\delta^2}\right)$$

Using these two relationships in the above expression yields the following expression for lock up time with $B_{L\,OPT}$ as:

$$T_L \doteq \frac{2\delta^2 (\Delta\omega)^2 \tau_c^3}{(SNR)_L^3}$$

The effective coherence time of an oscillator is defined as the time interval required for the RMS value of the input carrier phase to build up to one radian relative to the phase at the beginning of the interval. The coherence time τ_c is related to the stability (S) as follows:

$$\Delta\omega \cdot \tau_c = 1$$

$$\tau_c = \frac{1}{2\pi\Delta f} = \frac{1}{2\pi f_o (\Delta f / f_o)} = \frac{1}{2\pi f_o \cdot S}$$

Hence

$$T_L \doteq \frac{1}{\pi} \cdot \frac{\delta^2}{(SNR)_L^3} \cdot \frac{1}{f_o S}$$

For SNR = 35 dB, $\delta = 1/2$, $f_o = 960 \times 10^3$ Hz, and $S = 10 \times 10^{-6}$, T_L is the order of nanoseconds (10^{-9} sec) mainly due to the high loop signal to noise ratio $(SNR)_L$.

Since the optimum loop bandwidth is a function of the loop SNR, it is not possible to maintain an optimum bandwidth for all conditions, but this condition is usually approached by the use of limiters preceding the PLL to insure a constant signal into the PLL.

8.1.7 Instrument Errors

This name is given to errors which are caused by the following factors and are not assessable unless detailed circuitry is available.

(1) Variation in receiver delay or phase shift due to power supply variations
(2) Variation in receiver delay or phase shift due to automatic gain control
(3) Discriminator center frequency shift
(4) Calibration drift
(5) Dynamics lag of range servo system

It is assumed that all these errors can be made small. A variance in range due to these errors of three feet square (i.e., $\sigma_{R_I}^2 = 3\ \text{ft}^2$) will be assumed.

8.1.8 Variation in Threshold Setting in Leading Edge Comparator

It is difficult to maintain a voltage level stable over MIL-SPEC environmental conditions to better than ±0.75 dB (max) unless elaborate electronic compensation schemes are resorted to. For a leading edge ranging system, a percentage change in threshold level is correspondingly equal to the same percentage change in range, i.e.,

$$\frac{\Delta t_R}{t_R} = \pm \frac{\Delta V_T}{V_T}$$

Assuming that the probability distribution of ΔV_T is uniform, then:

$$\sigma_{R_V} = \frac{C\,\Delta t_{R\,max}}{4\sqrt{3}} = \frac{C\,t_R}{2} \cdot \frac{\Delta V_{T\,max}}{V_T}$$

for a ±0.75 dB max stability of the threshold voltage and $t_R = 65 \times 10^{-9}$ seconds

$$\sigma_{R_V} = 4.45 \text{ ft}.$$

8.1.9 Quantization

With modern digital techniques it is not difficult to achieve quantization steps down to the one foot level. The rms error due to quantization to an increment Δ is:

$$\sigma_{R_Q} = \frac{\Delta}{2\sqrt{3}} = \frac{1}{2\sqrt{3}} = 0.3 \text{ ft} \qquad (\Delta = 1 \text{ ft}).$$

8.1.10 Uncertainty in Airborne Transponder Delay

Assuming that the airborne transponder performs a minimum of processing, such as recovery of the ranging modulation and remodulation of another carrier frequency for retransmission to the ground, then the airborne transponder will have the same error as the instrument errors discussed above.

8.1.11 Multipath Propagation

Another factor contributing to the ranging error is multipath propagation or the process where a direct signal path and an indirect signal reflected from the ground add to cause a range error. In a leading edge technique, it is practical to gate out the multipath signal by having an antenna height which is equivalent to the difference in delay of between the direct and indirect signal paths. In a CW-DME system, the wavelength of the ranging modulation tone are usually such that gating out the multipath signal by antenna height is not practical. Hence, multipath error becomes a significant source of error in a CW-DME technique.

The error in CW-DME systems due to ground reflections have been assessed. [Reference 23]. It has been shown in Reference 23 that the ranging error due to ground reflection can be reduced if frequency modulation (FM) is utilized and high FM deviation ratios are employed. Significant range accuracy can be gained by using deviation ratios of 10 or greater. An approximate expression for a maximum phase error (α) for deviation ratios greater than 10 and reflection factors less than one and greater than zero (i.e., 1 > R > 0) is:

$$\alpha_{max} = \tan^{-1} \frac{\frac{2}{\beta}}{\left[1 - \frac{4}{\beta^2}\right]^{1/2}} \doteq \frac{2}{\beta} \qquad (\beta \geq 10)$$

Since this is a maximum value, the value may lay between zero to α_{max}; hence, the error must be treated in a statistical manner. It is assumed that the phase error is distributed uniformly between 0 and α_{max}; hence, the rms value is:

$$\sigma_{R_M} = \frac{1}{\beta\sqrt{3}} \qquad (\beta \geq 10)$$

Assuming a scale factor of K_{MR} to convert degrees phase shift to range, the expression for the range error is:

$$\sigma_{R_M} = \frac{K_{MR}}{\beta\sqrt{3}} \qquad (\beta \geq 10)$$

Hence for $\beta = 20$, $K_{MR} = \frac{1028 \times 57.3}{360}$ ft/deg, we have:

$$\sigma_{MR} = 4.65 \text{ ft.}$$

The bandwidth required would be equal to $2\beta f_m$ or approximately 38.5 MHz, which might prove to be excessive in a practical system application.

8.1.12 Summary of Errors

A comparison of the errors is given in Table IX with the assumption made for the comparison. The results are:

σ_R (leading edge) = 5.7 feet
σ_R (CW/DME) = 6.9 feet

which indicates that the leading edge ranging system will be more accurate. However, if the error due to multipath is removed, then both systems will be compatible in range accuracy with a standard deviation of approximately five feet.

SECTION IX

COMPUTER REQUIREMENTS

9.1 Cubic - ACMR

The Cubic Corporation Air Combat Maneuvering Range (ACMR) system is basically a multilateration system in combination with an airborne inertial navigation system, providing accurate estimates of A/C position, velocity, acceleration, and attitude within the prescribed test area. The ACMR was designed primarily for tracking air combat maneuvers of up to 16 A/C within the airspace above the range and evaluating the pilots' performance from the data obtained and from displays, all in real-time, complete with missile simulation. The 3-dimensional displays also allow post-flight analysis by the pilot and instructor [Reference Section 4.4.2].

9.1.1 Description of Subsystems

The ACMR consists of 4 subsystems (Figure 32):

1. Aircraft Instrumentation Subsystem (AIS)
2. Tracking Instrumentation Subsystem (TIS)
3. Computation and Control Subsystem (CCS)
4. Display and Debriefing Subsystem (DDS)

Their primary function is to compute and update in real-time the following 13 A/C parameters for up to 4 maneuvering A/C:

$$\left.\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}\right\} \text{A/C position}$$

$$\begin{bmatrix} \left.\begin{matrix} \dot{X} \\ \dot{Y} \\ \dot{Z} \end{matrix}\right\} \text{A/C velocity} \\ \left.\begin{matrix} A \\ B \\ C \\ D \end{matrix}\right\} \text{A/C Euler parameters} \end{bmatrix}$$

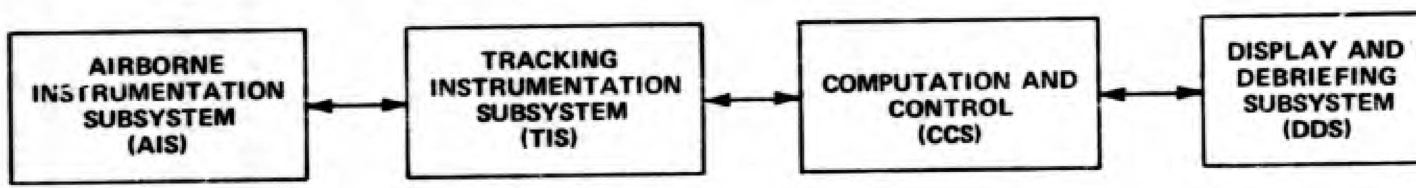

Figure 32. Data Flow between ACMR Subsystems

$$\begin{bmatrix} \dot{w}_x \\ \dot{w}_y \\ \dot{w}_z \end{bmatrix} \text{A/C angular rates}$$

Position data for up to 12 additional A/C is also computed. All these parameters are relative to the ACMR range coordinate system.

9.1.1.1 AIS

The Airborne Instrumentation Subsystem carried by each participating A/C consists of a pod containing the attitude reference unit, the ranging transponder, the inertial sensor assembly, the data pre-processor, and the weapons bus monitor.

The strapped-down inertial navigation system is an independent unit consisting essentially of 3 gyros and 3 accelerometers mounted to the frame of the pod. The accelerometers sense the 3 components of acceleration while the rate gyros determine the 3 components of angular rate. The coordinate system is fixed to the pod. The analog accelerometer and rate gyro signals are converted to digital measurements of velocity increments and angular rotation increments respectively (Figure 33).

The digital processing unit (DPU), a small hard-wired preprocessor, determines the A/C attitude (represented by the 4 Euler parameters) and velocity parameters in an earth-referenced coordinate system. To obtain the velocity vector, the DPU computes the direction cosine transformation matrix (body axis to tangent plane), converts the body axis acceleration vector to an acceleration vector in the pod reference axis coordinate system, integrates, and then, using the transformation matrix, converts the measured pod axis velocities to pod velocities in the tangent plane. A factor of ten difference is observed between the internal iteration time of the DPU (.005 sec) and the cycle time between downlinks of the parameters (pod velocities, pod Euler parameters, and the cycle time) to the TIS (0.05 sec).

The TIS interfaces with the AIS utilizing a 62 kilobit/sec full duplex data link.

The velocity vector and the 4 Euler parameter updates transmitted to the AIS by the TIS via a ground-to-air-data link are corrections for long-term drift errors inherent in an inertial navigation system.

9.1.1.2 TIS

The Tracking Instrumentation Subsystem consists of a 16-bit digital computer located at the TIS master site and a series of interrogators/receivers out on the range.

Under control of the TIS computer, the master site interrogates the transponder in the pod of the appropriate A/C. The AIS, in turn, retransmits

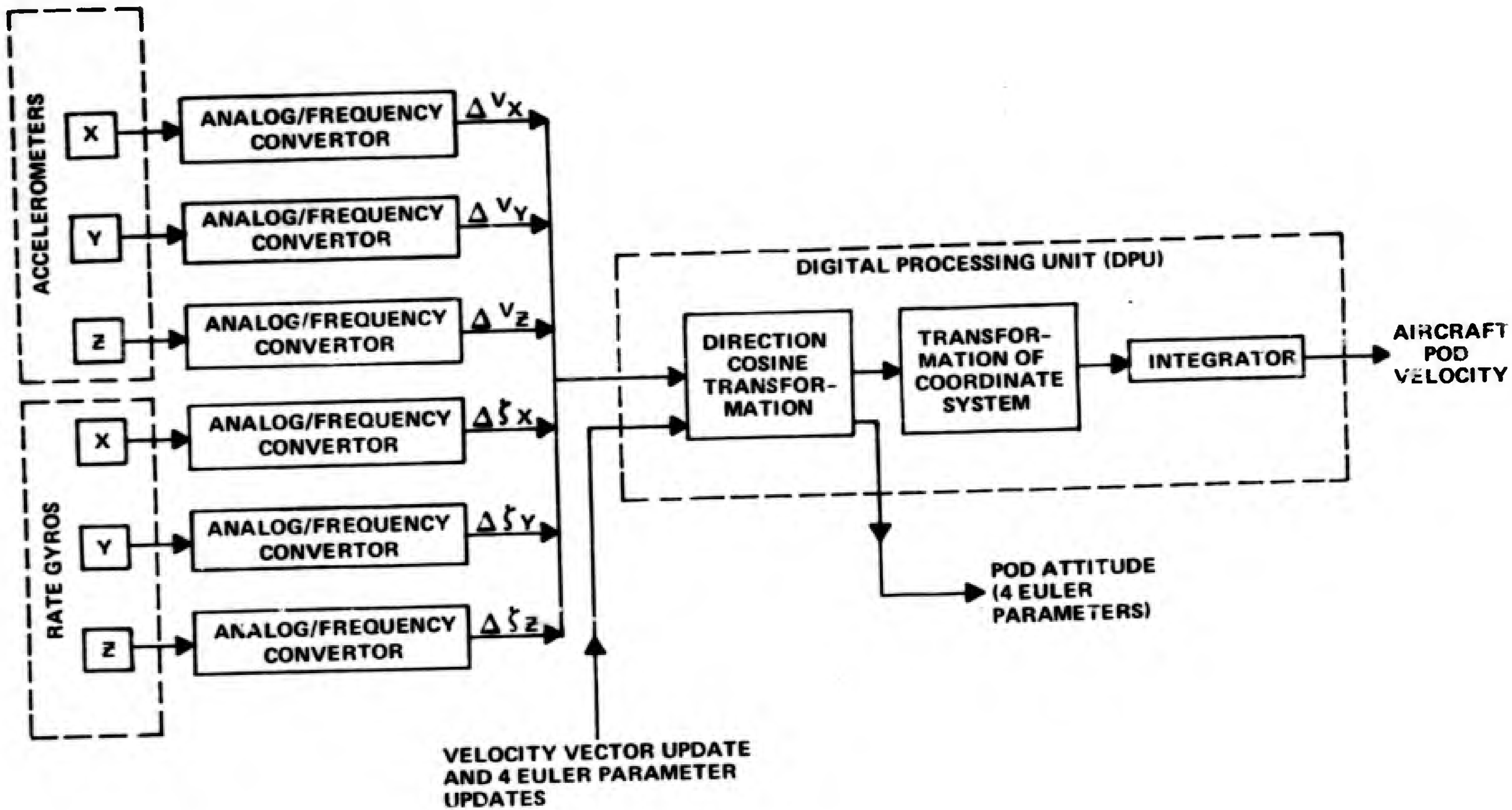

Figure 33. Inertial Reference Unit (IRU)

the ranging signal. This signal is received by all 7 interrogator/receivers. The interrogation sequence is repeated every 50 milliseconds, where the first 4 10-millisec time slots are allocated to the 4 high-performance A/C being tracked. The fifth slot is used by each of the 12 low-performance A/C in turn and also for range calibration.

Using phase-comparison ranging techniques, each A/C is tracked by obtaining seven simultaneous range measurements from the 7 ground stations. These 7 "range partials" are processed by the computer at the TIS master site. The resultant range values are measurements of the slant range, in 1 ft increments, between the pod of the A/C and the ground interrogator. Due to the accuracy of the range data, no smoothing of the data is required before transmission to the CCS.

9.1.1.3 CCS

The Computation and Control Subsystem consists of a large multiprocessor which performs the major ACMR mathematical computations. After checking the validity of the range data received from the TIS, the CCS computes the 13 A/C parameters (position, velocity, Euler parameters, etc.) for the 4 major A/C and positional information for the 12 accompanying A/C. The CCS sends and receives data from the TIS and up to 4 DDSs. The CCS computes the A/C velocity update and the Euler parameter updates that are transmitted through the TIS to the AIS. The CCS also simulates real-time and fast-time missile performance. In addition, the CCS performs hazard monitoring functions.

