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# DEFINITION OF EXPERIMENTS AND INSTRUMENTS FOR A COMMUNICATION/NAVIGATION RESEARCH LABORATORY

VOLUME II

EXPERIMENT SELECTION

CASE FILE COPY

STUDY REPORT
DR MA - 04

MAY 1972

PREPARED FOR MARSHALL SPACE FLIGHT CENTER
UNDER CONTRACT NO. NAS 8 - 27540

TRW
SYSTEMS GROUP

ONE SPACE PARK • REDONDO BEACH CALIFORNIA 90278

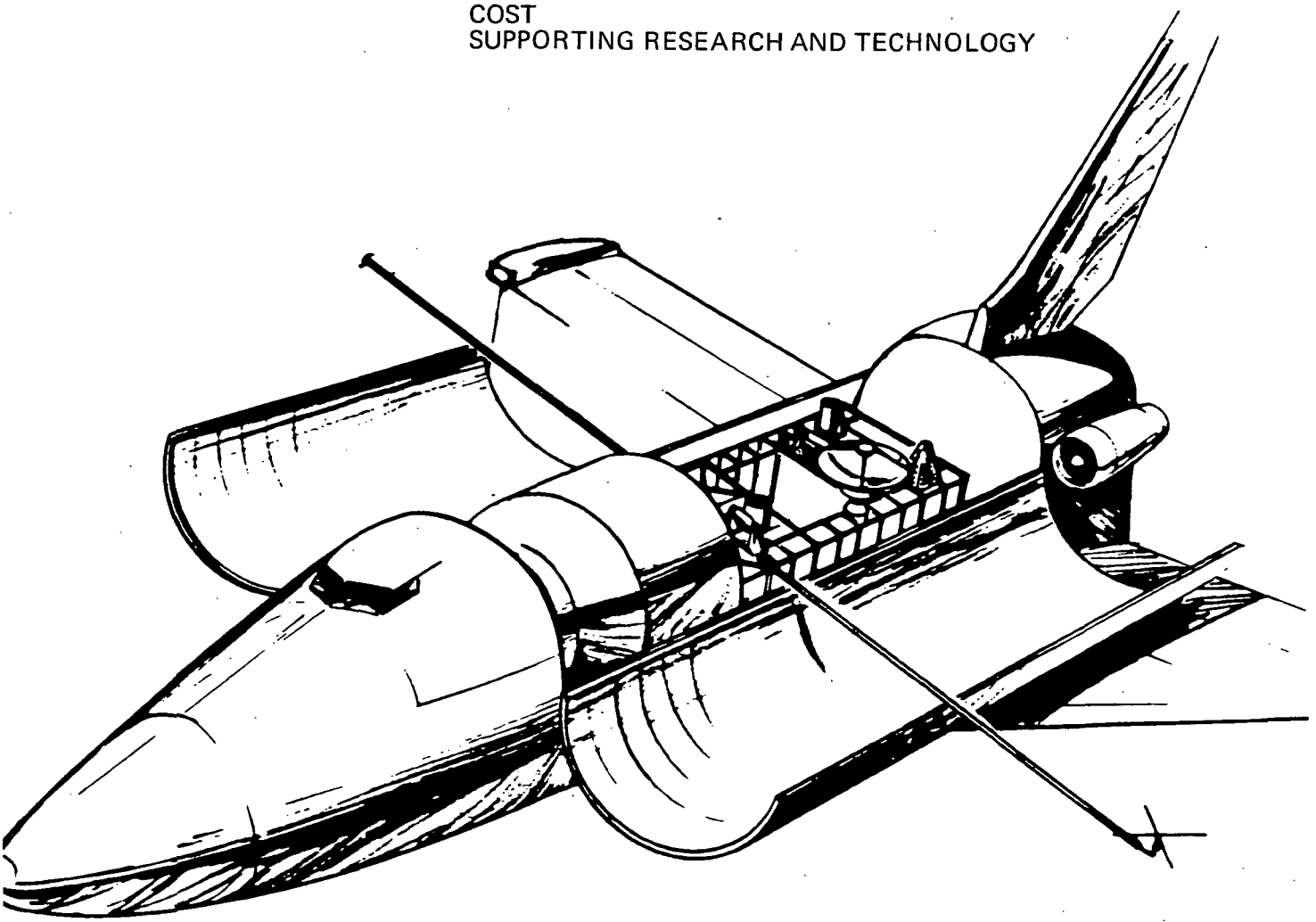
INSTITUTE FOR TELECOMMUNICATION SCIENCES

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY

COMMUNICATIONS SATELLITE CORPORATION

THE STUDY REPORT CONSISTS OF FOUR VOLUMES AS FOLLOWS

VOLUME I - EXECUTIVE SUMMARY
VOLUME II - EXPERIMENT SELECTION
APPENDIX - EXPERIMENT DESCRIPTIONS
VOLUME III - LABORATORY DESCRIPTIONS
VOLUME IV - PROGRAMMATICS
DEVELOPMENT SCHEDULE
COST
SUPPORTING RESEARCH AND TECHNOLOGY



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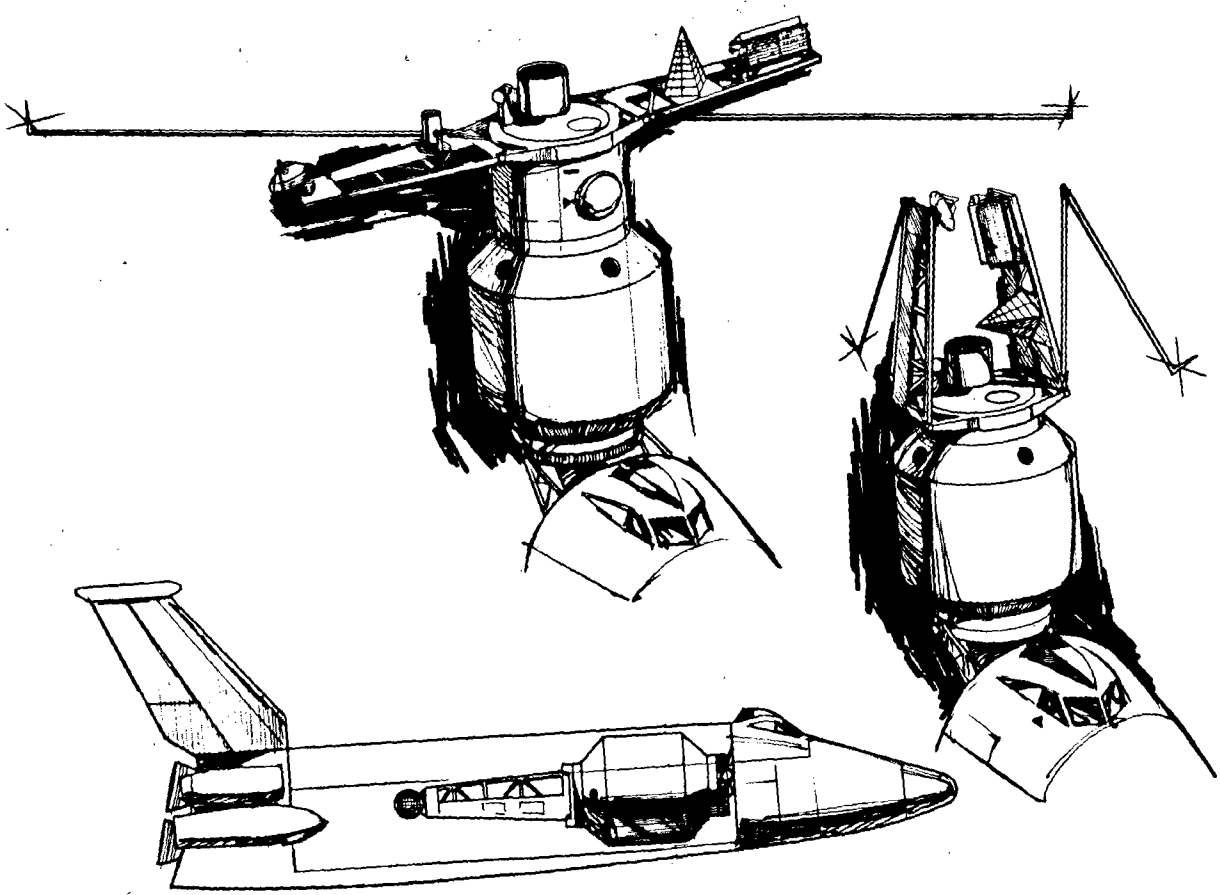

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APPENDIX II – EXPERIMENT DESCRIPTIONS


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# I. INTRODUCTION

Volume II is part of a four volume Study Report on a Phase A Study entitled "Definition of Experiments and Instruments for a Communication/ Navigation Research Laboratory". The purpose of the study is to develop conceptual designs for a Space Shuttle-supported manned communication/ navigation research laboratory capable of supporting various selected experiments in the applications discipline of communication and navigation. Volume I is a study overview and Executive Summary. Volume II describes in more detail the selection and definition of candidate experiments and the associated experiment instrumentation requirements. Volume III discusses identification of major laboratory equipment, systems and operations analysis, and conceptual design of the laboratory. Volume IV depicts cost, schedule, and SRT requirements.

Volume II, comprised of this book and an Experiment Description Appendix, presents information that addresses the following study objectives:

- Determine specific research and technology needs in the Comm/Nav field through a survey of the scientific/ technical community.
- Develop manned low earth orbit space screening criteria and compile lists of potential candidate experiments.
- In Blue Book format, define and describe selected candidate experiments in sufficient detail to develop laboratory configuration designs and layouts (Volume II Appendix).
- Develop experiment time phasing criteria and recommend a payload for Sortie Can/Early Laboratory missions.

# II. DISCUSSION OF COMMUNICATION/NAVIGATION TECHNOLOGY

Consistent with the objectives stated above, the following discussion presents the associated technological needs supporting future space communication/navigation systems. Of all the potential missions within the scope of operational space applications programs, communications satellite systems represent the one category of most direct use to the individual. Communication has always been a pacing item in the expansion of knowledge in the progress of mankind. A paramount and increasing need is the exchange of information and data both to private and public sectors. The many facets of mankind's expanding need for communications are represented by communities of users from governments, business, education, science, medicine, and agriculture.

The systems servicing these needs must be capable of complementing and supplementing existing services and in some instances providing the sole means of achieving these ends. The remarkable flexibility of satellite communication promises to be an elegant means of expanding communication services.

## A. POINT-TO-POINT (TRUNK) COMMUNICATIONS

Substantial economic and cultural benefits have already been obtained from operational communications satellites, such as the Intelsat series (I, II, III, and IV), which provide multichannel (trunk) communications to many participating countries around the world. These satellites operate within allocated 500 MHz frequency bands at 4 and 6 GHz and are stationed in geostationary orbits. The advantage of these orbits is to greatly simplify tracking requirements of earth stations and to eliminate the problem of "handover" between satellites.

In its point-to-point applications, satellite communication provides transmission links for terrestrial communication systems. This satellite service now is nation-to-nation and should become a city-to-city service, but not home-to-home except via the cities' earth stations and communication distribution systems. Such international and intercity links have thus far been provided (or could be) by terrestrial means such as cables, microwave relays, tropospheric scatter links, or by HF radio. Thus, the competitive break-even aspects of satellite links assume obvious importance.

Satellite links can transmit any of the various communications signals now transmitted via any other medium. System-design choices are likely to be made on the basis of economic considerations of total point-to-point traffic or total system traffic, with little attention given to the characteristics of particular applications.

Satellites already are in commercial and other operational use for the classical forms of telecommunication such a telephony, telegraphy, telex, facsimile transmission, and television program relaying. There is growing activity in the transmission of digital data at very low error rates for use with data-processing systems. The broad bandwidths available via satellite and the potentially low costs make visual telephony seem more attractive even for multiparty conferences in international scope; savings over travel costs become apparent.

Two classes of problems requiring further study and experimental work, however, are:

1) For the small user, or low-traffic earth terminal, a substantial amount of system design and other work must be done to reduce costs. For the developing nations in particular, the provision of some form of demand-assignment of circuits is essential for more efficient use of circuits, to permit direct access to points where the demand is too low to justify even one circuit on a pre-assigned full-time basis, and to reduce costs per call. In addition, work done to reduce the costs of earth terminals while retaining the use of high-discrimination antennas for the efficient use of frequencies and orbital-space segments will certainly be profitable.

2) For any system serving the United States domestic market, there is an ultimate need for more bandwidth than the presently allocated 500 MHz at 4 and 6 GHz. To provide more spectrum space for narrow-beam nodal systems, frequency space above 11 GHz should be developed as rapidly as possible. The available data indicate that millimeter waves would be practical and that there is little likelihood of obtaining adequate allocations elsewhere in the spectrum.

A brief look into the probable course of future technology indicates that current work toward reduction of costs of terrestrial microwave systems, future possibilities of millimeter wave-guides, and laser beams in a pipe will provide heavy competition with satellite systems in parts of the world such as the United States, where demand is great enough to permit using very large cross section facilities. On the other hand, this reinforces the need for more spectrum bandwidth for satellites so that they may gain the economies of scale on a comparable basis.

Investigation should also be made of longer-range technology such as the use of high-power laser beams for links between satellites and the earth which, for all practical purposes, could solve the problems of basic limits on frequencies available for Comm/Nav services. Study of the future uses of very large, perhaps passive, satellites, for example, possibly manned during installation and/or maintenance phases, could lead to pronounced changes in systems concepts and operations.

The next generation of international point-to-point satellite communication systems is likely to be the Intelsat V which may be initiated in the 1977-1980 time frame. This satellite is expected to require

extensive use of new technology including the possibility of the following:

1) Global or regional coverage transponders for telephony or TV.

2) Operation in the 4/6 and 12/13 GHz bands and possibly in the 20/30 GHz band.

3) Multiple satellite transponder configurations with alternative switching and routing subsystems to maximize frequency reuse (FDM, TDM, SDMA).

In order to prepare for the anticipated Intelsat V (and VI) developments, and the development of related point-to-point satellite communications systems, the following experiment involving space elements should be considered:

1) Propagation experiments at 12/13 and 20/30 GHz, on regional and global scales.

   To support exploitation of frequencies above 11 GHz that will be needed for global and regional communications, it will be necessary to accumulate geographically diverse data on the effects of rain on attenuation and noise by some or all of the following:

   a. Narrow-Angle Forward Scatter through Rain

      Because of the possibility of interference between closely spaced geostationary satellites due to narrow-angle forward scatter through rain, measurements of this effect are needed. Measurements should be made in the shared bands and above 11 GHz over terrestrial paths several miles in length to simulate the up-link and down-link paths in satellite communication systems.

   b. Subjective Effects of Terrestrial Interference with Satellite TV Distribution

      Measure the carrier-to-interference ratios required for various degrees of subjective quality, simulating the effect of a terrestrial carrier interfering with the down link of a satellite TV distribution system, and vice versa. Consider the effect of using carrier dispersal in the satellite system.

   c. Precipitation Off-Path Scatter Interference

      Measure precipitation scatter interference between terrestrial and satellite systems in the shared bands.

d. Ducting Interference in the Shared Bands

Determine the importance of ducting interference between terrestrial and satellite systems in the shared bands by measurement over many different paths and over a long period of time.

e. Aircraft Scatter Interference in the Shared Bands

Measure aircraft scattering cross section of the most common types of commercial aircraft for all scattering angles and attitudes. Study typical flight profiles and traffic patterns and predict the frequency of occurrence of aircraft scatter interference events for earth stations located properly with respect to air-traffic patterns. Verify predictions by measurements at a few selected locations.

2) Optimum Transponder Designs

a. Evaluate new multiple-access/modulation methods suitable for the existing and higher frequencies; in particular, the problems of switching on-board a satellite.

b. Design of Signals for Optimum Utilization of Orbit and Spectrum

The interaction of modulation and coding parameters with orbital spacing of geostationary orbits should be considered in determining optimized utilization of orbital space as well as spectrum.

c. Space-Qualified Low-Noise Amplifier

Problems of interference between satellite earth stations and terrestrial microwave facilities (but not from radio relay transmitters to receivers in satellites) could be reduced if more sensitive receivers were developed for use in satellites. This experiment would evaluate the effectiveness of using such receivers.

3) Optimum Antenna Designs

a. Explore the use of frequencies above 10 GHz, and for all frequencies, the concepts of frequency reuse by spot beams and orthogonal polarizations.

b. Multiple-Beam Antennas for Satellites

Develop and test multi-feed antennas capable of permitting a geostationary satellite to communicate separate traffic with several earth stations simultaneously.

c. Neutralization of Multiple Feeds

Develop techniques for summing signals among the feeds in a multi-feed antenna to minimize interference between beams, particularly between adjacent beams.

d. Satellite Stabilization and Antenna Pointing

Continue a program of improvement in geostationary satellite stabilization and antenna pointing, with emphasis on obtaining accuracies of the order of $\pm 0.1$ degree and better over periods of several years.

## B. ADVANCED DOMESTIC SATELLITE SYSTEMS

As noted above, presently operating communication satellites operate as relay points between small numbers of large, sophisticated ground terminals. These satellites have been capable of providing a sufficient number of channels within the available bandwidth of the allocated microwave S- and C-bands to satisfy the current Intelsat Consortium needs. In contrast, the advanced domestic communication satellite required for information networks will have to operate above 10 GHz to provide the bandwidth imposed by high data rate information transfer and to ease the spectral crowding in the UHF/microwave bands.

As presently planned, domestic communications satellite systems in the post-1975 period may provide the small user with a capability for demand access to such information sources as computer files, libraries, and ETV/ITV programs. Teleconferencing and telecomputing are other examples of services between small-user terminals. These information networks will supplement existing telecommunications facilities and typically could include biomedical communication networks, law enforcement networks, systems for rural/remote regions, educational satellite systems, direct-broadcast TV distribution systems, and so on. The rural/remote region systems could include systems for the state of Alaska, the Rocky Mountain region, the northwest and southwest states, Appalachia, the Pacific Basin and Trust territories, etc.

An example of the urgent need for domestic satellite services can be found in the field of education. Education in the U.S. and indeed the world is approaching a crisis wherein the key issues are cost, equality of educational opportunity and style of education. In the past ten years

the cost of education in the U.S. has risen by 160 percent to 70 billion dollars, while the student population has grown by 129 percent to 59 million students. Coupled with the rising student population and inflation is the fact that education is the most labor-intensive of all major U.S. economic sectors, with over 60 percent of the total expenditures going for salaries of instructors.

Equality of educational opportunity may be briefly stated as pertaining generally to disadvantaged minority groups and groups characterized by pupil mobility (such as migrant workers).

The changing style of education is evidenced by increasing number of alternatives to existing public schools which stress experiential learning and individualization. In addition, learning is taking place in home and community centers.

All these factors reinforce the applicability of a unified national educational system in those subject areas which satisfy national educational requirements. Furthermore, the possibility of implementing an educational communications satellite system is an extremely promising approach to solving the problem of linking large numbers of widely separated schools, libraries, existing or planned ITV, ETV, ITFS, CATV, statewide and regional networks, and public broadcasting networks. A feasible goal would be the establishment of a pilot experimental system in the 1976-1977 time period and earlier tests using ATS repeaters have already been scheduled. Initial studies and experimental tests will help identify critical technology requirements and provide the basis for developing the required spacecraft subsystems to meet total system needs.

Another example of the potential advantage of domestic satellite systems in solving pressing regional needs is the contemplated communication satellite system for Alaska. Various studies and proposals have been made, both within and without the government, in regard to a rural/remote region Alaskan communications network predicated upon user requirements not met by a common-carrier terrestrial network or satellite system.

Levels of user requirements and economics have become fairly well defined and a preliminary preferred approach for a dedicated type of satellite system has been developed at NASA/GSFC including performance

and configuration rationales. This approach requires further study, analysis, and coordination. Through appropriate channels further discussions are planned with Alaska to verify the concept and assist with continued refinement of user requirements. Further cost effectiveness studies will be made relative to common carrier domestic satellite systems. Studies will be performed to optimize the performance of the preferred satellite approach and the configuration including factors such as launch vehicle tradeoffs, stabilization, control, RF beam pointing mechanisms, power supply/battery/eclipse factors, color vs black and white TV vs voice channel capacity, power/bandwidth vs EIRP vs G/T factors, etc. The merits, economics and feasibility of using terrestrial network(s) must also be determined and considerations given to advantages and disadvantages of said use and of using a hybrid system that combines use with the preferred dedicated satellite system. The terrestrial and hybrid systems must also be appropriately discussed with the user. A report prepared by Computer Science Corporation for Goddard Space Flight Center, issued April 1971, describes the approach.

A final example of potential domestic satellite services, one involving some different technological problems, is that providing direct TV broadcasts to small earth stations for local distribution or even to individual homes. The general economic advantages and associated problems of transmitting TV from Intelsats to large earth stations (~30 meter diameter antennas) have been previously mentioned. For the direct TV broadcast case, however, much higher satellite transmit powers are needed to compensate for much lower receiver antenna gains. In addition, the high power, in the multi-kilowatt range, would have to be achieved with, say, a 5-year transmitter life--a very difficult requirement. To achieve this power level reliably, an exception may have to be made to the desired use of the 12/13 GHz or 20/30 GHz bands, and a lower band, say, 900 MHz, used instead.