The CCS monitors the status of the ACMR equipment units and relays this information to the DDS. The CCS also computes interactive A/C parameters, air mass information and assembles pilot performance data. This data is transmitted to the DDS over a 50 kilobit/sec data link.

9.1.1.4 DDS

The Display and Debriefing Subsystem [Reference Section 4.4.2] is the communication center of the ACMR. The DDS can be operated in 2 modes: real time (for the range safety officer and/or instructor) and post-flight, for debriefings for the instructor and student pilot. An alphanumeric display shows the essential A/C parameters, hazard warnings and flight safety information.

The most sophisticated and complex graphic display is a 3-dimensional CRT situation display portraying the A/C, their locations, flight paths, and range terrain in real time. The display allows coordinate rotation and zoom. The data collected during the ACMR exercise is stored on magnetic tape and can be played back later for debriefing.

9.1.2 Subsystem Computers

9.1.2.1 AIS

The AIS data preprocessor, which computes pod velocities and the

4 Euler parameters for each of the 4 major A/C with an iteration rate of 0.005 sec, is a Lear-Siegler Model LS-50 computer designed for the Boeing 747 and packaged to fit in the pod. The input/output has been modified to interface with the sensors. A user-programmable read-only memory is utilized.

9.1.2.2 TIS

The TIS consists of a controller/processor Xerox Sigma 3 with an 8K memory located at the master site to which is attached a 7-track magnetic tape drive and a teletype supplying operator I/O. A complete list of the equipment including peripherals is given in Table XVIII while a schematic diagram is shown in Figure 34.

The TIS can operate in 3 modes:

1. Monitor Mode - entered before the start of an ACMR exercise or after a termination of the exercise. The Monitor mode also calibrates the ranging system before exercise startup and detects any abnormal performance or data, transmitting this to the on-range personnel.

2. Test Mode - used to diagnose the performance of TIS on-range equipment by calculating the phase delay for each interrogator/receiver.

3. Active Mode - used during the actual exercise for control and transfer of A/C pod and range data. More specifically, the TIS transmits updates to the pod (AIS) from the CCS, interrogates all A/C, periodically calibrates the range, receives data from the pod, checks the data for validity and transmits this data, together with range partials which the TIS has converted to full range words, to the CCS.

9.1.2.3 CCS

The Computation and Control Subsystem contains a complex of 3 Xerox Sigma 5 Computers, with a 49,152-word, 32-bit core memory and 3 CPU's all connected in parallel (Figure 35). The memory is common to all the CPU's, allowing each CPU to have immediate and complete access to all of core memory.

The CCS uses the multiprocessor concept. The computer tasks are divided nearly equally among the 3 CPU's. The master CPU performs all I/O and interrupt handling and contains the main portion of the executive program. The 2 slave CPU's each with a floating point processor, compute AIS positions and provide the missile simulation respectively (Figure 36).

The master CPU is programmed in assembly language, due to the extensive amount of I/O and formatting operations required. Both slave CPUs are programmed in FORTRAN; the inefficiencies in execution time and memory storage are partially offset by their use of floating-point hardware. A complete list of CCS processors and peripherals is shown in Table XIX.

The CCS operates in 2 modes:

1. Monitor Mode - used to monitor equipment status messages of the

Table XVIII Configuration Table for TIS

COMPONENT NUMBER	DESCRIPTION	QUANTITY
8101	SIGMA 3 CPU/8k MEMORY/I/OP	1
8170	DIO	1
8119	EXTENDED ARITHMETIC UNIT	1
8114	FAULT INTERRUPT AND PROTECTION FEATURE	1
8113	POWER FAIL SAFE	1
8121	INTERRUPT CONTROL CHASSIS	1
8122	TWO-LEVEL PRIORITY INTERRUPTS	3
8192	KEYBOARD PRINTER (ASR-35)	1
7601	DATA SET CONTROLLER	2
7602	FULL-DUPLEX FEATURE	1
7861	TAPE DRIVE CONTROLLER	1
7862	TAPE DRIVE	1
7865	BCD OPTION	1
8110A	SYSTRON DONNER DIGITAL CLOCK	1
420	GE DIGINET MODEM	1

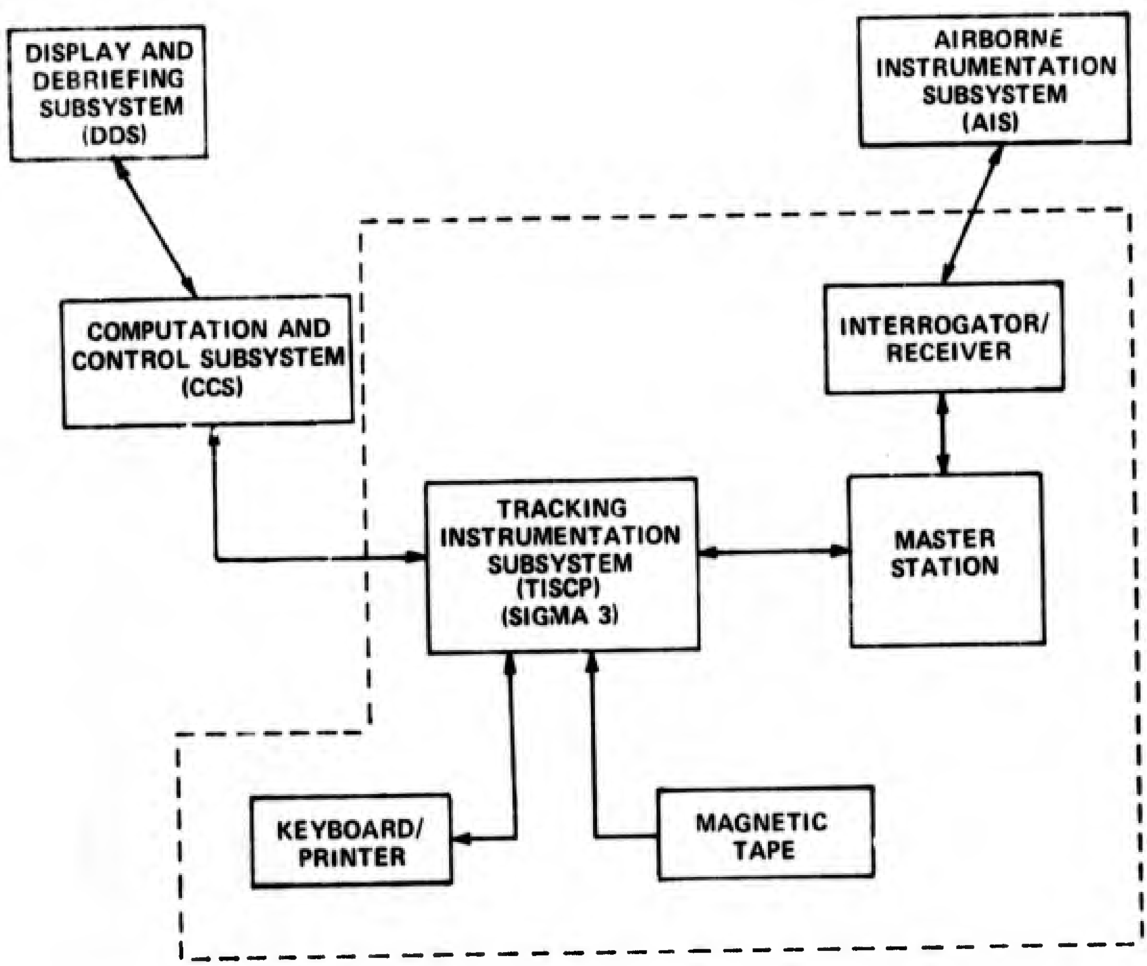

Figure 34. Interface Diagram: Principal Components of the Tracking Instrumentation Subsystem (TIS)

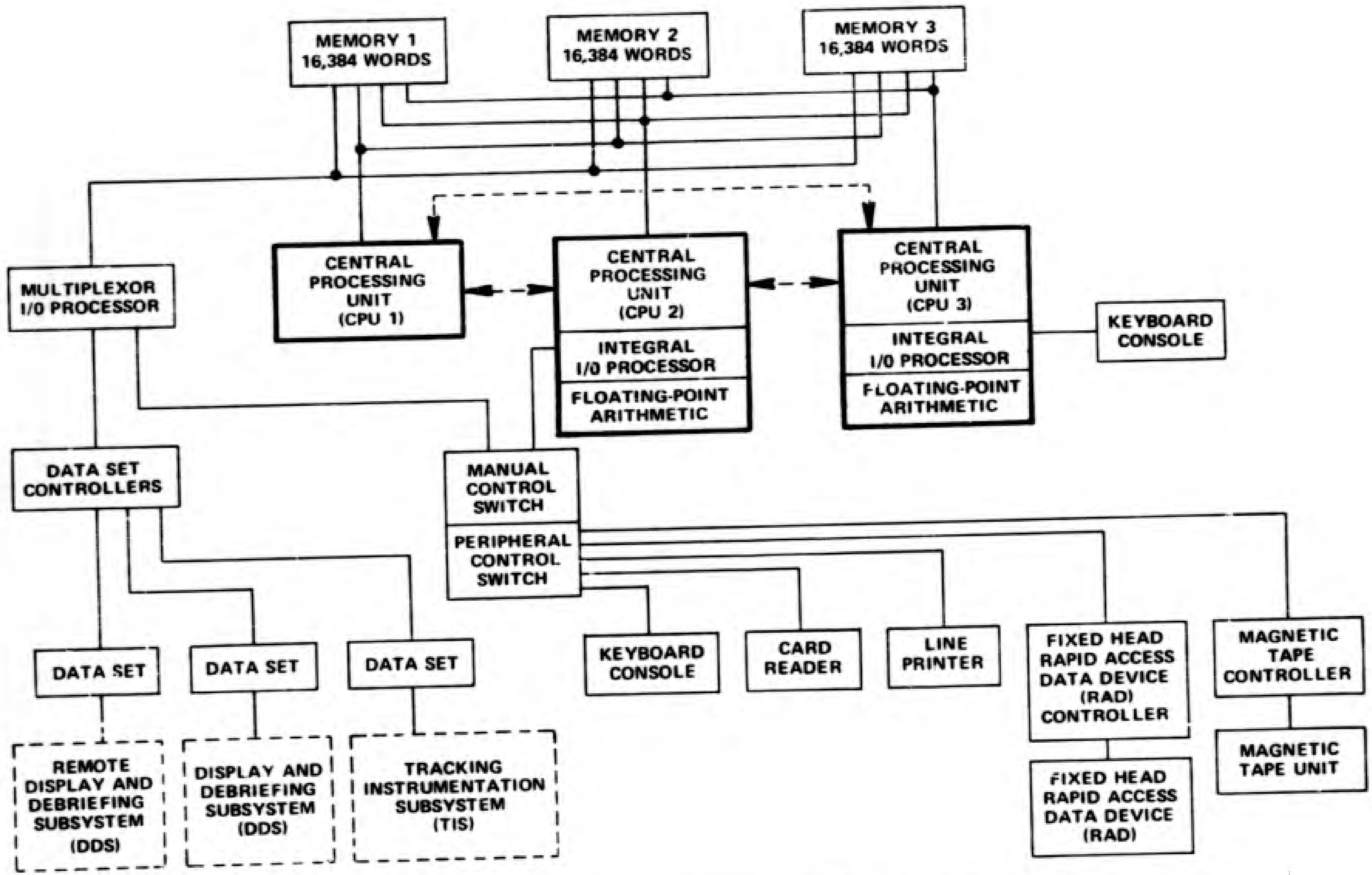

Figure 35. Computation and Control Subsystem (CCS) Working Environment and Equipment Interfaces

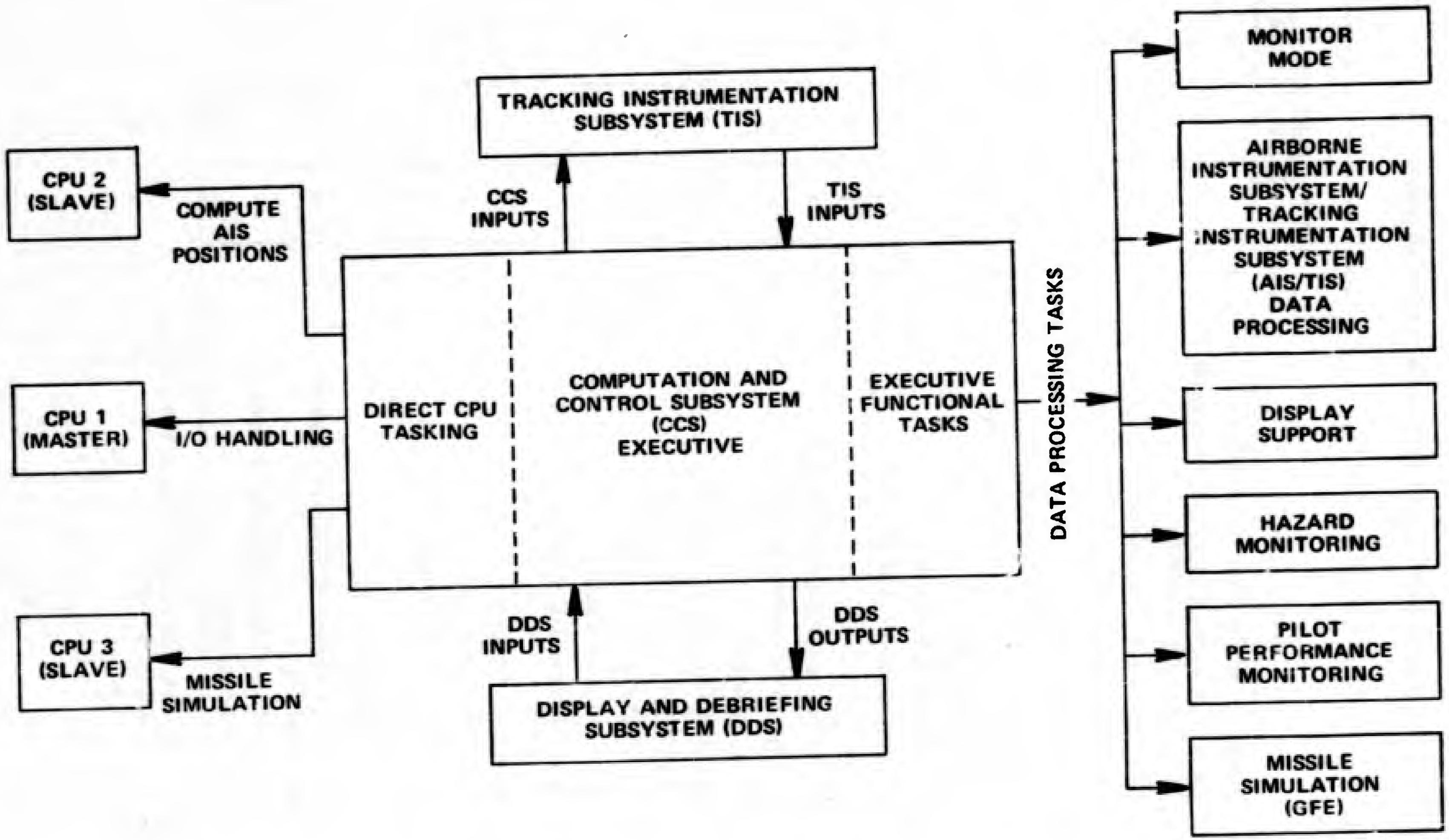

Figure 36. Computation and Control Subsystem (CCS) Computer Program Operation

Table XIX Computation and Control Subsystem (CCS) Equipment

XEROX DATA SYSTEMS (XDS) MODEL NO.	DESCRIPTION	NUMBER ASSIGNED			
		CPU-1	CPU-2	CPU-3	TOTAL
8202	SIGMA-5 CENTRAL PROCESSING UNIT	1			1
8201	SIGMA-5 CENTRAL PROCESSING UNIT WITH INTEGRAL I/O PROCESSOR		1	1	2
8218	FLOATING-POINT ARITHMETIC UNIT		1	1	2
8214	MEMORY PROTECTION UNIT	1	1	1	3
8213	POWER FAIL SAFE UNIT	1	1	1	3
8221	INTERRUPT CONTROL CHASSIS	1	1	1	3
8222	TWO-LEVEL PRIORITY INTERRUPT UNIT	6	4	4	14
8216	REGISTER BLOCKS	3	1	1	5
8261	8k CORE MEMORY MODULE	1	1	1	3
8262	8k CORE MEMORY INCREMENT	1	1	1	3
8264	MEMORY PORT	3	3	3	9
8270	EXTERNAL INTERFACE FEATURE	1	1	1	3
8273	MULTIPLEXOR I/O PROCESSOR	1			1
8276	8 I/O CHANNELS	1			1
7700	INTERPROCESSOR INTERRUPTS	1	1	1	3
7720	PERIPHERAL CONTROL SWITCH		1		1
7721	MANUAL CONTROL SWITCH		1		1
7601	DATA SET CONTROLLER	3			3
7602	DATA SET CONTROLLER FULL DUPLEX FEATURE	1			1
7371	TAPE CONTROLLER	1	*		1
7372	MAGNETIC TAPE UNIT	1	*		1
7374	BINARY PACKING OPTION	1	*		1
7440	LINE PRINTER	1	*		1
7121	CARD READER	1	*		1
7201	FIXED HEAD RAPID ACCESS DATA DEVICE CONTROLLER	1	*		1
7204	FIXED HEAD RAPID ACCESS DATA DEVICE	1	*		1
7012	KEYBOARD CONSOLE	1	*	1	2