The technology needs of the advanced domestic satellite systems described above parallel those of the point-to-point system needs. Some problems are unique, however, and others require added emphasis, particularly in the case of multibeam antennas which are essential in domestic systems if reliable inexpensive links are to be provided simultaneously to

many small users. These special problems can be categorized as follows:

Antennas

As mentioned, one of the essential subsystems of advanced domestic communications satellite systems is a satellite antenna capable of multiple, narrow-beam and shaped-beam transmission. Such a system must have shaped-beam patterns with low sidelobes in order to minimize spillover into areas not intended for reception, make more efficient use of radiated energy, diminish the problem of interference with terrestrial systems and nearby countries, and make more efficient use of the geostationary orbit and the shared frequency spectrum.

Different approaches must be analyzed and tested for meeting the above antenna requirements, including dielectric lens systems, multi-ported arrays such as the Butler array, retrodirective antennas, waveguide lenses, etc.

The use of spherical reflectors with array feed systems should be investigated in which phase and amplitude control of each feed element permits the formation of a large number of overlapping beam positions and a capability for "dial-up" of any given beam. Application of beam synthesis techniques to an array of relatively high gain antenna elements should also be studied where each element of the array provides earth coverage (or continental U.S. coverage) and highly directive and overlapping beams are formed by IF processing either on-board the satellite or in a ground communication control facility. A capability for radiation from more than one antenna element simultaneously will permit the number of beam positions to greatly exceed the number of antenna elements and at the same time provide a variable secondary pattern beamwidth and beam shape.

Repeater Technology

Various signal processing techniques to effect communication channel routing in multiple beam/multiple access systems must be studied and tested. This may require the development and test of new modulation and multiplexing techniques such as hybrid amplitude-phase and variable data rate TDM. Satellite repeaters capable of internally routing many channels

have to be evaluated and comparisons made of RF vs IF vs baseband switching approaches. The potential advantage of digital signal processing over analog demodulation must be also studied.

Direct-Broadcast TV Needs

The design and test in a space environment of reliable high-power transmitters is a particularly important problem which must be solved prior to the establishment of an operational system which can broadcast TV signals directly to small users.

The present state-of-the-art in spaceborne RF power amplifiers includes output powers of a few hundred watts. For output power levels above 0.5 kilowatt, further development is necessary. Technological advances are absolutely required to achieve a 5-year life with adequate reliability (>0.7) and to provide adequate and reliable cooling commensurate with the 5-year life requirement. Improved transmitter efficiency relaxes the cooling requirements, to a theoretical limit, and therefore is as important for feasibility as cooling capacity.

Enhancement of efficiency will further relax requirements on the design of large solar arrays and when developed will yield savings in satellite costs or earth receiver costs.

Recent studies of multi-kilowatt RF amplifiers have emphasized high overall efficiency. Designs feature multi-stage depressed collectors as the method of yielding the largest efficiency improvement. Heat-pipe configurations for cooling have been presented in all studies, while achievement of long life has been approached primarily from the viewpoint of cathode design and loading. Amplitude linearity for AM/VSB and phase linearity (group delay) have been examined in varying degree.

Clearly, experimental verification of efficiency, thermal design, life, and linearity are required. Experiments in simulated, and then a space environment, as well as considerable hardware development are required before operational spaceborne amplifiers with output levels above 1 kilowatt can be produced.

Development of lightweight RF circuit components (including diplexers and filters) capable of handling high average power (up to 10 kw) in space environment, is required. The critical issues are multipaction

(voltage breakdown due to the presence of secondary electrons), and cooling.

A fundamental requirement on antennas for television broadcast satellites will be the concentration of the total radiated power on a limited area. At the lowest frequency of interest, 0.9 GHz, this requirement dictates the use of satellite antennas as large as 30 feet (9m) to cover an area with a diameter of 1000 miles, or 60 feet for a 500 mile coverage.

The critical issues are weight, deployment reliability, and the geometric accuracy of the surface when subjected to dynamic and thermal distortion in space environment. The surface accuracy requirements are set primarily by the acceptable limits on sidelobe levels and pointing accuracy.

Substantial efforts have been spent on the design of unfurlable antennas with wire-mesh surfaces. To date, published space flight experience has not been obtained with antennas larger than 10 feet (3 m). Further full-scale model development and testing are required to obtain the level of confidence in reliability and performance which is required to commit a 30-foot deployable antenna to a space mission.

Feed configurations for large reflector antennas capable of handling multi-kilowatt power levels, are not state-of-the-art. Development is required to achieve illumination patterns for low sidelobe levels and power handling capability up to an average of 10 kilowatts. The critical issues of the latter objective are multipaction and thermal control.

Shroud limitations on spacecraft dimensions will, in general, prohibit the use of more than one large deployable reflector antenna. Multiple beam transmission by reflector antenna can then be achieved only with a multiple-feed arrangement. The main problems with this approach are geometric conflicts at the feed and the feasibility of low-level sidelobes. "Coma" lobes caused by off-axis location of feed radiation centers and coupling between feeds represent the basic limitation since they are excessively high before any reduction in gain is apparent. An array-type of feed is a potential solution. Further development is required if multiple-beam transmission by a single reflector is an actual requirement. Any decisions on such development should be made only after consideration of the potential capabilities of phased arrays.

The potential advantages of phased arrays are:

- Beam pointing without attitude disturbance torques
- More freedom in aperture distribution design than possible with reflector antenna feeds; permits achievement of lower sidelobe levels
- Multiple-beam capability without adverse effects on sidelobe level
- With active arrays, distributed power dissipation facilitates thermal control.

Phased arrays fed by a single transmitter compare unfavorably with reflector antennas, because of the large weight of a phased corporate feed network with full RF output power capability and the heavy power losses in such a network. Only active arrays, with final amplification at each element (or small group of elements), are potentially competitive and only at the lower frequencies, 0.9 GHz and 2.5 GHz.

Active arrays for the present application are not within the existing state-of-the-art. With the rapid development of solid-state devices for microwave power generation, it appears that active arrays at 0.9 GHz and 2.5 GHz could become competitive for missions in the 1975-1980 time period. This would require development in the following areas:

- Design elements such as a strain energy deployable reflector with a complementary pair feed or a strain energy deployable helix
- Power capability and efficiency of transmit modules
- Deployment of array with feed network
- Feed network development for multiple-beam capability.

The critical issues of RF rotary joint design for direct TV broadcast are multipaction and thermal control. Apparently there is not sufficient evidence of feasibility from tests in simulated space environment. RF rotary joints for power levels above 1 kilowatt can, therefore, not yet be considered state-of-the-art.

## C. DATA COLLECTION SYSTEMS

A very attractive application of satellites is the collection of data and the position location of low-cost fixed and mobile ground platforms. Requirements for data collection satellites have been identified in the

fields of meteorology, ecology, earth resources, and oceanography. There are also applications in sea and air rescue, the location of land vehicles, and long-range tracking of free roaming animals. The AEC, for example, has suggested the continuous surveillance of trucks carrying radioactive materials.

All known requirements can be met using low altitude and synchronous altitude satellites carrying appropriate transponders. The low-altitude systems provide for position location as well as data collection over all areas of the earth. These systems have an inherent capability for high accuracy because of low geometric dilution of position (GDOP). The synchronous systems provide continuous coverage and in the case of OPLE require only a single satellite for hemisphere coverage. Either system can be random or provided with an interrogation receiver.

A significant objective will be to meet increased requirements in terms of data traffic densities, location accuracy, velocity estimation, and real-time tracking.

Reasonable technical objectives concerning data collection systems are:

1) To develop data collection platform requirements and concepts optimized for user applications in meteorology, oceanography, ecology, and other disciplines needing data collection. Configurations will consider type of service, environment, type of deployment and input sensor characteristics.

2) To develop concepts and simulation models of satellite on-board processing techniques which will be used in parametric analysis of potential data collection systems. The benefits of on-board processing on factors such as satellite data storage requirements, transmission modes and loadings, ground processing operations and overall systems cost and efficiency will be determined.

3) The development of component technology needed to satisfy requirements for simple high quality and low cost platforms for data collection and position location systems. Detailed designs and working models will be developed.

4) The development of a real-time continuous monitoring system using retransmission of Omega tones through a synchronous satellite at UHF frequencies. The system will provide tracking of mobile platforms in random access or ordered modes for application to meteorology, oceanography, ecology and air sea rescue missions.

5) To develop techniques for correcting orbital ephemeris error in low orbiting satellite position location systems. Concepts will be developed and proven through use of Nimbus 4 IRLS experimental data.

More specifically, the technology needs can be described as follows:

a) Satellite On-Board Processing

The data capacity requirements of low orbiting satellite data collection systems is rapidly increasing with growth in users and user needs. Techniques must be developed to reduce the high data storage and wide band transmission readout requirements of future systems. On-board processing of platform signals offers a means of incorporating data redundancy reduction which in time greatly reduces storage and readout requirements and enables viable systems to be designed within capabilities of spaceborne data storage technology.

Techniques applicable to on-board processing of platform transmissions must be investigated as an alternative to continuous recording of signal plus noise. Advantages and tradeoffs as a function of total data collection system characteristics in random and ordered modes must be defined. Signal extraction and data redundancy reduction concepts must be studied and evaluated based upon use of techniques such as Fast Fourier Transform (FFT), Fast Handamard Transform (FHT), Abiguitous Analyzer, active filtering through multiple phase-lock loops, and passive filtering through cone filters. A comparative analysis in terms of minimum on-board storage requirements, minimum downlink transmission times and bandwidths, and complexity and reliability must be performed. Software simulations must be used in evaluating various techniques and viable concepts selected and considered from the standpoint of hardware complexity and future development requirements. The effort will result in the definition of optimum satellite on-board processing techniques, requirements, and needed development for subsequent tests of alternative approaches in a space environment.

b) Component/Technology Development

The reduction of size, weight and cost of sensory platforms has been established as a firm requirement for future systems by the user community. Data collection system designs have evolved which are compatible with lower complexity and, therefore, lower cost platforms. Designs must be developed which are reproducible in mass quantities while meeting performance and aircraft safety requirements.

A baseline platform has been designed and fabricated at NASA/GSFC in accordance with a representative set of

specifications for a random-access mode data collection system. Discrete components in combination with off-the-shelf integrated circuits were used in the implementation. The second phase of this effort will consist of miniaturizing the RF and digital portions of the design in a manner which will enable reproduction on a quantity basis at low cost. The effort will begin in the RF circuitry where stripline and hybrid techniques will be used, followed by reduction of digital circuitry through LSI techniques.