* PERIPHERALS MAY BE ASSIGNED TO CPU-2 THROUGH THE MANUAL CONTROL/PERIPHERAL CONTROL SWITCH.

DDS and the TIS and status information of the CCS computer and its peripherals (Figure 37). Upon obtaining the appropriate signal from the DDS, it can start-up or terminate the exercise. At the conclusion of the ACMR exercise, the CCS provides a summary of pilot performance to the DDS. Statistics on A/C maneuvers, missile launches and firings, hazards, etc. are relayed to the DDS for display purposes if the missile simulation program has been used.

2. Active Mode - used during normal range processing (Figure 38).

9.1.2.3.1 A/C State Variables and Parameters

The CCS (CPU-2) edits DME measurements transmitted from the TIS by checking the range quality, compensating for atmospheric refraction, eliminating "wild" unreasonable range values, and weighting the range data appropriately.

In addition the CCS computes the following sets of variables once each cycle:

A/C variables - A/C position, velocity, Euler parameters, and angular rate vectors are computed for the 4 main A/C, utilizing both DME range data and AIS downlink pod velocity and Euler pod parameters (after rotating and translating these pod variables to the A/C center of gravity). In addition, pod Euler parameter and velocity updates are computed for transmission to the AIS via the TIS. All this data has been first transformed from the individual A/C time frames and DME range times into a common CCS reference time. Extrapolation based on previous values provide the A/C parameters when AIS or DME data is not available. Position data is computed for the 12 additional A/C.

air mass parameters - The angle of attack, angle of attack rate, sideslip angle, mach number, calibrated air speed, and true air speed are computed once each display cycle for each A/C based on aerological sensor data.

individual A/C parameters - Using A/C variable information, the dive/climb angle, the rate of climb, the angles of roll, pitch, and heading, the normal acceleration, normal acceleration rate, and yaw are computed.

inter-aircraft parameters - Based on the A/C variables, the inter-aircraft parameters for up to 2 fighter-target pairs can be computed every display cycle. These include slant range, closing velocity, track crossing angle, aspect angle, velocity aspect angle, and antenna train angle. The inter-aircraft parameters are transmitted to the DDS and used in their displays.

9.1.2.3.2 Weapons Simulation

The CCS (CPU-3) simulates up to 2 missiles concurrently. A maximum of 2 fighter-target pairs are allowed in the missile simulation. A pair may be designated through an appropriate message to the CCS by the DDS during a display cycle. Pairing may also be specified by the CCS computer. Automatic pairing will result if firing is detected, establishing the firing A/C as the fighter.

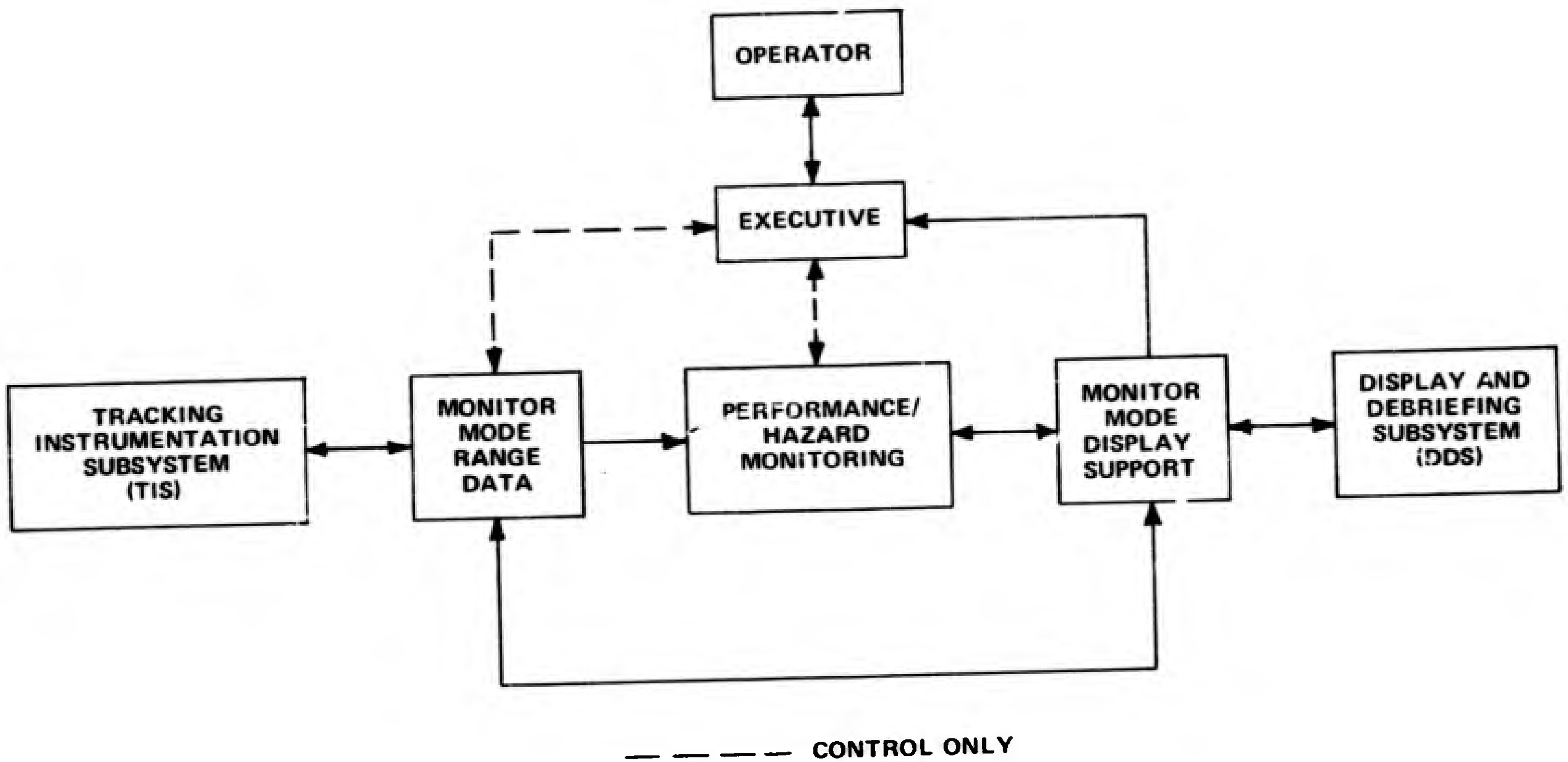

Figure 37. Computation and Control Subsystem (CCS) Functional Flow: Monitor Mode

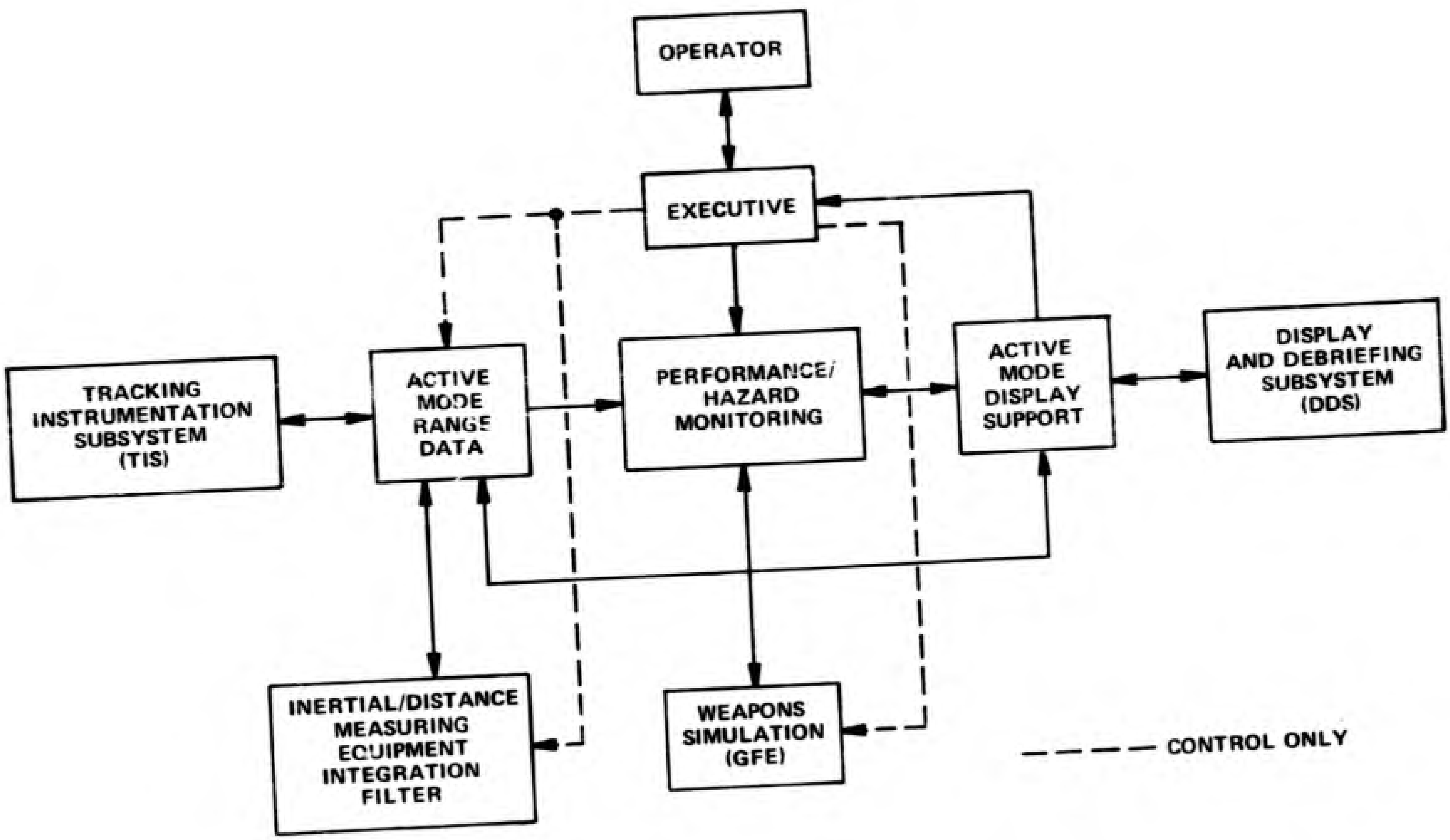

Figure 38. Computation and Control Subsystem (CCS) Functional Flow: Active Mode

During the missile flight simulation, missile position and miss distance are continuously computed. Information such as the number of successful launchings, kill/no kill determinations, success rate, and number of times successfully fired upon is updated, resulting in a useful summary of the fighter/target performance at the end of the missile simulation.

Missile and target performance during a mission can be simulated in any of 5 exercise modes:

Mode 1. Using rule-of-thumb criteria, the relative positions of the fighter and target are computed each display cycle to determine if the target is within the firing envelope of the fighter. The CCS notifies the DDS whenever the boundary criteria are met in order that the information can be conveyed to the fighter pilots by UHF radio. Weapons may be selected from the following group: AIM-7E, AIM-7E-2, AIM-9B, AIM-9D, AIM-9G, AIM-9H, cannons and guns. If unspecified, guns will be assumed to be the firing weapons.

Mode 2. From the time a simulated missile launching is attempted by the fighter (as indicated by the missile arming switch), the firing boundary is repeatedly checked to determine whether a weapon can be launched successfully.

Mode 3. A faster-than-real-time simulation is used to determine if the target A/C is within the firing envelope of the fighter. Notification of boundary compliance is performed in the same manner as in Mode 1, ultimately resulting in the start-up and actual simulation of the missile trajectory.

Mode 4. The boundary tests (same as Mode 2) are performed in faster-than-real time. The missile simulation is included.

Mode 5. A real-time simulation of missile flight is employed, where the missile responds to target maneuvers. During the missile flight, the missile trajectory is displayed in real-time while at the end of the simulated missile flight, firing results are reported.

9.1.2.4 DDS

The DDS is described in detail in Section 4 of this report. The section is dedicated to displays in general, with the DDS covered as a specific type of display in subsection 4.4.2.

9.1.3 Filtering Computations

9.1.3.1 Kalman Filtering

The Cubic ACMR combines 2 independent position measuring systems in a complementary manner to obtain better positional accuracy on both a short and long term basis than would be possible using either system alone.

The Distance Measuring Equipment (DME), which is part of the TIS subsystem, measures the slant range from the A/C to 7 receiver stations located on the range. Due to radio noise, the DME measurements may vary significantly between samples. In addition, rapid or extreme A/C maneuvers may result in weak signal reception by some or all of the ground stations.

The strapped-down inertial (SDI) navigation system located in the pod of the A/C provides accurate short-term velocity and heading information, irrespective of the type of A/C maneuver. The system capability for determining heading and attitude will deteriorate with time due to slow but fairly constant inaccuracies in the gyros and accelerometers. The buildup of errors causes long-term drift, requiring periodic resetting.

By combining both navigation systems, illustrated in Figure 39, the best features of each system can be employed. The long term accuracy of the DME is therefore coupled with the short-term accuracy of the SDI to attain accurate A/C position, velocity, and attitude information. The SDI utilizes the DPU to integrate the acceleration (obtained from the gyros and accelerometers) and so determine the pod velocity and attitude for transmission to the CCS. Differences in the position measurements between the two systems are computed by the CCS computer using the ACMR integration filter and the best estimates of A/C position, velocity and attitude are then calculated. By comparing the outputs of the filter and the SDI, corrections in velocity and attitude are computed, uplinked to the SDI and applied to future SDI measurements.