Satellite and ground data handling equipment requiring advancement in technology will be developed as needs arise. Specific areas regarded as problematical will be investigated through development at and testing of laboratory simulation models. From these efforts detailed functional, operational and design details will be developed.

c) Advanced OPLE

A synchronous satellite system operating in the UHF band and which uses retransmission of Omega navigation tones for location determination will be developed. Emphasis will be placed upon resolution of the ambiguity inherent within the Omega system to enable applications to search and rescue missions.

System studies will include (1) improvement in Omega location accuracy through use of improved skywave correction and differential Omega, (2) resolution of low ambiguity through use of time/distance measurements from Omega transmitters, recursive filtering techniques operating on Omega lines-of-position or incorporation of additional low frequency Omega tones, (3) analysis of total communication system to yield minimum power and bandwidth consistent with Omega retransmissions requirements, and (4) reduction of ground processing time of Omega signals from current 24 hours (ATS/VHF OPLE) to minutes.

The VHF platform design employed in the ATS/VHF experiment will be reviewed with the objective of converting to UHF. Improvements will be made in power efficiency, and as a design goal the package will be optimized to 100 cubic inches volume exclusive of antenna and external power source. A platform design will be generated with a target cost of $5K or less, in quantity

Upon completion of the above, the advanced OPLE system will be proposed as a flight experiment.

## D. TRACKING AND DATA RELAY SATELLITE

Various studies have been performed which indicate that the use of a tracking and data relay satellite system (TDRSS) to perform the tracking,

commanding and data retrieval from future NASA and other "user" satellites is cost effective. In certain cases, such as for a global earth resources program, or emergency and continuous wideband data services for a manned space shuttle and/or space station there is no other practical way to provide the support.

The TDRSS will consist of a number of relay spacecraft arranged about the earth at synchronous altitude. High data rate users such as Space Base and Space Station will communicate to ground via the TDRS spacecraft. In addition, very wideband (in the order of 100's of MHz) communication links are required between the TDRS spacecraft. Ku-band is envisioned as the operating frequency. The capabilities of these links are a function of four parameters, the first of which, the bandwidth, is fixed. The others are:

1) Transmitter power

2) Antenna gain

3) Preamplifier noise figure which establishes the system sensitivity.

The requirements for these links are barely achievable using state-of-the-art technology. Appropriate transmitter power using TWT's or bulk-effect solid state devices is limited to about 10 watts. Ku-band dishes having a diameter of about 6 feet corresponding to a gain of 47 dB are close to an upper limit. Using conventional Ku-band low noise mixers for the receiver front end would result in a system noise figure of about 8 dB. Reducing the effective noise temperature to 150 degrees is an increase in sensitivity of 10 dB. In terms of the other parameters, this is reflected as a 10 to 1 reduction in transmitter power or a 3 to 1 reduction in antenna diameter. Because of obvious limitations in transmitter power and antenna size, the preamplifier is considered here to be the unit which can and must be improved in order to meet the TDRS requirements with a reasonable margin.

The developed low noise preamp must have high reliability, long MTBF, small size and weight, low power consumption, for use by the low orbiting satellite (LOS) and the TDRS in a first space experiment.

The basic approach will be a hybrid microwave integrated circuit employing discrete components mounted on a microstrip structure. It is expected that an ultimate of 150 degrees Kelvin noise temperature can be realized.

Another objective is to study and implement a fully gimbaled antenna system to be used in RF links between advanced low orbiting satellites (LOS) and a tracking and data relay satellite and to identify key areas which must be developed to provide effective TDRSS support of such missions through the 1980's.

This task will define antenna acquisition techniques and pointing requirements for both observatory and relay spacecraft for a broad spectrum of future missions in both the pre-1980 and post-1980 time frames. Open-loop (programmed) and closed-loop (autotrack) antenna pointing systems shall be considered. Mechanical gimbal configurations to be studied include both X-Y and Az-El type biaxial systems and selected triaxial types. Problems to be addressed include initial acquisition optimization of pointing system design for both mission and relay spacecraft, and pointing ambiguity problems encountered in operations of gimbaled antenna systems in the TDRS system environment. Link frequencies to be considered include 15 GHz and 60 GHz.

Various studies and experiments must be performed to develop applicable high data rate communication devices and techniques. This area includes coding, modulation, frequency stability requirements, signal conditioning, matched filtering, and generally the problems associated with very broadband receivers and signal processing circuitry including intermodulation distortion and resulting intersymbol interference. Experimental studies will be performed to determine the most suitable set of parameters for the TDRS system. Delta modulation and quadriphase modulation experimentation will be pursued with the goal being to validate these beneficial pseudo data compression techniques for the TDRS.

The most recent developments in very high rate digital circuitry such as analog-to-digital and digital-to-analog converters have reached 200 Mbits/sec. Experimentation will be performed to validate the performance and packaging configuration for this state-of-the-art high speed

digital circuitry. Research and developments will be applied toward extending the operational bit rates to as high as 1000 megabits per second.

The task will emphasize the total system aspects of high data rate technology and will assume compatibility among elements of the system including the sensor, multiplexing system, user spacecraft telecommunication service system, and the TDRS relay and ground demodulation, distribution and recording system.

## E. NAVIGATION/AIR TRAFFIC CONTROL SYSTEMS

The unique ability of satellites to survey all mobile traffic at all times over large geographic regions (e.g., the United States or the North Atlantic Basin) makes them very attractive as a means to perform navigation, surveillance and communication functions for air traffic control services. These satellites can be designed to serve as integral elements in sophisticated navigation, surveillance and communication systems to improve or augment the present domestic and oceanic air traffic control (ATC) systems. The major services which can be provided by the navigation, surveillance and communication functions are: ground derived collision avoidance for aircraft, assistance to search and rescue operations, and assistance to flow control of aircraft from terminal to terminal.

The aeronautical traffic considered includes all types of aircraft (carrier, military, general aviation) operating in any region of airspace in both the domestic and oceanic traffic areas. Projections of the future air traffic environment clearly indicate the need for new and improved navigation, surveillance and communication systems for all types of aircraft.

There are, however, many questions that need to be answered if satellite systems are to be implemented to operate in place of, or in addition to, the present or future ground systems. In the process of developing candidate systems it may become apparent that certain new technology or development work may be required. This could take place in the satellite hardware, aircraft hardware, or ground processing systems. Several major problems that have been identified to date are:

1) Multiple access of 100,000 aircraft (domestic ATC system)

2) High position location accuracies (approx. 100 ft. in domestic terminal areas) with low-cost user equipment

3) Limited availability of frequency spectrum.

Existing techniques for position location must be studied to determine their capabilities in providing the surveillance and navigation functions from satellite-based systems. Some of the critical parameters requiring definition will be position location accuracy, update rate capacity, system capacity (i. e., number of users) and the required user and ground system equipments. Techniques showing the greatest potential will have to be further developed by laboratory test, computer simulations, component development and eventually by actual space tests. New techniques must be investigated on a continuing basis to determine the extent of their applicability.

Communication techniques will consist of those methods which are closely related to the navigation, surveillance or air traffic control functions. Although voice is still being considered for oceanic systems, the main emphasis will be on digital data methods needed to support a meaningful satellite system for ATC services. In the domestic operating area the major communication load should be carried by the ground systems.

The objectives of associated manned and unmanned satellite experiments will be to:

1) Demonstrate existing system concepts

2) Prove out new system concepts

3) Prove out new technology, e. g. multiple access, new ranging techniques, high power linear transponders,

4) Optimize satellite, aircraft, and ground equipment configurations, e. g. develop calibration and accuracy improvement techniques

5) Obtain statistical data required for future operational system designs, such as propagation effects (multipath, scintillation, dispersion), noise (man-made and natural), and RFI.

From the technique and system synthesis efforts, the most promising concepts and/or techniques will be considered for flight experiments. Additional activities will be hardware definition, prediction of expected results, schedule and cost development, examination of potential spacecraft for the experiment, and recommendations for experiment definition studies.

## F. NASA RESEARCH REQUIREMENTS FOR COMM/NAV PROGRAM

NASA's specific research objectives in establishing a balanced Communications Program Plan may be described by the six Comm/Nav Program Elements depicted in Figure 1.

### Multiple Access/Data Collection

This mode permits numerous users with small stations to utilize a single satellite repeater. Environment monitoring and weather data facsimile transmission for forecasting are examples.

### Navigation/Traffic Control

This mode is a specialized version of multiple access where mobile stations such as aircraft and ships would obtain information via the satellite from ground-based control or information centers.