The origin of the reference system is the center of the A/C pod, with the axes of the coordinate system aligned with the strapped-down system axes. By this appropriate choice of reference and coordinate systems, the measurements of the accelerometers and rate gyros need not be included in the observation matrix and the acceleration vector can be dropped from the state vector.

The observation noise of the accelerometers and rate gyros is assumed negligible. The accelerometer and rate gyro measurements are removed from the observation matrix (leaving the 7 range measurements as the only elements of the observation matrix) and added to the dynamic description of the state vector. The observation noise is assumed random and uncorrelated from sample to sample. The result is a reduction in the complexity of the filtering formulation, allowing computation of the A/C position, velocity, etc., estimates to be performed in the CCS in real-time.

9.1.3.2 State Vector Solution

Appendix A contains a detailed description and list of the Kalman filtering equations employed in the computation of the 13 state variables:

A/C pod position (X, Y, Z)
A/C pod velocity $(\dot{X}, \dot{Y}, \dot{Z})$
A/C pod Euler parameters (A, B, C, D)
A/C angular rates (w_x, w_y, w_z)

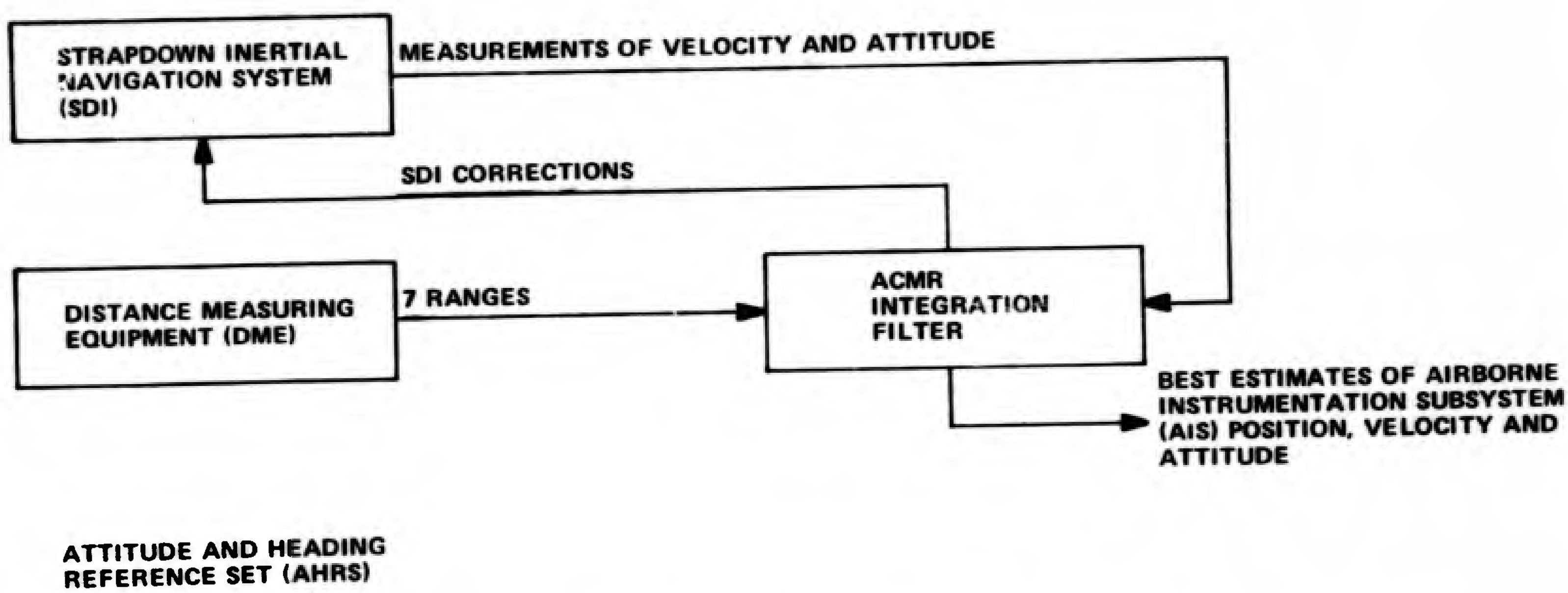

Figure 39. Block Diagram of AHRS/DME System

and the 7 updates:

A/C pod velocity update ($\Delta \dot{X}$, $\Delta \dot{Y}$, $\Delta \dot{Z}$)

A/C pod Euler parameter update (ΔA, ΔB, ΔC, ΔD)

The computation of these 13 state variables and 7 updates for an A/C must be done within 10 milliseconds. Although, in general, the solution of a 13 state variable system using Kalman filtering would require the inversion of a 13 x 13 matrix, the computation of the pod velocity and Euler parameters by the DMU of the AIS partially alleviates this problem. As a result, the 7 components of pod velocity and Euler parameters need only be updated to the time-reference of the CCS to provide valid estimates.

The determination of the A/C pod position estimate is a major time-consuming task, due to computations involving (1) a 3 x 3 matrix inversion, and (2) the square roots for 7 ranges. The other major computation involves the Euler parameter update, in which the derivatives of the Euler parameters are obtained. This is performed using a least square fit to five successive observations (cycles) of A/C Euler parameters, including the inversion of a 3 x 3 matrix.

Basic block diagrams showing input and output are illustrated in Figure 40. The diagram has been structured to display the interdependence between blocks. It is apparent that many of the computations--those in vertical groups of blocks--could be performed simultaneously instead of sequentially. This approach is explored further in Section 3., where the use of multiple small processors is compared to ACMR's use of a single processor.

9.1.3.3 Initialization

Initialization is performed at the start of the exercise and after prolonged periods of signal outages. Aircraft position, velocity, and Euler parameters are determined by applying the least squares technique. Range measurements from the five previous cycles are used in the computation. Once the solutions have converged sufficiently, the uplink pod data is transmitted to the AIS and the initialization process is terminated. Normal updating then commences.

9.1.3.4 Extrapolation

When the present TIS range measurement is not available due to no/bad DME range or downlink data, the last reliable values of aircraft position, velocity, Euler parameters, and downlink parameters are extrapolated to obtain valid state variable values at the present time.

Analysis of the equations used in both the initialization and extrapolation processes is not undertaken in this report since these computations are performed infrequently when compared with normal updating.

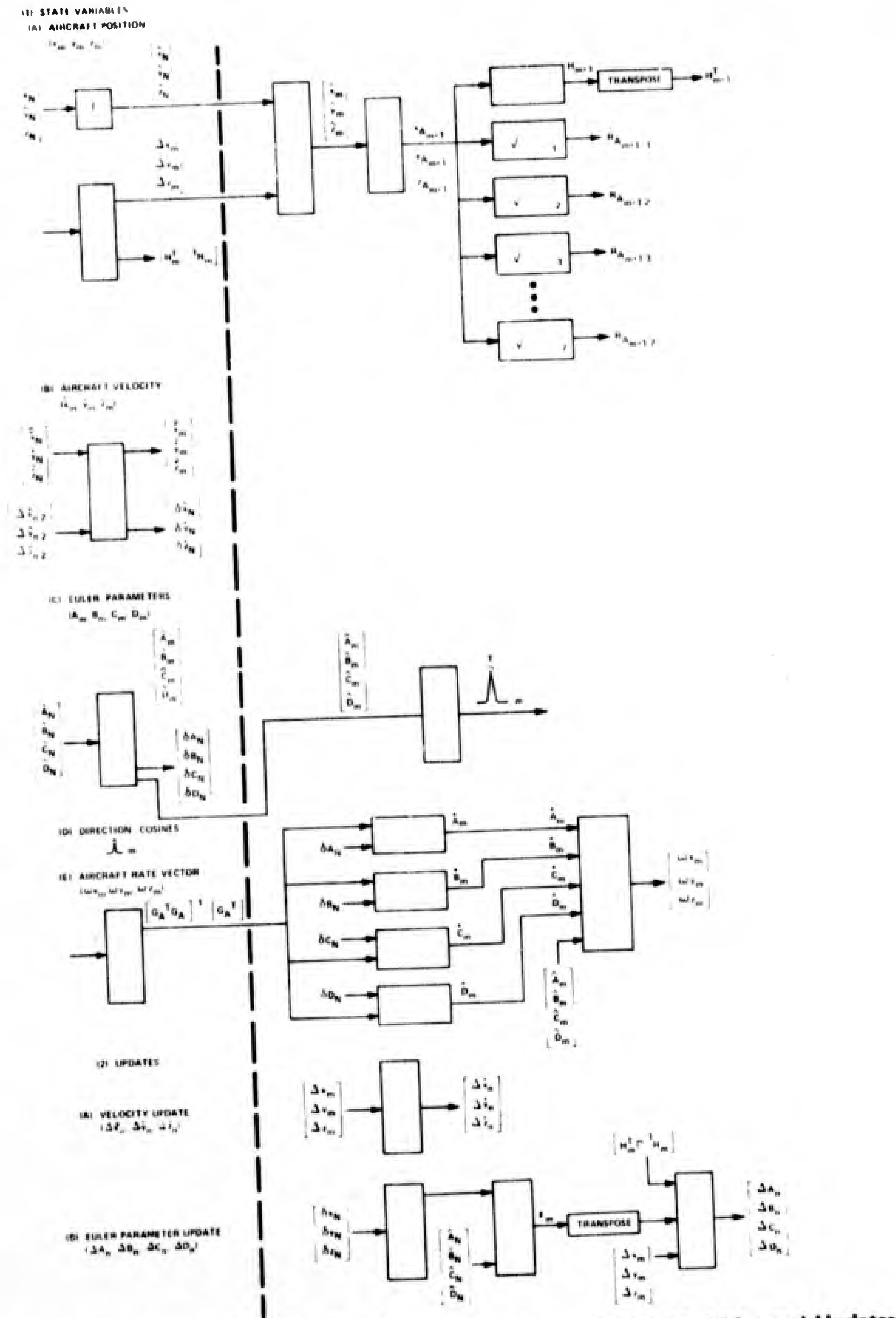

Figure 40. Block Diagrams of Data Flow For Computations of State Variables and Updates

9.1.4 Timing

Factors affecting the length of time required to perform the necessary computations include the speed of the computer instructions, its core size, ease of addressability, number and type of instructions, word length, and desired accuracy. Computing time may be expressed as a multiple of unit time (in μ sec), thereby not limiting the results to a specific computer.

Reference 24 summarizes the computation requirements (computational time per cycle) for a Kalman filter as a function of the dimensions of the system matrices. The logic times were determined using a set of instructions typical of 1968 aerospace computers. (It should be borne in mind that present-day mini-computers such as the PDP-11/45 have a much more varied and complete instruction set, therefore requiring significantly less logic time than specified by Mendel [Reference 24]).

The total time required for computations (such as for the Cubic 13 state variables and 7 updates) may be divided into the following catagories:

1. Execution time: time necessary to perform mathematical operations such as add, multiply, matrix add, matrix multiply.

2. Logic time: time utilized in making computer decisions such as loops and branches, subroutine and subfunction calls, and loading and storing values.

Based on Mendel's paper, [Reference 24] the execution, logic, and total computing times were determined for the Cubic system for each state variable and update. The results are listed in Table XX. It is readily seen that the time required by a computer to perform the MUL and DIV operations will greatly affect the total overall computing time. A comparison of computation times required using MUL and DIV times for a PDP-11/45, Xerox Sigma 5, and Sigma 8 are shown in Table XXI. (It must be remembered that the PDP computer has a 16-bit word while the Sigma's are based on a 32-bit word).

9.1.5 Conformance to TSPI Requirements

The ACMR computers are well suited to the near-term requirements of a TSPI system for the COR. In addition, they provide a pair of missile (air-to-air) simulations in real-time or faster. Subject to constraints associated with the tracking hardware, it would be possible to track a small number of additional low-interest aircraft without saturating the heavily-loaded filtering computer. For the high-interest aircraft, however, an additional CPU would be required for every additional group of 5 aircraft. Larger numbers of aircraft per CPU would be accomodated using the advanced techniques of Section 3., at a cost of modification of the existing software. In summary, the present ACMR computers are not capable of meeting far-term TSPI requirements, and substitution of their family successor (Sigma-8's) will not be a sufficient improvement.

Table XX Logic, Execution, and Computation Times Required to Compute the 13-State Variables

VARIABLE	TOTAL LOGIC TIME	TOTAL EXECUTION TIME	TOTAL COMPUTATION TIME
AIRCRAFT POD POSITION VECTOR	6674+16 MUL +21 DIV	732+201 MUL	7206+217 MUL +21 DIV
AIRCRAFT POD VELOCITY VECTOR	476+3 MUL	33+18 MUL	509+21 MUL
AIRCRAFT POD EULER PARAMETERS	936+4 MUL	152+32 MUL	1088+36 MUL
AIRCRAFT POD RATE VECTOR	410+329 MUL	10361+18.5 MUL +20 DIV	10771+411.5 MUL +20 DIV

Table XXI Comparison of Execution Times (in μs) for Xerox Sigma 5, Xerox Sigma 8, and PDP 11/45

INSTRUCTION	SIGMA 5	SIGMA 8	PDP 11/45
FIXED POINT:			
ADD WORD	2.1	0.73	0.3
SUBTRACT WORD	2.1	0.73	0.3
MULTIPLY WORD	7.5 TO 8.9	3.32	3.3
DIVIDE WORD	14.8	9.5	6.9 TO 7.5
PDP 11/45 FIXED-POINT INSTRUCTIONS ARE BASED ON A 16-bit WORD. SIGMA -5 AND -8 FIXED-POINT INSTRUCTIONS ARE BASED ON A 32-bit WORD.			
FLOATING POINT			
ADD	4.8 TO 9.5	2.05 TO 5.33	2.4 TO 3.8
SUBTRACT	4.8 TO 9.5	2.05 TO 5.33	2.4 TO 3.8
MULTIPLY	9.0 TO 12.5	3.32 TO 6.12	3.8 TO 5.8
DIVIDE	14.0 TO 19.0	7.69 TO 10.86	3.8 TO 9.2
PDP 11/45, SIGMA-5, AND SIGMA-8 FLOATING-POINT INSTRUCTIONS ARE BASED ON A 32-bit WORD.			

9.2 General Dynamics RMS-2/DCS

The General Dynamics Range Measuring System/Data Collection System (RMS-2/DCS) is a multilateration system which obtains the precise ranges to A/C troops, and ground vehicles in relation to known stations on a setup range as a function of time. The system can be composed of a maximum of 7 D stations, 127 A stations, and 1023 B units with one central (C) station. The basic elements of the system are a central station (C station), interrogator/receiver stations (A stations), repeater stations (D stations) where loss of line-of-sight prevents transmission between C and A stations, and the elements being tracked (B units) (Section 9.2.1).

The B units (both A/C and ground vehicles) are interrogated by the A stations on command from the master control (C station). The B station replies to the A station, which in turn sends the range information to the C station. Both the A station which is interrogating and the B station addressed by the A station are specifically designated by the C station.

Each A/C B unit aboard an A/C is interrogated by each A station while each ground B unit is interrogated by a minimum of 3 A stations. The range and event data are recorded in real-time onto magnetic tape. The data transmission rate is 100,000 bits per second maximum per channel. After the exercise, the recorded data is processed, analyzed, and displayed.