### Data Relays

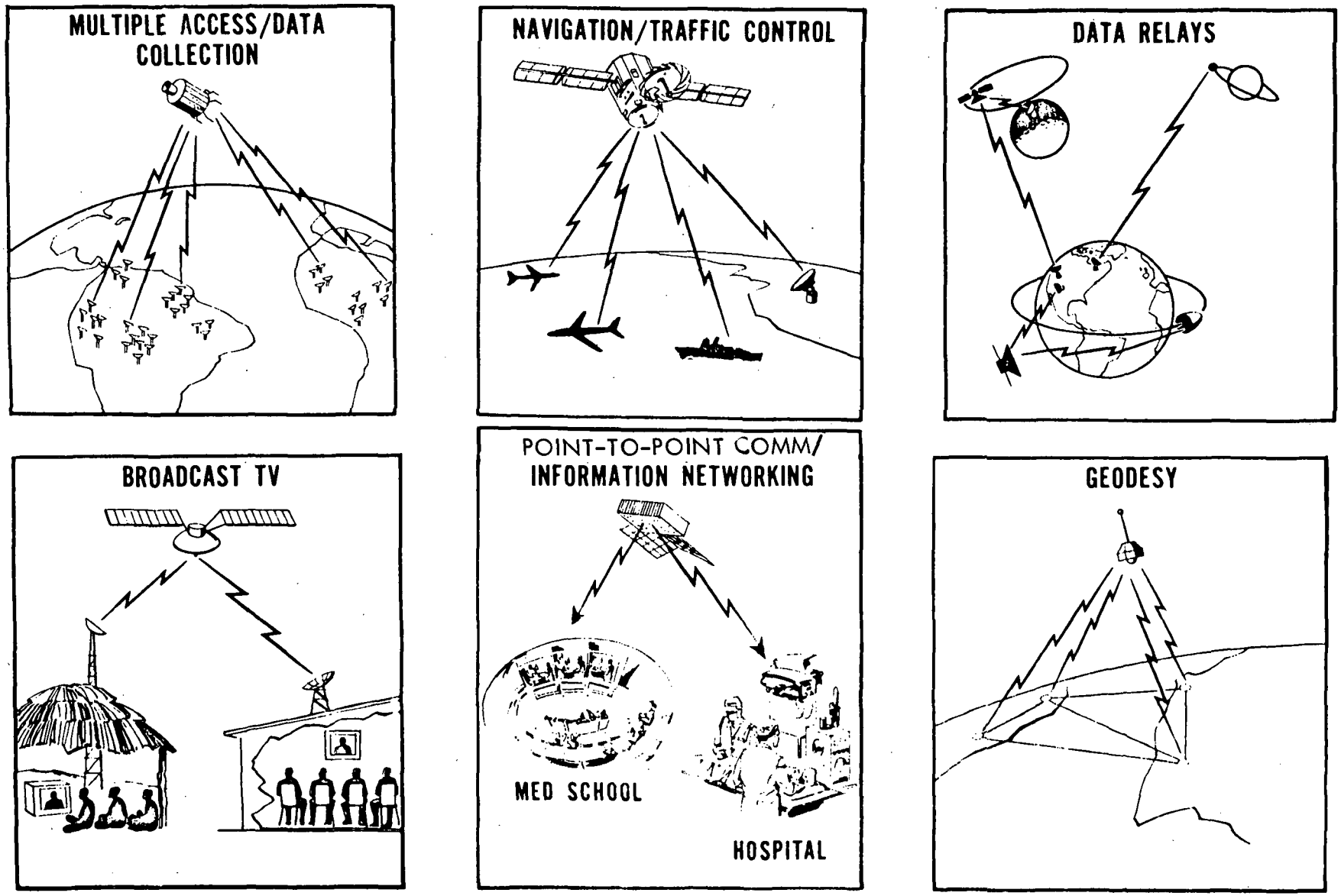
Present ground station networks permit limited (approximately 30 percent) contact with manned and unmanned spacecraft. The efficiency and effectiveness of space operations may be improved significantly by establishing a synchronous tracking and data relay satellite system (TDRSS).

### Broadcast TV

This application is directed toward providing satellite broadcast services directly to the user with a conventional TV receiver via multi-kilowatt power level satellites. It has the potential for providing instant national service and is particularly suitable for educational purposes.

### Point-to-Point Comm/Information Networking

This service provides transoceanic or transcontinental communication via relatively low-powered satellites operating with pairs of complex ground stations.




Reference: Communications Program Review
Office of Space Science and Applications
NASA Headquarters, January 1970

Figure 1. Comm/Nav Program Elements

The information networking service is related to interconnecting members of specialty groups over extended distances for information interchange. The National Library of Medicine in their Biomedical Communications Net is an example of development in this service.

Geodesy

This discipline includes utilization of communications, radar, and optical technologies to locate satellites precisely in their orbit. A goal of this program is the development of the technology needed to measure time variations in the gravity field.

Figure 2 relates these six major program elements to the ultimate benefits which will accrue from an experiment program directed to providing solutions to the recognized technological problems. An important experiment selection criterion for the Comm/Nav Laboratory Study has been a determination of its usefulness in contributing to the resolution of problems facing projected operational systems.

## G. ADVANTAGES OF MANNED RESEARCH IN LOW EARTH ORBIT

Two very important factors associated with the proposed Communications and Navigation Laboratory are the need for man, and the merits of a low earth orbit relative to a synchronous orbit.

The rationale for involving man in a key role in the Comm/Nav program is predicated on his ability as a scientist, development engineer, and technician. In early missions his greatest worth will probably be in the area of a spaceborne principal investigator conferring with a ground based scientific crew on results, measurements, and analysis of test data.

Examples of specific functions that can be performed by astronaut-experimenters in support of the Comm/Nav experiments include:

1) Set up and reconfigure experiment

2) Deploy/assemble experiment hardware (e.g. large antenna structures)

3) Program appropriate software

4) Perform on-board calibration and test procedure

| NASA COMM/NAV PROGRAM ELEMENTS | SPECIFIC OPERATIONAL APPLICATIONS | BENEFITS TO USERS |
|---|---|---|
| Point to Point Communications/ Information Networking | Intelsat V, VI, .....<br>European Comsat<br>Military DSCS-III, IV | • Lower Telephone Rates<br>• More Reliable, Quicker Service<br>• More Efficient Business Transactions<br>• Extension of Domestic Communications to Include Better Educational, Medical, Law Enforcement, Earth Resource Management, etc., Services to Heavily Populated and Rural Areas<br>• More Secure and Reliable Global Military Networks and International "Hot Line" Services |
| Broadcast TV | Advanced Domestic Satellites (Direct Broadcast TV; Advanced TV, Telephone Dist.)<br>Information Networks<br>Alaskan Network | |
| Multiple Access/Data Collection | Advanced TIROS, ERS, etc.<br>Search and Rescue | • Improved Weather and Hurricane Forecasting Services and Agriculture, Mining, Water Control, Fishing and Other Earth Resource Control Operations |
| Data Relay | TDRSS | • More Efficient, Less Expensive Relay of Collected National and International Data to Centralized Data Processing Centers |
| Navigation/Air Traffic Control | Advanced Aeronautical Services<br>Position Location of Mobile Transmitters<br>Defense Navigation Satellite System | • Safer, Quicker Air Transportation Services Through Better Air Terminal Control, Collision Avoidance and Improved Search and Rescue Operations |
| Geodesy | GEOS | • Improved Overall Communications and Navigation Services by Providing Means to Locate and Place Satellites More Accurately |

Figure 2. NASA's Future Comm/Nav Program Elements and Their Potential Benefits

5) Operate experiment pointing controls

6) Manipulate experiment switches and controls

7) Monitor and record data (including photography)

8) Perform on-board computation, data analysis, evaluation

9) Operate data handling equipment

10) Provide manned override of out-of-tolerance or malfunctioning automated routines

11) Verify physical integrity of experiment hardware (may involve EVA)

12) Restructure and optimize experiment flight plan based on in-flight evaluation or ground station direction

13) Conduct equipment maintenance, malfunction isolation, and repair.

Most of the recommended crew functions will entail some degree of specialized education, training, and experience. In order to adequately define the training and skill demands which the selected experiments would place upon the crew, each experiment was analyzed in some detail. As an illustration the laser communication experiment was evaluated to derive the required crew skills; the results are presented in Volume III, Section 3.5.

The second important factor to be considered is the relative merit of low altitude and synchronous orbits for the laboratory during the experimental program. Past experience with satellites has indicated the superior value of geostationary (synchronous) orbits for operational systems where continuous broad viewing of the earth's surface is required, but of low-altitude orbits for data collection systems where close observation of the earth on a global basis is the critical need.

Figure 3 identifies a number of characteristics which can be used as a checklist to judge the value of a candidate experiment. The characteristics have been grouped into three general categories: altitude, satellite motion, and operational factors, with the synchronous and low-orbit systems compared for each of the operational characteristics.

| CHARACTERISTIC | SYNCHRONOUS ORBIT (S) | LOW-ORBIT (L) | PREFERABLE MODE |
|---|---|---|---|
| ALTITUDE | | | |
| 1. INSTANTANEOUS VIEW | 1/3 THE EARTH | 2800 MI. DIAMETER | S |
| 2. VIEWING TIME | CONTINUOUS | A MAXIMUM OF 12 MINUTES/100 MINUTE PERIOD | S |
| 3. TRANSMIT POWER | HIGH BECAUSE OF DISTANCE | 30-40 DB LOWER | L |
| 4. RECEIVED SIGNAL LEVELS | LOW BECAUSE OF DISTANCE | 30-40 DB HIGHER | L |
| 5. ANTENNA RESOLUTION | LOW BECAUSE OF DISTANCE | 80 TIMES BETTER | L |
| 6. EMI | HIGH, BECAUSE OF LARGE VIEWING AREA | LOW BECAUSE OF ANTENNA DISCRIMINATION | L |
| 7. OPERATION FROM WITHIN IONOSPHERE | NO | YES, REQUIRED FOR ELF/VLF AND DUCTING EXPERIMENTS | L |
| 8. COST/POUND IN ORBIT | HIGH | LOW, BECAUSE OF ORBIT AND BECAUSE OF REUSABLE SHUTTLE | L |
| 9. TRANSFER OF EXPERIMENTAL DATA TO GROUND | HIGH SPACECRAFT ERP REQUIRED | RELATIVELY LOW ERP | L |
| 10. INTERFERENCE TO TERRESTRIAL SYSTEMS | MEDIUM | LOW, BECAUSE OF ANTENNA | L |
| SATELLITE MOTION | | | |
| 1. GLOBAL COVERAGE | NO | YES, UP TO ABOUT 65° LAT. | L |
| 2. DOPPLER SHIFT | NOT APPRECIABLE | MUST OFTEN BE CORRECTED FOR | S |
| 3. STRIP-SCANNING OF EARTH AREAS | COARSE | SIMPLE DUE TO ANTENNAS AND SPACECRAFT MOTION | L |
| 4. MEASUREMENTS WITH VARIABLE ELEVATION ANGLE | REQUIRES NUMEROUS GROUND EQUIPMENTS OR CONSIDERABLE EQUIPMENT MOVEMENT | SIMPLE BECAUSE OF SPACECRAFT MOTION | L |
| OPERATIONAL | | | |
| 1. SIMULATION OF LOW-ORBIT USERS | NOT FEASIBLE | IDEAL | L |
| 2. MANEUVERABLE ATTITUDE | DIFFICULT | SIMPLE | L |
| 3. CAPABILITY TO DOCK OR APPROACH OTHER SPACECRAFT | VERY DIFFICULT | INHERENT IN SHUTTLE DESIGN | L |
| 4. SIMULATION OF OPERATIONAL SYNCH. SATELLITES | IDEAL | ONLY PARTIAL | S |
| 5. EXPERIMENTAL LEAD TIME | TIME BETWEEN EXPERIMENT SELECTION AND FLIGHT IS LONG (3-4 YRS.) | QUICKER REACTION FLIGHT TEST CAPABILITY | L |

Figure 3. Relative Advantages of Synchronous and Low Orbit Communication/Navigation Experimentation

The resulting comparison indicates that a low-orbit Comm/Nav Laboratory can indeed play a useful role in supplementing synchronous orbit experiments (the ATS series of experiments for example) by taking advantage of the factors indicated by an "L" in the righthand column.

In summary, the rationale for low orbit missions is that the low altitude offers the possibility of global coverage, advantages in spacecraft subsystem design (lower power, reduced interference from and to terrestrial radio systems, better antenna resolution, etc.) and of course the opportunity to fly a manned laboratory with the space Shuttle.