9.2.1 Description of Subsystems

The system consists of 4 types of units, all located on the test range: C stations, A stations, D stations, and B units.

9.2.1.1 C Station

The C station is comprised of 2 basic units: (1) a C4 station and (2) a digital computer.

The Varian 620/f digital minicomputer generates the interrogation sequences and commands for the appropriate A and D stations. In addition, it collects the information received from all units in real-time and stores this data for later (post-exercise) analysis.

The C4 station contains both receiver and transmitter assemblies for messages which are sent to and received from the A and D stations. The commands from the Varian computer contain codes with the addresses of the D, A, and B stations to which commands are to be transmitted and specify the required paths. These parallel output commands (either ranging or digital communications) are converted to serial form for transmission to the field units. On return to the C4, the responses are converted back from serial to parallel form for input to the computer.

9.2.1.2 A Station

The A station serves as both an interrogating station and communications link. Depending on commands, the A station relays communications messages or ranging signals between the C4 station and B units.

When a properly coded ranging interrogation command is received by the A station the ranging signal is retransmitted to the B unit. The B-unit response is then received and retransmitted to the C station where range is computed based on signal propagation time and hardware delays.

In serving as a digital data communications link, the A station transmits the digital message it receives from the C station to the addressed B unit, waits for a reply from the B unit, and then retransmits the reply back to the C station.

9.2.1.3 D Station

The D station is a directly addressable station the function which is to relay messages between the C4 station and one or more A stations where direct communications paths do not exist. The D station is not used to perform ranging.

9.2.1.4 B Unit

The B unit may be mounted on A/C troops, or ground vehicles or a combination of these. The B unit acts as a transponder in the ranging mode by receiving the range pulse sent out by the A station, waiting a fixed period of time, and then transmitting a range pulse back to the A station. The unit also sends and receives digital messages from the C4 station via the A station.

9.2.2 Subsystem Computers

The only computer in the RMS system is at the C station site. A description of the Varian 620 computer used at the C station follows.

A schematic of the Varian 620/f computing system with its associated peripherals is shown in Figure 41. The Varian Data Machine 620/f minicomputer has a 32K total of 16-bit 750-nanosecond core memory. Options which have been included as part of the system are the Varian optional instruction set, real-time clock, power failure/restart, priority interrupts, buffer interface controller, expansion power supply, and floating point processor and interface. Peripherals included are an ASR-33 teletype, 2 magnetic tape 7-track transports, a card reader, and a line printer.

9.2.2.1 Computing System Software

Software for the Varian 620/f includes a Master Operating System (MOS), AID II Programmers Debugging Aid, BASIC Interpreter, and a complete set of diagnostics for the Central Processing Unit, memory, mainframe options and peripherals. Included in the MOS are the following system programs:

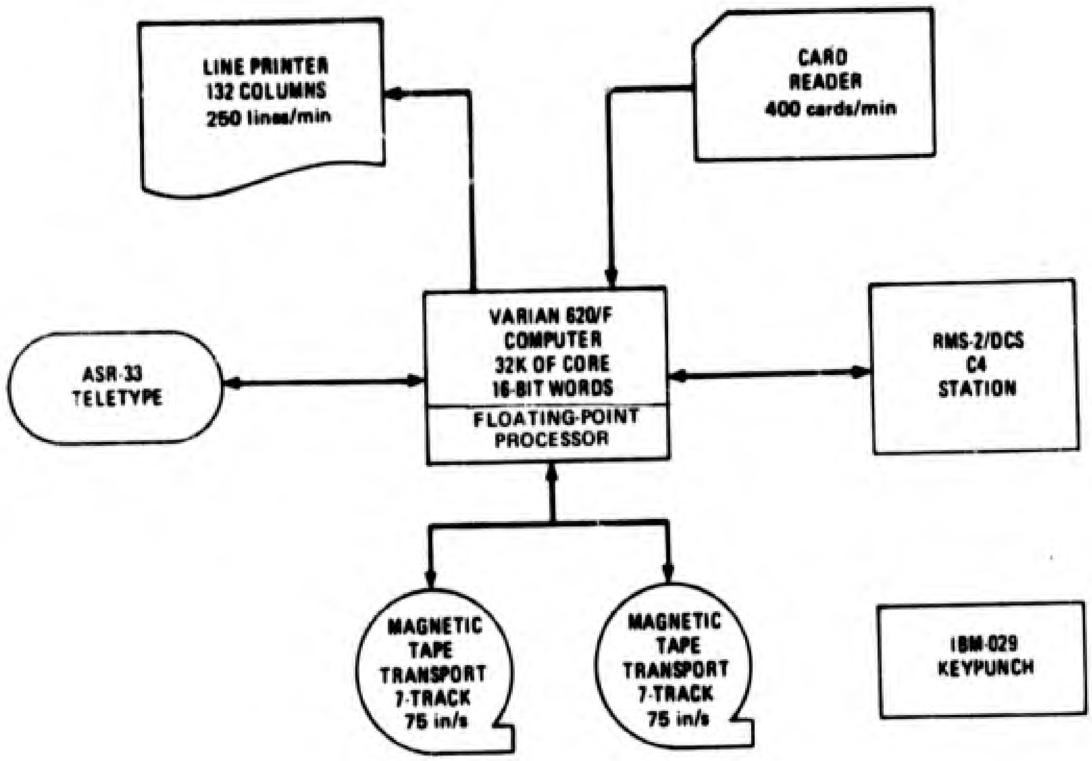

Figure 41 RMS-2/DCS Computer System, Functional Diagram

a. FORTRAN IV Compiler
b. DAS Macro Assembler
c. Loader
d. Source File Editor
e. System Maintenance Program
f. System Preparation Program
g. Debug Package
h. FORTRAN Run-Time Input/Output (I/O) and Mathematical Library.

9.2.2.2 System Test Software

The RMS-2/DCS Logic Test Program, a computer test program written in Varian 620 assembly language in modular form, checks the status and operation of all stations and units, real-time clock, C4 pushbutton, data ready interrupts, and C4 station logic. The 8 main test modules in the program are:

a. Time Interrupt Test
b. Sense Test
c. Instruction Loop Test
d. System Command/Response Test
e. IRIG Time Test
f. C4 INTERRUPT Pushbutton Test
g. C4 Data Ready Interrupt Test
h. 1000 Commands/Responses Test.

9.2.2.3 Computer Commands

The sequence and number of interrogations of B units by A stations and the path chosen depend on the software program of the computer. By determining the distance to a B unit from 3 or more A stations, the computer can compute the B unit position. The software program may, for instance, require the interrogation of every B unit by every A station or may select the A stations closest to the B unit for interrogation.

Each command the computer issues includes 4 basic fields:

Field 1 - D station address
Field 2 - A station address
Field 3 - B Unit address
Field 4 - Mode

using one of 4 discrete modes:

1. Ranging
2. Short communication (SCOM)
3. Extended communication, A-to-B (EAB)
4. Extended communication, B-to-A (EBA).

The message or data size and content for all 4 modes are listed in Table XXII. In the ranging mode, range information is transmitted using a selected path: C-D-A-B or C-A-B. An address of 000 in the D station field of the command indicates that there is no D station in the link path.

Table XXII RMS-2/DCS Modes of Operation

4 MODES OF OPERATION:

RANGE	-	RETURNS A 15-bit RANGE PLUS MESSAGE BIT FROM SELECTED A-B COMBINATION TO THE COMPUTER.
SCM	-	SENDS A 4-bit MESSAGE FROM COMPUTER TO SELECTED B-UNIT AND RETURNS A 13-bit MESSAGE FROM B-UNIT TO COMPUTER.
EAB	-	SENDS A 42-bit MESSAGE FROM COMPUTER TO SELECTED B-UNIT AND RETURNS A VERIFICATION BIT PLUS THE A-STATION AND D-STATION STATUS.
EBA	-	RETURNS A 42-bit MESSAGE FROM SELECTED B-UNIT TO COMPUTER.

Each station and unit on the range is discretely addressable. The commands contain addresses of the specific units and stations that are to be utilized during the transmission. All units "listen" to the command being transmitted and react accordingly. If the address is not the one for that particular unit, the unit re-initializes its state and waits for the next command.

The data flow between stations and units is illustrated in Figure 42.

9.2.2.4 A-Station/B-Unit Interrogation Technique

The sequence for interrogations of B units using A stations is performed using the Range/Scan technique. The implementation is done strictly through software, thereby allowing fast changes if desired. The technique ranges from A stations having previous valid responses and also checks, the other A stations less frequently to determine if the B unit is now visible to any of these stations.

The interrogation scheme as it is presently incorporated in the RMS system uses a 3, 10, 3 order and is as follows:

1. Interrogate a set of 10 selected A-B links.
2. Save A-B links with valid responses.
3. Select another set of 10 A-B links, including A-B links saved in (2).
4. Once an A-B link responds use it until it has 3 consecutive no responses.
5. If the number in (2) is greater than 7 select at least 3 new A-B links. (Always scan at least 3.)
6. Repeat (1) - (6) each duty cycle.

A flow chart illustrating this algorithm is presented in Figure 43.

9.2.2.5 Real-Time Data Collection System

The main program of the data collection system is written in Fortran IV. Input read in on cards includes run title, A station addresses, B unit addresses, and range member identifications. The status of all stations is checked before the start of the field exercise.

The data collection program collects, monitors, and records data in real-time during an exercise. The program interrogates all stations and units every quarter second. In addition, a summary of system performance is printed out on the line printer and used to determine if any units have failed or are not operating properly.

The data stored on magnetic tape is processed after the exercise and is used to evaluate the trials.

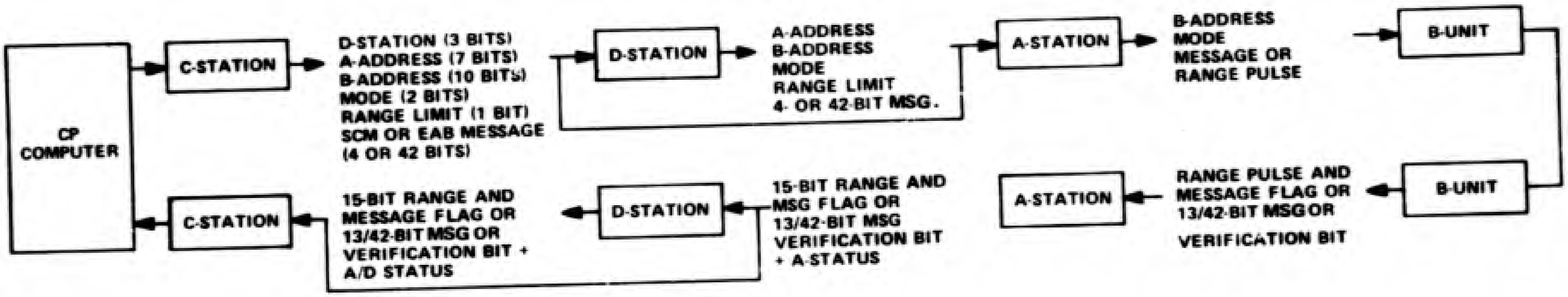

Figure 42. RMS-2/DCS Data Flow: 200-kHz Data Rate

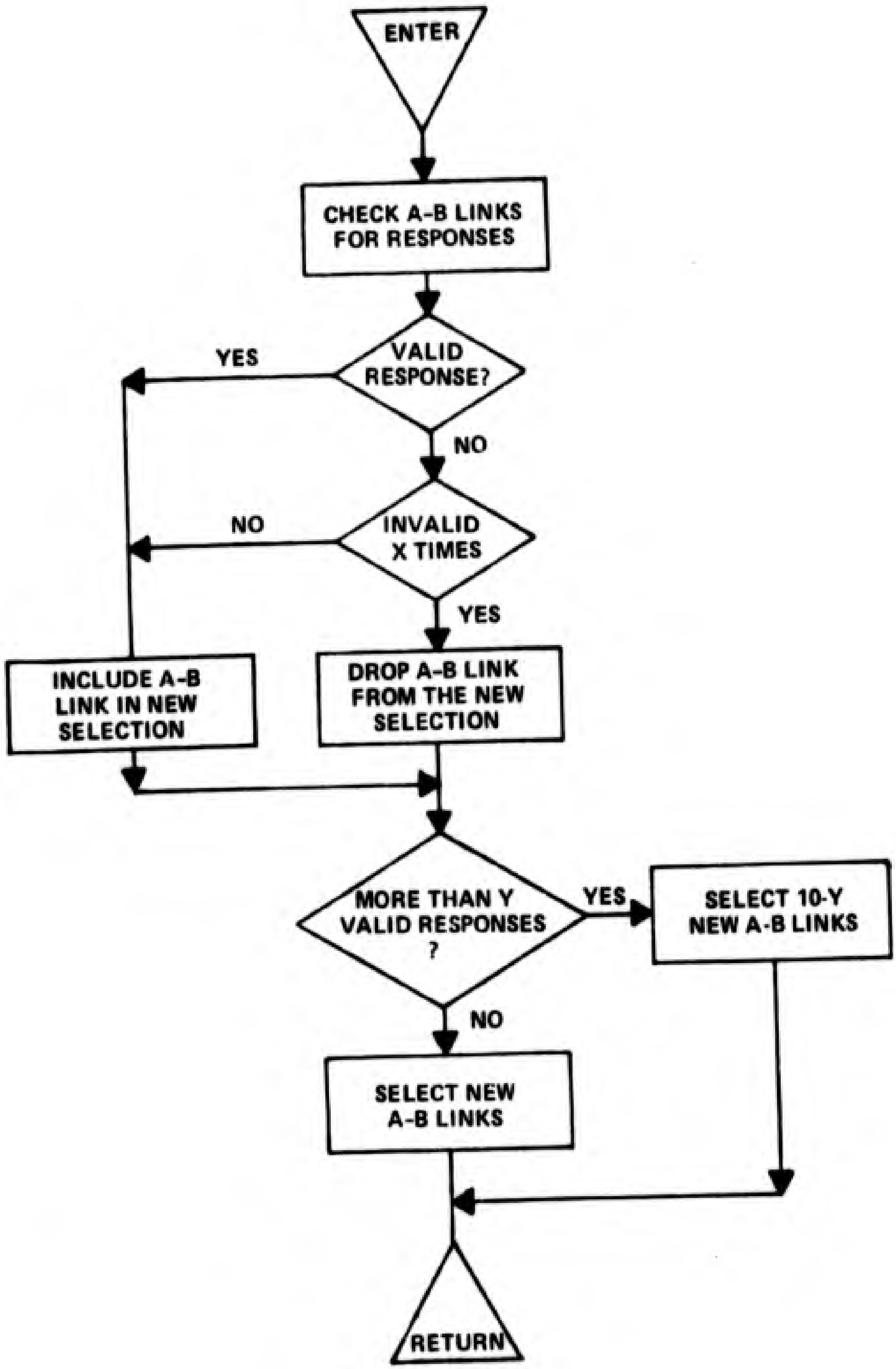

Figure 43. Range/Scan Flow Chart

9.2.3 Filtering Computations

The estimated position, velocity, and acceleration of troops, vehicles, and A/C in the RMS system are computed by performing Kalman filtering on the range measurements.