*Inherent in the combination of manned and low altitude missions in earth orbit is that the development of technology and hardware for operational systems will be advanced in time over conventional testing with unmanned, single purpose spacecraft.*

## H. TIME PHASING RELATIONSHIP TO UNMANNED SPACECRAFT

A major objective in selecting and phasing Comm/Nav Laboratory experiments is to ensure the collection of timely data which can be used to improve the designs of projected operational systems. Of particular value will be the information, from propagation and radio interference measurements, which can be used to optimize the use and reuse of allocated frequency bands. The experiments should also be selected to complement those performed using concurrent unmanned spacecraft, taking full advantage of the special benefits to be derived from low-orbit, variable-altitude tests, such as increased spatial resolution of RF sources, the possibility of receiving very low level signals, and the changing geometry resulting from the spacecraft motion.

The applications for the anticipated beneficial technology data from the Comm/Nav flights are identified in terms of specific data needs for various space programs in Figure 4.

The probable technology needs for future satellite programs were established by identifying current and anticipated communication and navigation problem areas by operational class or system. The results of this investigation are summarized in Table 1. Programs that constitute potential customers for laboratory results are identified in Table 2.

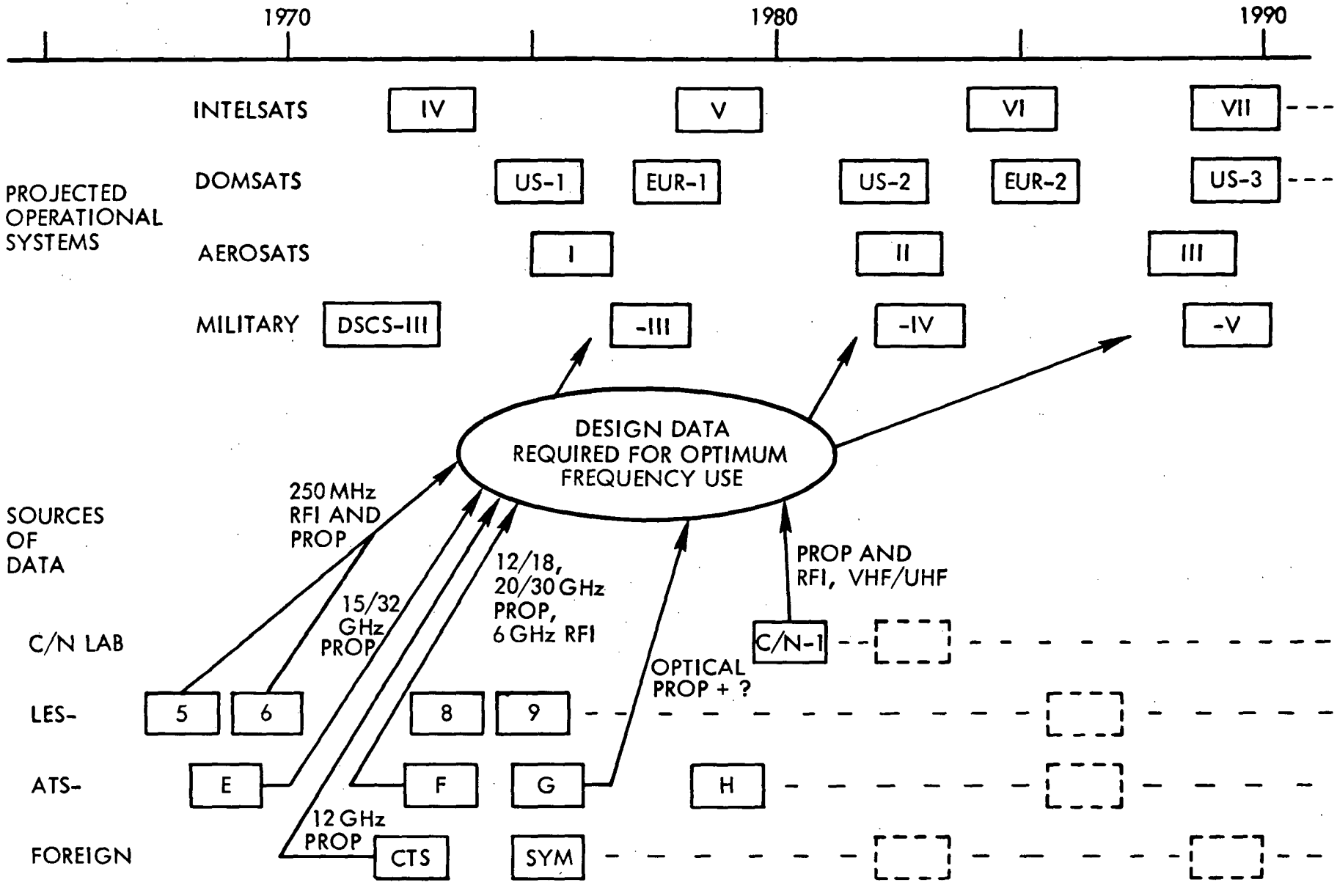



Figure 4. Time Phased Program Needs for Comm/Nav Data

## Table 1. Anticipated Technological Problems

| OPERATIONAL CLASS | PRINCIPAL BAND | RFI | PROPAGATION | SYSTEMS | SUBSYSTEMS | COMPONENTS |
|---|---|---|---|---|---|---|
| POINT-TO-POINT COMMUNICATIONS | MILITARY<br>30HZ-30KHZ<br>225-400MHZ<br>7/8GHZ<br>COMMERCIAL<br>4/6GHZ<br>>11GHZ | TERRESTRIAL NOISE<br>TERRESTRIAL NOISE; GROUND EQUIPMENT SUSCEPTIBILITY TO SAT RADIATION | MULTIPATH AND SCINTILLATION AT UHF<br>ATTENUATION AS A FUNCTION OF WEATHER AT > 11GHZ<br>PHASE COHERENCE OVER WIDE BANDS | FREQUENCY REUSE<br>NEW MULTIPLE ACCESS/MOD METHOD | SWITCHING AND ROUTING REPEATERS<br>ANTENNA ACQUISITION & TRACKING | ELF/VLF ANTENNAS<br>MULTIBEAM, POLARIZATION DISCRIMINATION ANTENNAS, ESPECIALLY >11GHZ |
| ADVANCED DOMESTIC SATELLITES | DIRECT TV BROADCAST<br>TV, TELEPHONE DISTRIBUTION; INFORMATION NETWORKING | NOISE<br>NOISE | >11GHZ<br>PHASE COHERENCE | LARGE NUMBER OF USERS<br>HYBRID MOD METHODS<br>VARIABLE TDM RATES | SWITCHING AND ROUTING<br>SYNCHRONIZATION & REMOTE OSCILLATORS | KILOWATT, LONG LIFE TRANSMITTERS<br>3'0'-60' ANTENNAS, UNFURLABLE<br>MULTIBEAM ANTENNAS (20-30) WITH NARROW, SHAPED, ISOLATED BEAMS |
| DATA COLLECTION | 100MHZ<br>3GHZ | NOISE (400MHZ) | MULTIPATH | POSITION LOCATION ACCURACY<br>REAL TIME ACCURATE LOS TRACKING<br>HIGH TRAFFIC DENSITY | DATA COMPRESSION, REDUCTION TECHNIQUES<br>ERROR CORRECTION CODING<br>ON-BOARD PROCESSING<br>REDUCE DATA STORAGE<br>REAL TIME TX<br>REDUCE OVERALL SYSTEM COSTS | SMALL, LIGHT COMPONENTS<br>POSSIBLY OF PHASED ARRAY ANTENNAS ON TDRS FOR TRACKING |
| DATA RELAY SATELLITES | 140MHZ<br>2GHZ<br>>11GHZ<br>60 GHZ<br>LASER | 140MHZ | >11GHZ<br>60GHZ<br>LASER | 200BPS ⟶ 1GBPS<br>FOR FUTURE TDRS/TDRS LINKS | ACQUISITION AND TRACKING OF CODING/MODULATION | LOW NOISE PARAMP<br>MULTIBEAM ANTENNA<br>PHASED ARRAY FOR FULLY GIMBALLED ANTENNA SYSTEMS |
| NAVIGATION/ATC | 1.5/1.6GHZ | NOISE | MULTIPATH | 100,000 USER MULTIPLE ACCESS<br>HIGH POSITION ACCURACY (100' NEAR TERMINALS)<br>FREQUENCY CONSERVATION | IMPROVED RANGING TECHNIQUES (LOW COST)<br>HIGH POWER LINEAR TRANSPONDERS | |
| MANNED LOW-ORBIT SPACECRAFT | 2GHZ<br>>11GHZ<br>LASER | | TOPSIDE ATMOSPHERE GRAZING<br>REENTRY (PLASMA) BLACKOUT (SHUTTLE) | TDRS TRACKING<br>TERMINAL LANDING (SHUTTLE)<br>HIGH DATA RATE STATION/TDRS LINKS | ON-BOARD PROCESSING | HIGH TEMPERATURE SURFACE ANTENNAS (SHUTTLE)<br>2GHZ PARAM |
| DEEP SPACE/LUNAR COMMUNICATIONS | >11GHZ<br>LASER | | | ACCURATE TRACKING | | LONG LIFE |