The Kalman estimation equations at time t are:

$$x(t) = \phi(t, t-1)\ x(t-1) + u(t-1)$$

$$P(t) = \phi(t, t-1)\ P(t-1)\ \phi^T(t, t-1)$$

$$K(t) = P(t) M^T(t) \left[M(t) P(t) M^T(t) + Q(t)\right]^{-1}$$

$$x(t) = x(t) + K(t)\left[y(t) - M(t)\ x(t)\right]$$

$$P(t) = p(t) - K(t) M^T(t) P(t)$$

where

$x(t)$ is the state vector
$\phi(t)$ is the transition matrix
$M(t)$ is the measurement gradient vector
$y(t)$ is the observation vector
$p(t)$ is the covariance of the state vector (t)
$u(t)$ is the independent Gaussian process of n vectors with zero means
$K(t)$ is the weighing factor which weighs the residual vector.

By assuming no correlation between observation errors from one observation time to another, the state vector may be simplified to exclude observation errors. In addition, if sets of measurements are assumed uncorrelated at any given observation time, the matrix which is to be inverted in the third equation reduces to a scalar, requiring no inversion. The solution of the equation reduces to matrix addition, subtraction, and multiplication. Further simplifications are possible if range measurements are incorporated into the solution, one at a time. This compensates for timing differences between range measurements.

9.2.3.1 Kalman Update Computations

Using the elapsed time since the previous update, a new state vector and its associated covariance matrix can be determined based on the former state. By partitioning the matrices and utilizing the fact that some of the matrix elements are zero, matrix operations can be simplified, thus decreasing computing time.

9.2.3.1.1 Transition and Covariance Matrices

The transition matrix ϕ can be represented as:

$$\phi = \begin{bmatrix} I & (DT)I & \frac{(DT)^2}{2} I \\ 0 & I & (DT)I \\ 0 & 0 & I \end{bmatrix}$$

where the I is the 3x3 identity matrix, 0 is a 3x3 xero matrix, and DT is the elapsed time since the previous update.

The covariance matrix which can be described as:

$$P = \phi P \phi^T + Q$$

is partitioned as follows:

$$P = \begin{bmatrix} C_1 & C_2 & C_4 \\ C_2^T & C_3 & C_5 \\ C_3^T & C_5^T & C_6 \end{bmatrix}$$

where Ck's are 3x3 submatrices. Then the partioned matrices of the covariance matrix can be expressed as:

$$C_1 = C_1 + DT\left(C_2 + C_2^T + DT\left(C_3 + 0.5\left(C_4 + C_4^T + DT\left(C_5 + C_5^T + 0.5\, DT\, C_6\right)\right)\right)\right)$$

$$C_2 = C_2 + DT\left(C_3 + C_4 + DT\left(C_5 + 0.5\left(C_5^T + DT\, C_6\right)\right)\right)$$

$$C_3 = C_3 + DT\left(C_5 + C_5^T + DT\, C_6\right)$$

$$C_5 = C_5 + DT\, C_6$$

$$C_6 = C_6$$

9.2.3.1.2 <u>State Vector Predicition</u>

The 9-element state vector utilized by the RMS system is composed of position, velocity, and acceleration vectors. It can be expressed as:

$$\bar{x} = \left[x\ y\ z\ \dot{x}\ \dot{y}\ \dot{z}\ \ddot{x}\ \ddot{y}\ \ddot{z}\right]^T$$

An optional feature allows the state vector to contain 6-elements (no acceleration terms):

$$\bar{x} = \left[x\ y\ z\ \dot{x}\ \dot{y}\ \dot{z}\right]^T$$

Then the prediction of the state vector $\bar{x}$ is computed using the following relationship

$$\bar{x} = \phi\ \bar{x}$$

Q represents an error matrix which is added to the diagonal elements of the covariance matrix. This matrix accounts for the variations of the dynamics from the mathematical model.

The state and associated covariance matrix are updated at each range measurement time.

9.2.3.1.3 Residual and Variance

An update of the state vector is obtained next, based on the latest valid range measurement. To determine this new state vector, the following computations are performed.

M, the partial derivative of the range measurement, is computed first. It is the unit vector directed from the A-station site to the B-unit.

The residual ΔR is the difference between the measured and computed ranges. The partial M and the residual ΔR are obtained from the following set of equations:

$\bar{R}_c = \bar{R}$ (B-unit) $-$ $\bar{R}$ (A-station)

$R_c = \left|\bar{R}_c\right|$ (computed ranges)

$\bar{1}_{R_c} = \bar{R}_c / R_c$ unit vector

$M = \left[1_R\ 0\ 0\ 0\right]$ 9 element vector

$\Delta R = R_n$ (measured range) $-$ R_c (computed range)

The variance of the predicted residual ΔR is given by:

$$\text{Variance} = MPM^T + V$$

where V is the estimate of the range measurements.

The geometric weight factor K_G is then given by:

$$K_G = PM^T(MPM^T + V)^{-1}$$

9.2.3.1.4 State and Covariance Update

A 3-sigma rejection criteria is then applied to the range measurement. If the range data is within bounds, corrected covariance P and state vectors $\overline{X}$ are computed using the following equations:

$$P = P - K_G M^T P$$

$$\overline{X} = K_G \Delta R$$

9.2.3.2 RMS Post Real-Time Position, Velocity, and Acceleration Determination Program

This RMS data reduction program is a Fortran computer program which processes data logged by the data collection program after the termination of the field exercise. It determines the position, velocity, and acceleration of ground vehicles, troops and A/C using a 9 state Kalman filter. The program performs 6 basic functions:

1. Sets up A-station and B-unit input parameters from the initial records on tape and/or card input. These include the station and unit addresses and their x, y, and z positions on the range.

2. Reads RMS range data from log tapes and if necessary formats the RMS range data into a usable form for B-unit position, velocity, and acceleration determination.

3. B-unit position, velocity and acceleration determination using Kalman filtering techniques. The RMS B-unit location basic program flow chart is shown in Figure 44. The program utilizes 12 subroutines. The 9 state Kalman filter is described in more detail in the next section.

4. A-station site determination using the survey mode. Differences between computed and measured ranges to B-unit position are used in the Kalman filtering estimation equations to obtain corrections for A-station positions. The survey mode flow chart is given in Figure 45.

5. Statistical analysis of RMS range data. The parameters computed are the number, means, and standard deviations of the range differences for positive edited range differences, negative edited range differences, and unedited range differences. The differences represent the differences between measured and computed ranges to B-unit position locations. Statistics on up to 24 B-units and 24 A-stations can be obtained.

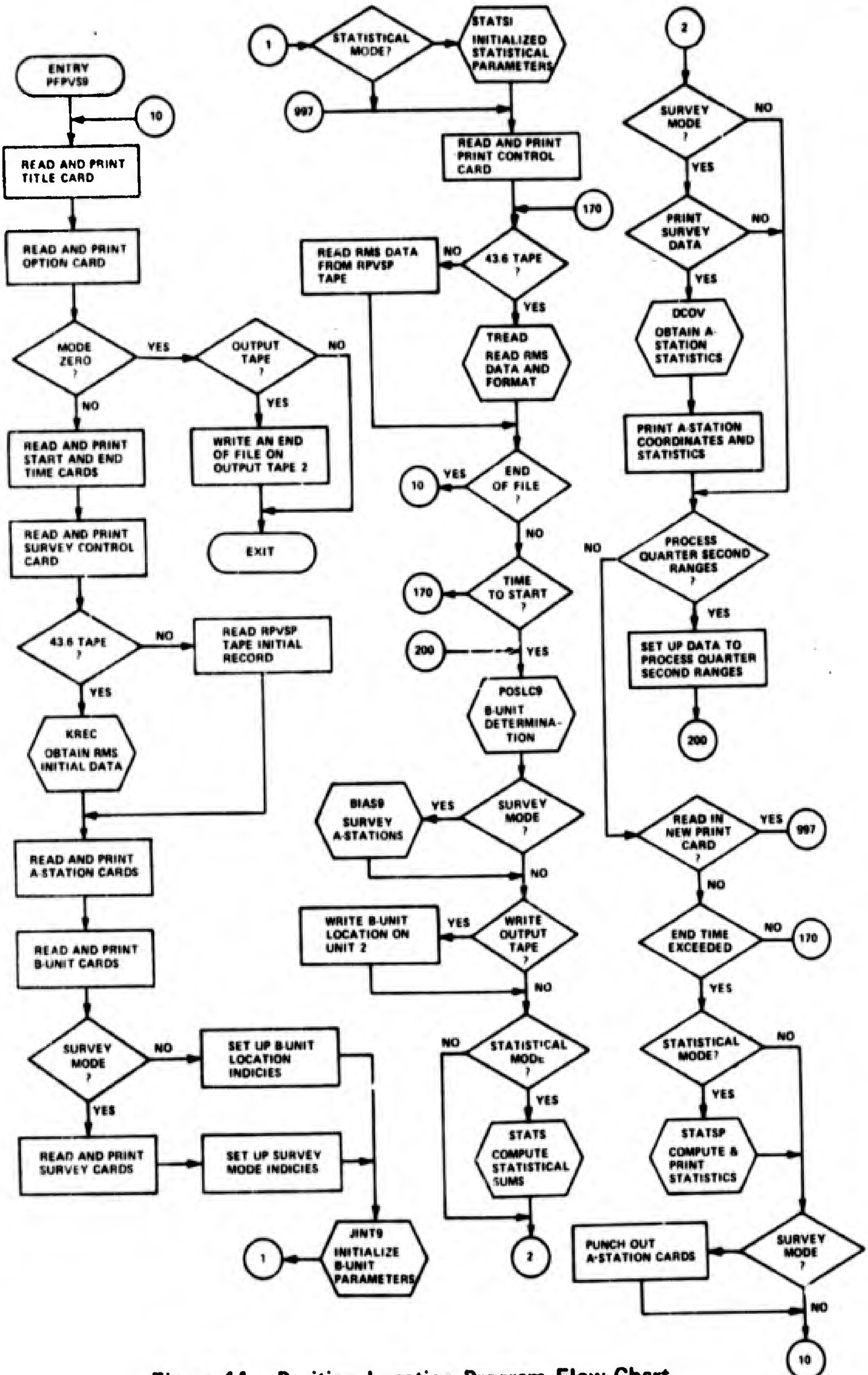

Figure 44. Position Location Program Flow Chart

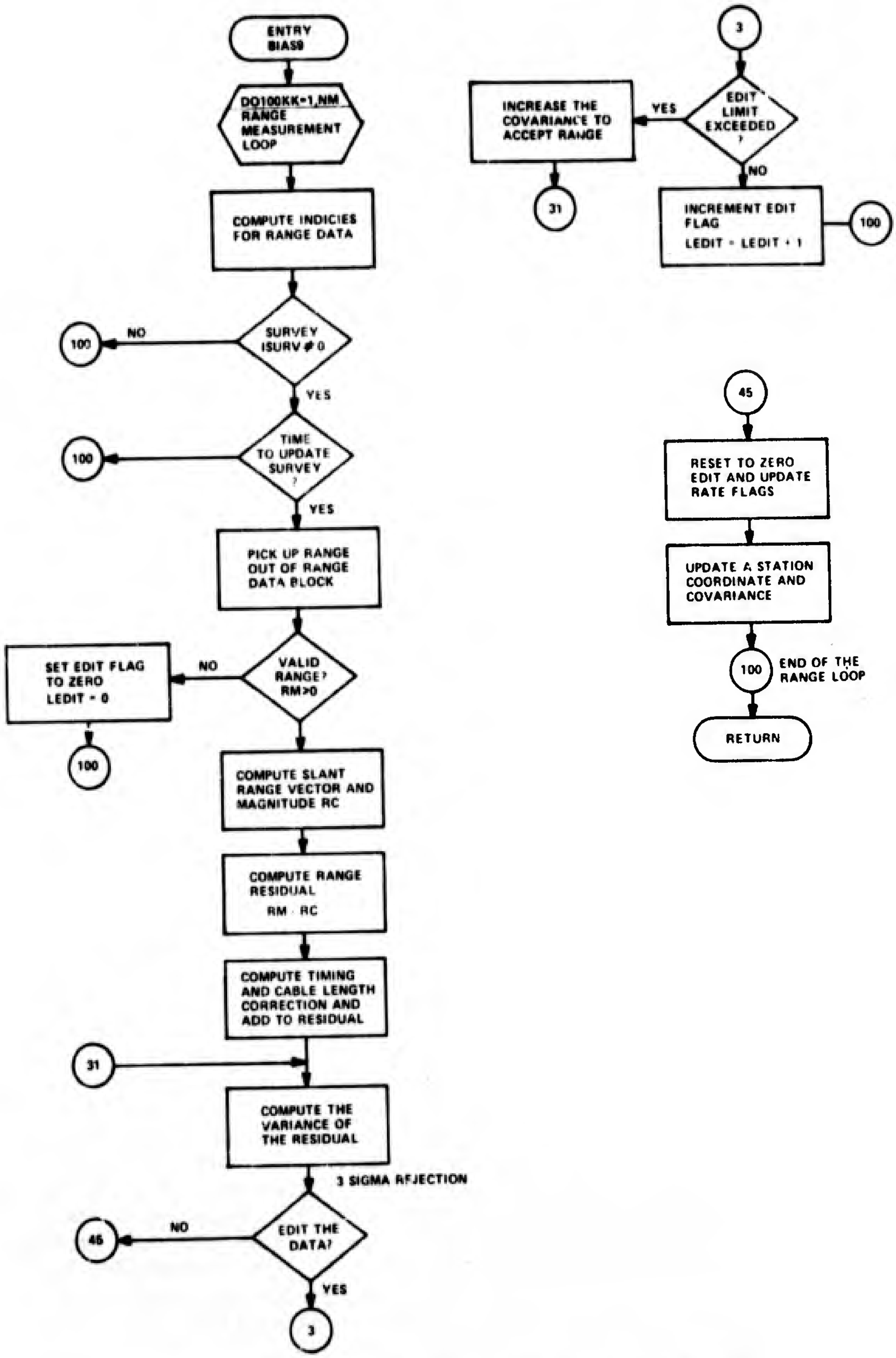

Figure 45. Survey Mode Flow Chart (Subroutine BIAS9)

6. Data logging of the B-units' position, velocity, and acceleration as a function of time. The line printer prints the following for each B unit: B-unit octal address, time in sec, position components in meters, velocity components ($\frac{m}{sec}$), 10 A-station addresses for range identification, number of valid ranges received, the number of ranges used in the Kalman update, state vector length, range residuals and one sigma value for the X and Y position components.

9.2.4 Timing Constraints

Since the B-unit's position, velocity and acceleration determination using the modified Kalman filter are not computed at the time of the actual maneuvers but are processed after the completion of the exercise, timing has not been of critical importance.

Most of the computer programs have been written in Fortran with execution time and core requirements not optimized. Core storage of tables and arrays depends mainly on the number of B-units and the number of states in the Kalman filter. The following estimates are based on the six-state Kalman filter.

With 2 milliseconds required for the update of the Kalman filter and 1.4 milliseconds per range, the computing time using 7 range measurements is

$$\text{time} = 7. \times 1.4 + 2 = 11.8 \text{ m sec/unit}$$

If 20 units are being updated on an exercise range, then (11.8)(20) = 236 milliseconds are required by the computer to determine new positions and velocities of the B-units. It is estimated that 12 K of core is necessary.