Table 2. Current Comm/Nav Experiment Programs

| PROGRAM | TIMING | EXPERIMENTS |
|---|---|---|
| NASA RESEARCH TECHNOLOGY OPERATING PLANS (RTOPS) AND ADVANCED APPLICATIONS FLIGHT EXPERIMENTS (AAFE) | CONTINUING | CONCEPTUAL DESIGNS AND DEVELOPMENT IN GROUND LABORATORIES OF REQUIRED TECHNOLOGICAL SYSTEMS TECHNIQUES AND DEVICES FOR SUBSEQUENT SPACE TEST: ANTENNAS, TRANSMITTERS, RECEIVERS, MODEMS, ON-BOARD PROCESSING COMPONENTS, LASERS, ETC. |
| NASA/ESRO BALLOON/AIRCRAFT TESTS | FY 72/73 | L-BAND RANGING, VOICE AND DATA COMMUNICATIONS UTILIZING A HIGH ALTITUDE BALLOON TO SIMULATE ONE SATELLITE OF AN AIR TRAFFIC CONTROL SYSTEM.<br>1. PROPAGATION EFFECTS AT L-BAND (1.5/1.6 GHZ)<br>2. VOICE PERFORMANCE DATA (NBFM, PDM, ETC.)<br>3. DATA ERROR RATES<br>4. COMPARISON OF DERIVED RANGE WITH RADAR-DERIVED RANGE<br>5. OPERATIONAL PROBLEMS |
| NASA APPLICATION TECHNOLOGY SATELLITES | LAUNCH OF ATS-F IN 1973, ATS-G IN 1975 | PERFORMANCE OF DATA COLLECTION, COMMUNICATIONS AND NAVIGATION EXPERIMENTS USING GEOSYNCHRONOUS SATELLITES. ATS-F EXPERIMENTS :<br>1. POSITION LOCATION AND AIRCRAFT COMMUNICATION EXPERIMENT (PLACE) AT 1.5/1.6GHZ<br>2. TELEVISION RELAY USING SMALL TERMINALS (TRUST)<br>3. RFI MEASUREMENTS (6GHZ)<br>4. MILLIMETER WAVE PROPAGATION (20 AND 30 GHZ)<br>5. DATA RELAY (WITH NIMBUS) |
| NASA SMALL APPLICATION SATELLITES (SATS) | ENGINEERING MODEL PLANNED FOR COMPLETION IN CY-73 | SPACECRAFT DESIGNED TO CARRY OUT SPECIALIZED EXPERIMENTS IN THE APPLICATIONS DISCIPLINES. WILL PROVIDE AN IN-ORBIT ENVIRONMENTAL AND SYSTEMATIC TEST CAPABILITY FOR CRITICALLY NEEDED APPLICATIONS-ORIENTED INSTRUMENTATION, IN A QUICK-REACTION, LOW-COST BASIS, FOR ERTS, NIMBUS, ATS, NAVSATS, ETC. |
| DOD's SPACE EXPERIMENTS SUPPORT PROGRAM (SESP) | PERIODIC; LATEST LAUNCH (9 POLAR-ORBIT SATELLITES) AUGUST 6, 1971 | PROVIDES FOR ORBITING OF SPACE RESEARCH PROJECTS NOT AUTHORIZED THEIR OWN BOOSTERS. ANY MILITARY OR OTHER GOVERNMENT AGENCY CAN SPONSOR A PAYLOAD, BUT IT MUST HAVE A POTENTIAL MILITARY VALUE. ONE OR TWO EXPERIMENTS (USUALLY) PER SATELLITE. THE SATELLITES JUST LAUNCHED WILL MEASURE:<br>1. ATMOSPHERIC CONDITIONS<br>2. GEOPHYSICAL PHENOMENA<br>3. PRECISION RADAR CALIBRATION OF TARGETS |
| COMSAT's EXPERIMENTAL SATELLITE | PLANNED LAUNCH IN 1974 | FULLY-STABILIZED DELTA-LAUNCHED SPACECRAFT TO TEST FREQUENCY REUSE BY MEANS OF SPOT BEAMS, (1-2°) ON-BOARD SWITCHING, AND PROPAGATION EXPERIMENTS AT 12/13GHZ AND 20/30GHZ. |
| CANADA's COMMUNICATION TECHNOLOGY SATELLITE | PLANNED LAUNCH IN 1973 | THREE-AXIS STABILIZED SYNCHRONOUS-ORBIT SATELLITE TO SPACE-QUALIFY A NUMBER OF DEVICES AND TECHNIQUES FOR NORTH AMERICAN DOMESTIC SATELLITE SERVICES:<br>1. COLOR TV AND AUDIO BROADCASTS TO SMALL LOW-COST EARTH TERMINALS<br>2. TWO-WAY VOICE COMMUNICATIONS<br>3. WIDE-BAND DATA TRANSMISSION EXPERIMENTS<br>4. DATA RELAY EXPERIMENTS<br>5. TEST OF A 50% EFFICIENCY TWT, 200W, 12GHZ<br>6. LONG-TERM STATISTICAL PROPAGATION TESTS |

Examples of other space activities that are expected to yield technical information that will need to be coordinated with that from the Comm/Nav laboratory flights are shown in Figure 5.

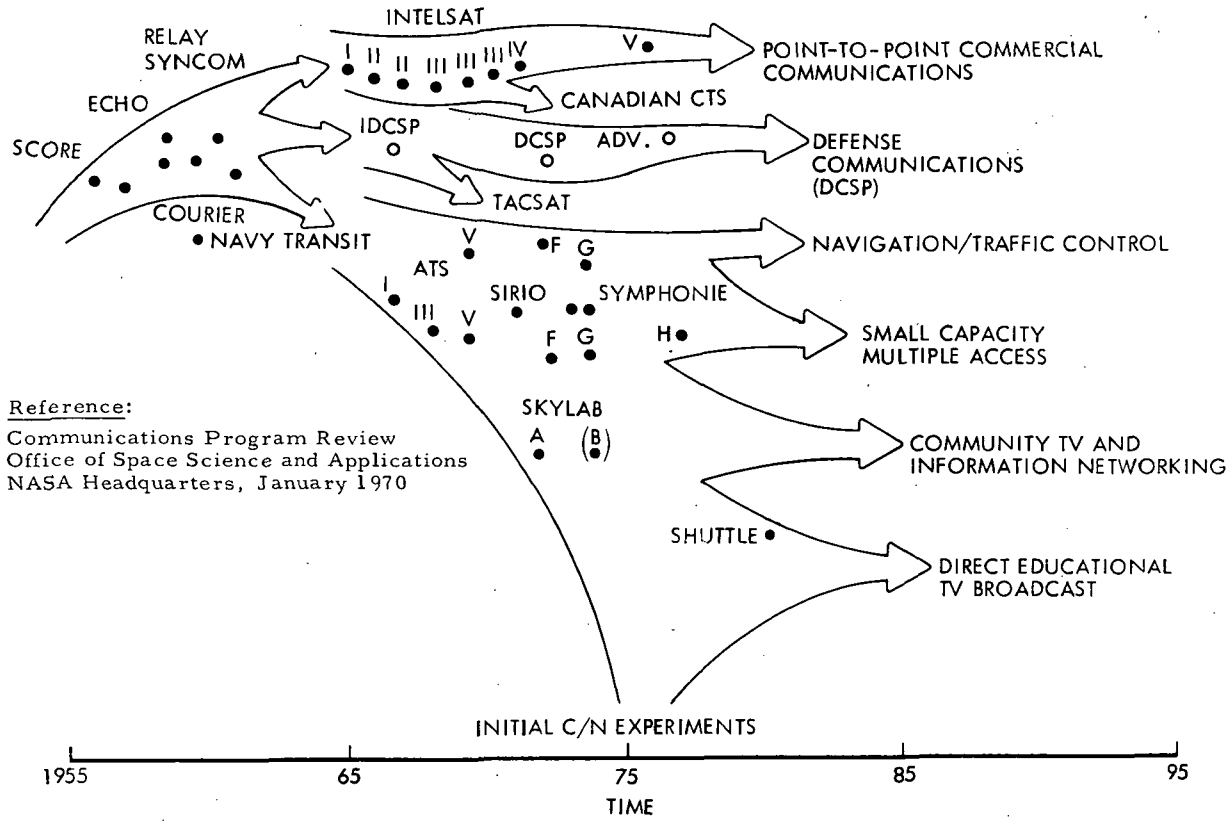



Figure 5. Communications and Navigation Space Program Evolution

# III. SELECTION AND DEFINITION OF CANDIDATE MANNED SPACE EXPERIMENTS

## A. STUDY ASSUMPTIONS AND GUIDELINES

The contract Statement of Work contained certain assumptions and guidelines which were utilized for the initial study effort. Most of these original guidelines have been substantially changed during the course of the study. The following are some of the major guidelines which were in effect during the principal decision-making phases of the study:

1) The Comm/Nav Research Laboratory will be designed to be compatible with the Sortie Can

2) The IOC date for the initial Comm/Nav Laboratory is assumed to be 1980

3) A Data Relay Satellite System (DRSS) will be available concurrent with the implementation of the Comm/Nav Research Laboratory

4) Stability limits of 0.5 degree attitude control dead bands and 0.01 deg/sec maximum limit cycle rate for each axis shall be provided by the Shuttle Orbiter.

5) The Orbiter crew shall consist of two (2) payload crewmen.

## B. STUDY METHODOLOGY

Figure 6 reflects the general flow of the six principal study tasks comprising the study program. Two key events not reflected on this flow diagram are worth mentioning since they have a major impact on the study results. The first event was the solicitation from all known sources (government, the academic community, industry, and foreign) for candidate laboratory experiments. The screening process and the results of this endeavor are described in this volume. The second major event was the survey of commercial hardware for possible use in a manned orbiting vehicle. The results of this survey are reported in Section 3.5 of Volume III.