9.2.5 Conformance to TSPI Requirements

Since the data reduction for RMS-2/DCS is not performed in real-time, this system does not meet even the near-term TSPI requirements. General Dynamics is actively engaged in the development of software to complement their inertially-aided DME system, but their efforts lag far behind the ACMR. Their Kalman filter was inaugurated as a 23-state-variable model, and is presently being reduced to a 16-state-variable model in order to alleviate the computational problems of solving such a model for multiple aircraft in real-time. Even this reduced model requires a large amount of computation, so that in our real-time environment it will be necessary to use the multi-processing concepts described in Section 3.2. For low-interest aircraft and slowly-moving field elements, however, the near-term TSPI requirements can easily be satisfied by a single minicomputer. Even the far-term requirements can be satisfied by, at most, a pair of minicomputers. The tremendous computational load imposed by the filtering equations for the far term system is beyond the capacity of all but the largest computers at present.

SECTION X

ESTIMATED COSTS

Cost estimates are presented for two near term TSPI systems. The two systems considered are the ACMR developed by the Cubic Corporation and the RMS-2/DCS developed by General Dynamics.

The ACMR system is the more advanced of the two systems. The RMS-2/DCS system, as considered here, incorporates several improvements not presently part of the system. Chief among these are the addition of IMUs in the airborne transponders, central computer van for real-time data analysis, and expanded display presentations. Technical and performance characteristics of the two systems are described in Section VII.

Both systems are presently developed and essentially comparable ranging system hardware has been fabricated. No additional RDT&E expenditures are anticipated prior to procurement. The costs shown are based largely on data provided by the system developer. All costs are in 1973 dollars.

10.1 SYSTEM EQUIPMENT

The systems costed are comprised of the following equipment:

Airborne Transponders	16
Remote Ground Transponders	7
Ground Relay Transponders (RMS-2/DCS only)	1
Master Station	1
Computer Van	1
Display Van	1
Test Equipment	1

10.2 SYSTEM INITIAL INVESTMENT COSTS

Estimated system initial investment costs are presented in Table XXIII.

Table XXIII System Initial Investment Costs
(in $ Millions)

		ACMR	RMS
Airborne Transponders	(16)	$1.280	$ .960
Remote Ground Transponders	(7)	.490	.357
Ground Relay Transponders	(1)	----	.052
Master Station	(1)	.500	
Computer Van	(1)	1.500	2.650
Display Van	(1)	.870	.870*
Test Equipment	(1)	.500	.500
Initial Spares		1.040	.900
Data		.104	.090
Initial Setup		.012	.012
	TOTAL	$6.295	$6.391

The cost of the display van is based on two sets of displays, one set at each end of the van. A set of displays consists of two adage - 110's for alpha-numeric displays and one AGT-150 for 3-D graphics. The cost of initial spares is computed as 20 percent of initial equipment cost. Data cost is estimated at 2 percent of initial equipment cost. The initial setup is estimated to require 15 people working for 2 weeks. The setup cost includes only personnel cost. The personnel consists of 2 company representatives at a cost of $50,000/representative/year and 13 Air Force personnel at an annual cost of $15,000/person/year.

The subsequent system setup cost following transport of the equipment to a different site is estimated to be the same as the initial setup cost.

It is believed that the ACMR costs represent the more valid estimate because of the more advanced state of the system at the present time. Accordingly, the total initial procurement cost of the type system considered is estimated to be $6.0 - 6.5 million.

Discussion with the contractors indicated that equipment software has been fully developed. The need to modify existing or develop additional software could represent an additional cost of $0.5 - 2.0 million.

10.3 OPERATION AND MAINTENANCE COSTS

Estimated failure rates per million hours of operation were provided for the ACMR system. These are:

* Estimated same as ACMR.

Item	Failures/10^6 Hrs.
Airborne Transponder	733
Remote Ground Transponder	810*
Ground Relay Transponder	810*
Master Station	1620
Computer	3518
Displays	1250
Test Equipment	3518**

* Estimated at .5 Master Station failure rate.

** Estimated to be same as Computer.

The cost/repair is estimated to be 20 percent of the initial equipment cost for the airborne transponder and 10 percent of the ground-based equipment.

The maintenance costs per hour of operation shown in Table XXIV are computed from the above assumptions and the ACMR procurement costs presented in Table XV.

To this cost must be added the cost of operating personnel. It is estimated that 6-8 persons are needed for system operation. If the staff consists of 6 Air Force personnel at $15,000/year and 1 contractor representative at $50,000/year, the total annual cost is $140,000 and the cost/hour based on a 2000-hour manyear is $70/hour. This cost, together with the maintenance cost yields a total hourly cost of $1150. Thus a total annual system up-time of 1000 hours results in a cost of $1,150 million.

The operations and maintenance costs are crude estimates at this time and must be examined in more detail. It is likely that the up-time may not be the same for all equipment. For example, the remote ground and ground relay transponders may be kept in almost continual operation while the airborne and other ground equipment may only be operated during the conduct of tests. The approach employed to estimate maintenance costs, however, can be adapted to compute the costs of alternative modes of operation.

Table XXIV Estimated System Maintenance Costs

EQUIPMENT	QUANTITY	COST/REPAIR ($)	FAILURES/HOUR	REPAIR COST/HOUR ($)
AIRBORNE TRANSPONDER	1	12,000	0.000733	8.80
AIRBORNE TRANSPONDER	16			140.00
REMOTE GROUND TRANSPONDER	1	7,000	0.000810	5.70
REMOTE GROUND TRANSPONDER	7			40.00
GROUND RELAY TRANSPONDER	1	6,000	0.000810	4.90
MASTER STATION	1	50,000	0.001620	81.00
COMPUTER	1	150,000	0.003518	530.00
DISPLAY	1	87,000	0.001250	108.80
TEST EQUIPMENT	1	50,000	0.003518	175.90
TOTAL SYSTEM MAINTENANCE COST/HOUR				1080.00

SECTION XI

PROBLEM AREAS

During the study several problem areas arose because of unknown user requirements and misinterpretation or lack of sufficient definition in the Statement of Work.

11.1 DISPLAY REQUIREMENTS

The Statement of Work specifies two-dimensional displays of range, members, equipment stations, and events with a growth capability to include three-dimensional presentations. These specifications are so general that without range user inputs or specific range requirements, it was difficult to recommend displays that would satisfy the near and far term requirements. This problem was resolved by sponsor definition of the near term and far term display requirements. The near term system will use two-dimensional type displays for range safety, scenario monitoring, and range control. The future system will retain the near term system displays with the addition of large screen displays combined with Air Traffic Control inputs and major event information.

As a result, the display section of the report discusses displays in general terms. A survey of types, available technology, and cost versus capability is provided. Examples of two contractor display systems are also provided along with recommendations for the near and far term TSPI systems.

11.2 FUTURE SYSTEM REQUIREMENTS

Another problem area occurred in the interpretation of future system requirements for discrete events and the data rates required. The Statement of Work defines a requirement to obtain position data for discrete events at 20 operator selectable locations with an update rate of 100 positions per second. The sponsor's interpretation of this requirement is that event data could be required at 20 locations simultaneously and that all 100 range members could be involved. This creates a requirement to obtain position data on 100 range members at 100 positions per second. In order to determine if these update rates are consistent with the other parameters specified in the Statement of Work, an investigation was performed which is described in the next section.

11.3 POSITION UPDATE RATE REQUIREMENTS

An update rate of 100 positions per second on up to 100 range members requires a large computing capacity to process the data. None of the existing systems approach this data rate for 100 range members and this rate also precludes the use of a centrally located scanning radar (see Section 2.1).

A study was performed to determine position update rates required to satisfy the TSPI technical requirements. A computer simulation was used to determine the number of position samples necessary to describe a particular maneuver.

Using the near term system parameters, an aircraft was flown in a semicircular flight path. The aircraft flew at 2000 feet per second with a g loading of 8.5. The resulting radius for this maneuver was 2.4056 n.mi.

A radar, with known accuracy, was used to determine the flight path of the aircraft. The radar made estimates of the aircraft's position at fixed time intervals. It was desired to determine the error in the flight path of the aircraft that the radar makes, as a function of the number of aircraft position estimates that were taken.

In order to introduce errors into the radar's estimate of aircraft position, the radar was assumed to be corrupted by noise. The noise had a Gaussian distribution with zero mean. Three values of the standard deviation, σ , of the noise density function were used. Data was taken for σ = 150 ft, 300 ft, and 600 ft.

The number of position estimates (points on the flight data path where data samples were taken) made was varied in steps of five from five to 25. At each point in space where a position estimate was desired, Monte Carlo estimates of the position were made to assure that the results reflect the randomness due to the assumed Gaussian distributions and not due to the number of noise samples used. After all desired position estimates were made, a minimum mean-square error estimate of the turn radius of the aircraft was made. This was accomplished with an IBM subroutine package which fit a first order curve to the data using three data points for each calculation of the smoothed radius estimate. Finally, those smoothed estimates are averaged to give a final estimate of the turn radius.

Table XXV presents a summary of the radius estimate results. The data indicates that the estimated radius does not monotonically vary as the number of position estimates vary. However, this nonmonotonic variation is to be expected when the parameter estimate is biased. (An analysis showed that estimates were positively biased and the effect of the bias is dependent upon the variance of the Gaussian noise density function. For this reason, data runs were made at levels of noise variance where the influence of the bias was not predominant.) For more information see Reference 25.

The actual aircraft turn radius was 2.4056 n.mi. for the specified maneuver. The data shows that using 15 position estimates results in a radius estimate that does not change significantly with additional increases in the number of position estimates. This trend can be seen in the data for the σ = 150 ft, σ = 300 ft, and σ = 600 ft cases. For this reason, the use of 15 position estimates appears to be sufficient to accurately describe this maneuver. This corresponds to a data rate of approximately 0.6 position samples per second, which is appreciably lower than specified in the Statement of Work.

Table XXV Summary of Estimate of Turn Radius

NUMBER OF POSITION ESTIMATES*	RADIUS (nmi) FOR σ = 150 ft	DIFFERENCE BETWEEN TRUE AND ESTIMATED RADIUS (ft)	RADIUS (nmi) FOR σ = 300 ft	DIFFERENCE BETWEEN TRUE AND ESTIMATED RADIUS (ft)	RADIUS (nmi) FOR σ = 600 ft	DIFFERENCE BETWEEN TRUE AND ESTIMATED RADIUS (ft)
5	2.4062	3.6	2.4075	11.4	2.4114	34.8
10	2.4065	5.4	2.4080	14.4	2.4124	40.8
15	2.4055	0.6	2.4060	2.4	2.4085	17.4
20	2.4054	1.2	2.4059	1.8	2.4082	15.6
25	2.4059	1.8	2.4067	6.6	2.4099	25.8

*POINTS ON THE FLIGHT PATH WHERE DATA SAMPLES WERE TAKEN

APPENDIX A

CUBIC STATE VARIABLE COMPUTATIONS

This appendix lists the equations used to compute the best estimates of A/C pod position, velocity, Euler parameters, and rate vector in the CCS computer once every cycle. Uplink parameters in the form of velocity and Euler parameter updates are also computed once per cycle and transmitted to the AIS via the TIS. These updates are then utilized by the A/C pod to compensate for drift and other inertial sensor inaccuracies.

Since t_N, the time at which the downlink parameters (velocity vector and Euler parameters) are made available to the CCS, does not correspond to t_m, the time of the TIS range measurement of the same cycle $(t_{m-1} < t_N < t_m)$, a linear transformation of the downlink parameters to the t_m time reference is required.

A.1 A/C Parameters

A.1.1 A/C Pod Position Vector $(\hat{x}_m, \hat{y}_m, \hat{z}_m)$

$$\begin{bmatrix} \hat{x}_m \\ \hat{y}_m \\ \hat{z}_m \end{bmatrix} = \begin{bmatrix} x_{m-1} \\ \hat{y}_{m-1} \\ \hat{z}_{m-1} \end{bmatrix} + \frac{(t_m - t_{m-1})}{2} \begin{bmatrix} \hat{x}_N + \hat{x}_{N-1} \\ \hat{y}_N + \hat{y}_{N-1} \\ \hat{z}_N + \hat{z}_{N-1} \end{bmatrix} + (UPADD\text{-}1) \begin{bmatrix} \Delta\dot{x}_{n-2} \\ \Delta\dot{y}_{n-2} \\ \Delta\dot{z}_{n-2} \end{bmatrix} + \begin{bmatrix} \Delta x_m \\ \Delta y_m \\ \Delta z_m \end{bmatrix}$$

where

$$\begin{bmatrix} \Delta x_m \\ \Delta y_m \\ \Delta z_m \end{bmatrix} = K_4 \left[H_m^T \Gamma_m^{-1} H_m \right]^{-1} H_m^T \Gamma_m^{-1} \left[R_m - \hat{R}_{Am} \right]$$

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and $$\hat{R}_{Am} = \begin{bmatrix} \sqrt{(\hat{x}_{Am} - x_1)^2 + (\hat{y}_{Am} - y_1)^2 + (\hat{z}_{Am} - z_1)^2} \\ \sqrt{(x_{Am} - x_2)^2 + (\hat{y}_{Am} - y_2)^2 + (\hat{z}_{Am} - z_2)^2} \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \sqrt{(\hat{x}_{Am} - x_7)^2 + (\hat{y}_{Am} - y_7)^2 + (\hat{z}_{Am} - z_7)^2} \end{bmatrix}$$

R_m = 7 measurements of range obtained from the DME. (7x1) matrix.

$\hat{R}_{Am}$ = predicted 7 ranges which are computed in the previous cycle. For timing considerations, the $\hat{R}_{Am}$ equation should be included since the $\hat{R}_{Am+1}$ would be computed during the mth cycle.

K_4 = positive gain vector which is less than unity.

Γ_m^{-1} = 7x7 diagonal matrix. Γ_m is the variance of the range errors V, i.e., $Y = h(X) + V$ where V is the zero mean vector noise sequence.

H_m = 7x3 matrix which represents the partial derivatives of the range with respect to x, y and z.

$UPADD$ = indicates whether or not the updates computed 2 cycles previous were available to the DPU.

$\Delta\dot{x}_{n-2}, \Delta\dot{y}_{n-2}, \Delta\dot{z}_{n-2}$ = uplink pod velocity updates which were computed 2 cycles previously.

A.1.2 A/C Pod Velocity Vector $(\hat{\dot{x}}_m, \hat{\dot{y}}_m, \hat{\dot{z}}_m)$

The A/C pod velocity vector, computed by the DPU of the AIS and downlinked at time t_n, is linearly transformed to time t_m by the CCS computer so as to correspond in time with the rest of the A/C parameters.

$$\begin{bmatrix} \hat{\dot{x}}_m \\ \hat{\dot{y}}_m \\ \hat{\dot{z}}_m \end{bmatrix} = \begin{bmatrix} \hat{\dot{x}}_N \\ \hat{\dot{y}}_N \\ \hat{\dot{z}}_N \end{bmatrix} + \left(\frac{\Delta S}{t_m - t_{m-1}}\right) \begin{bmatrix} \delta \dot{x}_N \\ \delta \dot{y}_N \\ \delta \dot{z}_N \end{bmatrix}$$

where

$$\begin{bmatrix} \delta \dot{x}_N \\ \delta \dot{y}_N \\ \delta \dot{z}_N \end{bmatrix} = \begin{bmatrix} \hat{\dot{x}}_N \\ \hat{\dot{y}}_N \\ \hat{\dot{z}}_N \end{bmatrix} - \begin{bmatrix} \hat{\dot{x}}_{N-1} \\ \hat{\dot{y}}_{N-1} \\ \hat{\dot{z}}_{N-1} \end{bmatrix} - (1 - UPADD) \begin{bmatrix} \Delta \dot{x}_{n-2} \\ \Delta \dot{y}_{n-2} \\ \Delta \dot{z}_{n-2} \end{bmatrix}$$

$$\Delta S = t_m - t_N$$

$\hat{\dot{x}}_{N-1}, \hat{\dot{y}}_{N-1}, \hat{\dot{z}}_{N-1}$ = downlink pod velocity data from the previous cycle.

A.1.3 <u>A/C Pod Euler Parameters</u> ($\hat{A}_m, \hat{B}_m, \hat{C}_m, \hat{D}_m$)

Similarly as in the A/C pod velocity vector computation, the Euler parameters, which were computed by the small digital computer in the AIS pod and transmitted at time t_N, are updated to the CCS time t_m.

$$\begin{bmatrix} \hat{A}_m \\ \hat{B}_m \\ \hat{C}_m \\ \hat{D}_m \end{bmatrix} = \begin{bmatrix} \hat{A}_N \\ \hat{B}_N \\ \hat{C}_N \\ \hat{D}_n \end{bmatrix} + \frac{\Delta S}{(t_m - t_{m-1})} \begin{bmatrix} \delta A_N \\ \delta B_N \\ \delta C_N \\ \delta D_N \end{bmatrix}$$

where

$$\begin{bmatrix} \delta A_N \\ \delta B_N \\ \delta C_N \\ \delta D_N \end{bmatrix} = \begin{bmatrix} \hat{A}_N \\ \hat{B}_N \\ \hat{C}_N \\ \hat{D}_N \end{bmatrix} - \begin{bmatrix} \hat{A}_{N-1} \\ \hat{B}_{N-1} \\ \hat{C}_{N-1} \\ \hat{D}_{N-1} \end{bmatrix} - (1 - UPADD) \begin{bmatrix} \Delta A_{n-2} \\ \Delta B_{n-2} \\ \Delta C_{n-2} \\ \Delta D_{n-2} \end{bmatrix}$$

$\hat{A}_{N-1}, \hat{B}_{N-1}, \hat{C}_{N-1}, \hat{D}_{N-1}$ = downlink Euler parameter data from previous cycle.

$\Delta A_{n-2}, \Delta B_{n-2}, \Delta C_{n-2}, \Delta D_{n-2}$ = uplink pod Euler parameter updates that were computed 2 cycles previously.

A.1.4 A/C Pod Rate Vector $(\omega_{x_m}, \omega_{y_m}, \omega_{z_m})$

The rate vector is estimated by using the values of the downlinked Euler parameters and the time derivatives of the Euler parameters. A least squares fit to five successive observations (M_{LS} = 5) is applied to determine the variation of the parameter with time. The derivative of this parametric description is then computed.

The least squares estimate for $\hat{A}_m$ can be expressed as:

$$\begin{bmatrix} \beta_0 \\ \beta_1 \\ \beta_2 \\ \beta_3 \end{bmatrix} = \left[G_A^T G_A \right]^{-1} G_A^T \begin{bmatrix} \delta A_{N-3} \\ \delta A_{N-2} \\ \delta A_{N-1} \\ \delta A_N \end{bmatrix}$$

where

$$G_A = \begin{bmatrix} 1 & \delta t_1 & \delta t_1^2 & \delta t_1^3 \\ 1 & \delta t_2 & \delta t_2^2 & \delta t_2^3 \\ 1 & \delta t_3 & \delta t_3^2 & \delta t_3^3 \\ 1 & \delta t_4 & \delta t_4^2 & \delta t_4^3 \\ 1 & \delta t_5 & \delta t_5^2 & \delta t_5^3 \end{bmatrix}$$

$$\delta A_N = \hat{A}_N - \hat{A}_{N-1} - (1 - UPADD)\Delta A_{n-2}$$

$$\Delta S = t_m - t_N$$

$\delta t_\ell = \ell \cdot \delta T$ where δT = cycle time = $0.05\ sec$

The β's are the coefficients in the polynomial curve fit.

The derivative $\hat{A}_m$ can be obtained from:

$$\hat{A}_m = \beta_1 + 2\beta_2(\Delta S + 5 \cdot \delta T) + \ldots 3\beta_3(\Delta S + 5 \cdot \delta T)^2$$

Similar expressions can be derived for $\hat{B}_m, \hat{C}_m$ and $\hat{D}_m$.

Then the rate vector can be defined in terms of the Euler parameters and their derivatives:

$$\begin{bmatrix} \omega_{x_m} \\ \omega_{y_m} \\ \omega_{z_m} \end{bmatrix} = 2 \begin{bmatrix} C & D & -A & -B \\ D & -C & B & -A \\ B & -A & -D & C \end{bmatrix} \begin{bmatrix} \hat{\dot{A}}_m \\ \hat{\dot{B}}_m \\ \hat{\dot{C}}_m \\ \hat{\dot{D}}_m \end{bmatrix}$$

A.2 Uplink Parameters

A.2.1 A/C Pod Velocity Vector Update $(\Delta\dot{x}_n, \Delta\dot{y}_n, \Delta\dot{z}_n)$

The velocity vector update which is transmitted to the A/C pod to correct for errors in the gyros and accelerometers is described as:

$$\begin{bmatrix} \Delta\dot{x}_n \\ \Delta\dot{y}_n \\ \Delta\dot{z}_n \end{bmatrix} = K_2 \begin{bmatrix} \Delta x_m \\ \Delta y_m \\ \Delta z_m \end{bmatrix}$$

K_2 = positive gain factor which is less than 1

$\Delta x_m, \Delta y_m, \Delta z_m$ = A/C pod position update vector which has been computed in the process of determining the A/c pod position vector.

A.2.2 Euler Parameter Updates $(\Delta A_n, \Delta B_n, \Delta C_n, \Delta D_n)$

The Euler parameter updates can be computed by making use of F_m, the velocity vector change which approximates the A/C acceleration vector.

$$\begin{bmatrix} \Delta A_n \\ \Delta B_n \\ \Delta C_n \\ \Delta D_n \end{bmatrix} = \frac{K_1}{K_4 A^2_{Tm}} F_m^T \left[H_m^T \Gamma_m^{-1} H_m \right] \begin{bmatrix} \Delta x_m \\ \Delta y_m \\ \Delta z_m \end{bmatrix}$$

where $A^2_{Tm} = a^2_{xm} + a^2_{ym} + a^2_{zm}$

$$F^T_m = \begin{bmatrix} F_{11m} & F_{12m} & -F_{14m} \\ F_{12m} & -F_{11m} & F_{13m} \\ F_{13m} & -F_{14m} & -F_{12m} \\ F_{14m} & F_{13m} & F_{11m} \end{bmatrix}$$

$$\begin{bmatrix} F_{11m} \\ F_{12m} \\ F_{13m} \\ F_{14m} \end{bmatrix} = \begin{bmatrix} \hat{A}_N & -\hat{B}_N & \hat{D}_N \\ \hat{B}_N & \hat{A}_N & -\hat{C}_N \\ \hat{C}_N & \hat{D}_N & \hat{B}_N \\ \hat{D}_N & -\hat{C}_N & -\hat{A}_N \end{bmatrix} \begin{bmatrix} a_{xm} \\ a_{ym} \\ a_{zm} \end{bmatrix}$$

$$\begin{bmatrix} a_{xm} \\ a_{ym} \\ a_{zm} \\ \omega_{xm} \\ \omega_{ym} \\ \omega_{zm} \end{bmatrix} = \begin{bmatrix} 1-K_4 & 0 & 0 & \delta T & 0 & 0 \\ 0 & 1-K_4 & 0 & 0 & \delta T & 0 \\ 0 & 0 & 1-K_4 & 0 & 0 & \delta T \\ -K_2K_4 & 0 & 0 & 1 & 0 & 0 \\ 0 & -K_2K_4 & 0 & 0 & 1 & 0 \\ 0 & 0 & -K_2K_4 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} a_{x\,m-1} \\ a_{y\,m-1} \\ a_{z\,m-1} \\ \omega_{x\,m-1} \\ \omega_{y\,m-1} \\ \omega_{z\,m-1} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \delta \dot{x}_N \\ \delta \dot{y}_N \\ \delta \dot{z}_N + g \cdot \delta T \end{bmatrix}$$

APPENDIX B

COMPARISON OF XEROX SIGMA 5 AND SIGMA 8 COMPUTERS

Although the present Cubic ACMR system contains 3 Xerox Data System Sigma 5's in the CCS, the system is operating almost at capacity. Any fairly large additions or refinements to the system will require a change to a larger and faster computer - the Sigma 8. Only minor modifications would be necessary since the Sigma 5 and Sigma 8 are compatible. The major reasons for upgrading the Cubic ACMR system to the Sigma 8 from the Sigma 5 are:

(1) Increased speed of Sigma 8 ($\sim$50% for some operations)
(2) Sigma 5/8 compatible software.
(3) Increased reliability (greater MTBF).
(4) Improved maintainability.
(5) Similar spares complement (the Sigma 8 uses several additional types of modules).

Some of the improvements of the Sigma 8 over the Sigma 5 are listed below:

- The instruction set includes automatic conversion operations, including binary/BCD and any other weighted-number systems, and searching shift operations.

- Built-in reliability and maintainability features include:

  - Diagnostic programs with capabilities for: system verification and testing to determine the faulty unit; unit functional testing to determine the specific function of a unit that is faulty; and fault location diagnosing to analyze what physical component is malfunctioning.

  - Extensive error logging. When a fault is detected, system status and fault information are available for program retrieval and logging for subsequent analysis.

  - Full parity checking on all data and addresses communicated in either direction on busses between memory units and processors, providing fault detection and location capability to permit the operating system or diagnostic program to quickly determine a faulty unit.

  - Address stop feature that permits operator or maintenance personnel to:

Stop on any instruction address.
Stop on any memory reference address.
Stop when any word in a selected page of memory is referenced.

- Programmable "snapshot" registers that enable diagnostic routines to compare contents of a snapshot register with unknown correct information, thus accurately determining system fault conditions.

- CPU traps, that provide for detection of a variety of CPU and system fault conditions, designed to enable a high degree of system recoverability.

- Partitioning features that enable system reconfiguration. SIGMA 8 units can be partitioned from the system by selectively disabling them from busses. Thus, faulty units or an entire subsystem, consisting of a CPU, memory unit, input/output processor (IOP), and attached peripherals, can be isolated from the operational system to enable diagnosis and repair of a faulty unit while the primary system continues operation.

- An independently operating I/O system with up to eleven I/O processors (restricted only by port limitations) as opposed to 5 I/O processors for the Sigma 5.

- Scientific Features

  - Instruction Set. More than 100 major instructions permit short, highly optimized programs to be written, which are rapidly assembled and minimize both program space and execution time. (Sigma 5 provides 89 instructions).

  - Translate Instruction. The Translate instruction permits rapid translation between any two 8-bit codes; thus data from a variety of input sources can be handled and reconverted easily for output.

  - Conversion Instructions. Two generalized conversion instructions provide for bidirectional conversions between internal binary and any other weighted number system, including BCD.

- Multiprocessing Features

SIGMA 8 is designed to function as a shared-memory multiprocessor system. It can contain up to four central processing units and up to 11 input/output processors (the sum of both types of processors is restricted by the maximum memory port limitation of 12). All processors in a SIGMA 8 system address memory uniformly.

This section describes the major features of SIGMA 8 that will allow growth from a monoprocessor to a multiprocessor system.

- Multiprocessor Interlock

In a multiprocessor system, one of the central processing units often needs exclusive control of a system resource. This resource may be a region of memory, a particular peripheral device or, in some cases, a specific software process. A special instruction provides this required multiprocessor interlock. The special instruction, LOAD AND SET, unconditionally sets a "1" bit in the sign position of the referenced memory location during the restore cycle of the memory operation. If this bit had been previously set by another processor, the interlock is said to be "set" and the testing program proceeds to another task. If the sign bit of the tested location is a zero, the resource is allocated to the testing processor, and simultaneously the interlock is set for any other processor.

- Homespace

Since all processors in a multiprocessor system address memory in a uniform manner, it is necessary to retain a private memory that is unique to each processor for its trap and interrupt locations, I/O communication locations, etc. This private memory is called Homespace and consists of 1,024 words for each CPU. Each Homespace region begins with real address zero. The implicitly assigned trap locations, interrupt locations, and IOP communication locations, plus the 16 locations that are reserved for the registers, occupy the first 320 locations of Homespace. The remaining words in the Homespace region can be used as private, independent storage by the CPU.

- Multiport Memory System

SIGMA 8 has growth capability of up to 12 ports per memory unit. A memory unit consists of two banks of 8K words, each expandable to 16K, in which each bank can be concurrently operating when addressed by two of the possible 12 ports.

This system architecture allows flexibility in growth patterns and provides a large memory bandwidth, essential to multiprocessor systems.

- Manual Partitioning Capability

SIGMA 8 has manual partitioning capability for all system units. Thus, besides its primary advantage of increased throughout capability, a secondary advantage of a multiprocessor system is its fail-soft ability. Any SIGMA 8 unit can be partitioned by selectively disabling it from the system busses. Faulty units are thus isolated from the operational system. Re-enabling the connection allows repaired units to be returned to service.

- Multiprocessor Control Function

A multiprocessor control function is provided on all multiprocessor systems. This function provides three basic features:

1. Control of the External Direct Input/Output bus (External DIO), used for controlling system maintenance and special purpose units such as A/D converters.

2. Central control of system partitioning.

3. Interprocessor interrupt connection, allowing one processor to directly signal another processor that an action is to be taken.

- Shared Input/Output

Provisions have been made in a SIGMA 8 multiprocessor system for any CPU to direct I/O actions to any I/O processor. That is, any CPU can issue an SIO, TIO, TDV, or HIO instruction to begin, stop or test any I/O process. However, the end-action sequence of the I/O process is directed at one of the possible four CPUs. This feature (accomplished by setting a pair of configuration control switches) allows assigning I/O end-action tasks to a single processor and avoids conflict resolution problems.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This study was performed to identify tracking techniques and systems that could be used to track multiple targets in a realistic threat environment. The work performed provided technical support to IRAQ for analysis and evaluation of tracking systems and techniques for a Continental Operating Range (COR).

The tracking requirements for the COR are twofold. The near term (or initial system) requirements (1-5 years) are for tracking 16 aircraft

20. within a 75 n.mi. diameter circle. The far term (or future system) requirements (5-10 years) are for tracking 60 aircraft and 40 ground vehicles within a 200 n.mi. diameter circle. The study was to provide guidelines of techniques that would satisfy near term requirements as well as having long term growth potential for satisfying the far term requirements.

The study included the investigation of measurement techniques, navigation systems, range measurement systems, range displays and computer requirements. Major emphasis was given to the analysis of hardware developed ranging systems that could, with modifications, satisfy the Air Force's near term tracking requirements. The two systems which will most likely satisfy the near term requirements are Cubic Corporation's Air Combat Maneuvering Range (ACMR) and General Dynamic's Range Measurement System/Data Collection System (RMS-2/DCS).

Appendix C (Secret) of this report, prepared for RADC and published separately, will discuss ALSS technology and its relationship to TSPI requirements.