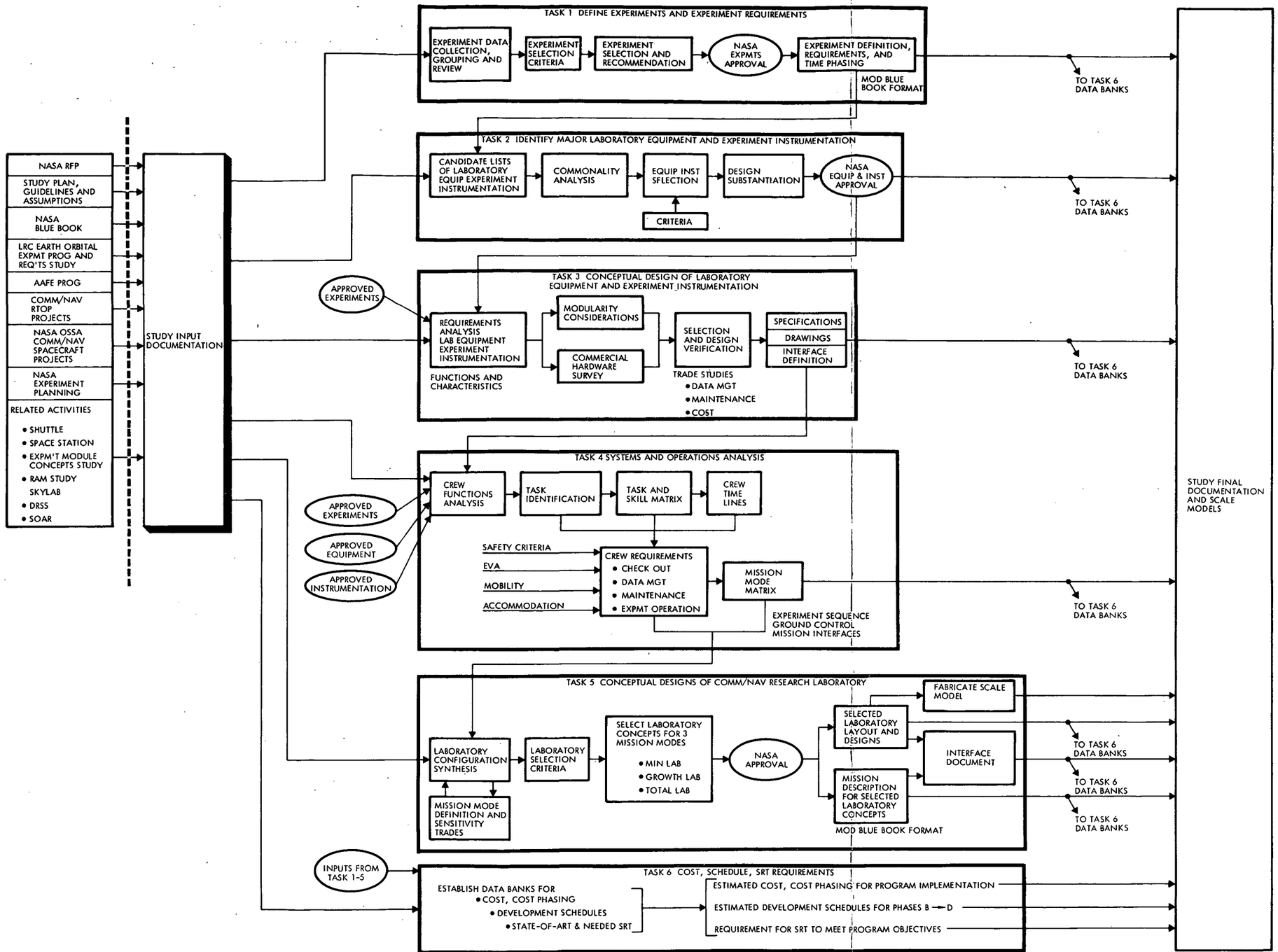



Figure 6. Task Flow

The initial or Early Comm/Nav Research Laboratory is associated with Seven-day Shuttle Orbiter Sortie flights in the 1980-1985 time period. About 1985 this Early Laboratory will probably expand into Growth versions where these growth versions would take various forms. At the end of the 1980 decade an all-purpose, or Total, Comm/Nav Research Laboratory is envisioned. This total laboratory may be attached to the Space Station, be outfitted for two to ten year usefulness, and include the equipment needed to conduct all research across the entire range of experiment classes.

The rationale for the selection of experiments for each of laboratory versions discussed above, as well as the suggested payload complements derived therefrom, is described in subsequent sections. Where the Early Laboratory may accommodate four to seven experiment classes, and the Growth version may include up to 12 experiment classes, the Total Laboratory will be capable of research in all 18 experiment classes. Of course, over the time period between now and start of Space Shuttle Missions, these 18 experiment classes may undergo significant new alignment.

The evolutionary concept of three laboratory versions (Early, Growth, and Total) was carried throughout most of the study period, but was de-emphasized in the latter phase of the study. Instead, the Early Laboratory version was selected for detailed payload configuration and mission study and this detail is reflected in this report.

## C. EXPERIMENT SELECTION

Experiments were solicited from a wide cross section of the scientific community including government agencies, industry, and universities having interest and capabilities in the communication and navigation fields. A copy of the letter of solicitation and a sample response are given in Appendix I.

As a direct result of these efforts, a total of 114 experiment suggestions were received. The organizations contributing these candidate experiments, and the number submitted by each group, are presented in Table 3.

Using these inputs, TRW then screened, combined, and regrouped these into 18 experiment classes in the manner shown in Figure 7. The basic selection criteria applied in screening the candidate experiments were:

Table 3. Source of Candidate Experiments

| Organization | No. of Experiments |
|---|---|
| GOVERNMENT (51) ≈45 percent | |
| Goddard Space Flight Center | 10 |
| Marshall Space Flight Center | 1 |
| Langley Space Flight Center | 1 |
| Manned Spacecraft Center | 5 |
| Langley Space Flight Center/North American Rockwell | 1 |
| Environmental Science Services Administration | 2 |
| Institute for Telecommunication Sciences | 16 |
| Mitre Corporation | 1 |
| January-1971 Blue Book, Volume 5, Comm/Nav | 13 |
| National Oceanic and Atmospheric Administration | 1 |
| INDUSTRY (54) ≈47 percent | |
| TRW Systems Group | 25 |
| McDonnell Douglas Astronautics Company | 3 |
| Comsat Corporation | 11 |
| Bell Laboratories | 4 |
| Honeywell | 1 |
| Raytheon/Wright-Patterson Air Force Base | 1 |
| Hughes Aircraft Corporation | 2 |
| General Electric Space Systems | 1 |
| Westinghouse Space Systems | 2 |
| Radiation Systems | 1 |
| National Scientific Laboratories | 1 |
| Fairchild Hiller Corporation | 1 |
| IBM | 1 |
| UNIVERSITY (8) ≈7% | |
| University of Illinois | 2 |
| University of Pennsylvania | 1 |
| University of Houston | 3 |
| Massachusetts Institute of Technology | 1 |
| Stanford University | 1 |
| INTERNATIONAL SOURCES (1) 1% | |
| Hawker-Siddeley Dynamics, England | 1 |
| TOTAL | 114 |

- Ultimate usefulness of the experiment in providing techniques required for future operational systems beneficial to the national interest
- Compatibility of the experiment with those planned for unmanned, automated spacecraft programs
- Practicality of performing the experiment in low-orbit
- Usefulness of man in performance of the experiment.

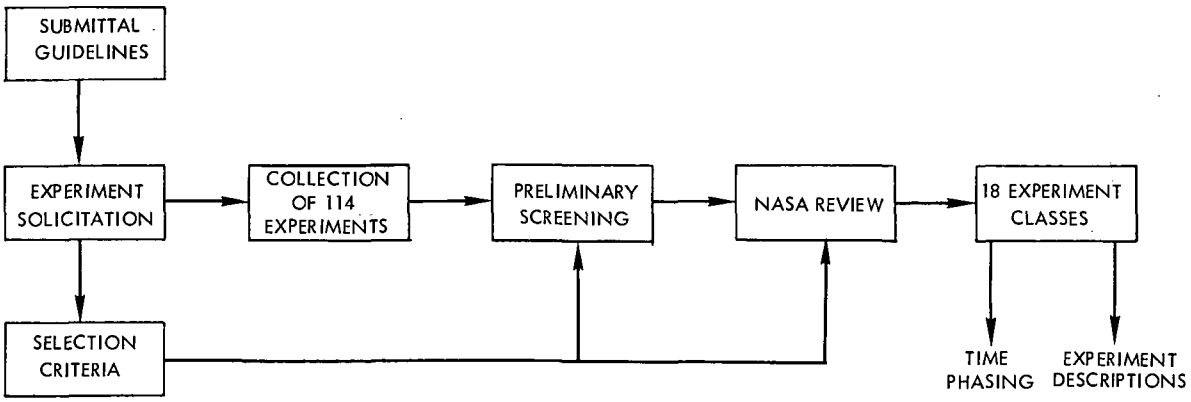



Figure 7. Sequence of Operations in Experiment Selection

The detailed experiment definitions presented herein evolved from the conceptual recommendations derived from the original 114 experiment suggestions submitted by the scientific and technical community. Acknowledgement of these contributions and traceability to the relevant Comm/Nav investigative area are shown in Figure 8.

The 18 candidate experiment classes were further catalogued into four basic, major areas of investigation:

1) Radio frequency interference (RFI)
2) Propagation phenomena
3) Communication techniques and services
4) Navigation methods and demonstrations.

# COMM/NAV CANDIDATE EXPERIMENT SOURCES VS CLASS GROUPING

| EXPERIMENT SOURCES | COMMUNICATION/NAVIGATION RESEARCH LABORATORY STUDY–EXPERIMENT CLASS GROUPING | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | #1 | #2 | #3 | #4 | #5 | #6 | #7 | #8 | #9 | #10 | #11 | #12 | #13 | #14 | #15 | #16 | #17 | | |
| | TERRESTRIAL SOURCES OF NOISE AND INTERFERENCE | SUSCEPTIBILITY OF TERRESTRIAL SYSTEMS TO SATELLITE RADIATION | RF PROPAGATION | OPTICAL FREQUENCY PROPAGATION | PLASMA PROPAGATION | DIRECT BROADCAST DEMONSTRATION | COMMUNICATION RELAY TESTS | ON-BOARD DATA PROCESSING | LASER COMMUNICATION | ELF/VLF ANTENNAS | FIXED MULTIBEAM ANTENNAS | LARGE REFLECTOR DEPLOYMENT | NARROW BEAM TRACKING | R&E NAV/SURVEIL. TECHNIQUES | INTERFEROMETRIC NAVIGATION SURVEILLANCE TECHNIQUES | LANDMARK TRACKING | LASER RANGING | HORIZON ALTITUDE & RADIANCE MEASUREMENT | ELIMINATED DURING SCREENING/SELECTION PHASE |
| **GOVERNMENT** | | | | | | | | | | | | | | | | | | | |
| GODDARD SPACE FLIGHT CENTER (10) | RFI Measurement - V. HENRY (GSFC) H. WEINBERGER (Hughes) | | Millimeter Wave Propagation/Communication - L. IPPOLITO | 10.6 Micron Laser Exp. - N. McAVOY | | Television Relay Using Small Terminals - J. MILLER | Data Relay Exp. - R. PICKARD | | $CO_2$ Laser Sys. Dev. - (RTOP) - N. McAVOY<br>Nd Laser Sys. Dev. - M. FITZMAURICE<br>Neodymium Laser Sys. Dev. - (RTOP) | | Communication Satellite Antenna Research - (RTOP) | | | Position Location & Aircraft Comm. - C. LAUGHLIN | | | | | |
| MARSHALL SPACE FLIGHT CENTER (1) | | | | | | | | | Devel. of an Nd:YAG Laser and Laser Altimeter - RANDALL | | | | | | | | | | |
| LANGLEY SPACE FLIGHT CENTER (1) | | | | | | | | | | | | | | | | | | | Low Acceleration Guidance, Navigation, and Control |
| MANNED SPACECRAFT CENTER (5) | | | High Frequency Channeling Between Ionization Layers Around Earth - J. FOWLER (MSC); M. GROSSI (Raytheon) | | | | | | Near-Earth Laser Comm. System - D. LILLY | | | | | | Radar Attitude Sensing Sys. - J. LAMOREUX<br>Radar Attitude Sensor System - BELL | | | | Long Baseline Radio Astronomy Using Time Base Integration Techniques - H. CUBLEY |
| LANGLEY SPACE FLIGHT CENTER/ NORTH AMERICAN ROCKWELL (1) | | | | | | | | | | | | | | | | | | Horizon (UV & IR) Radiance Profile | |
| ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION (2) | | | Noise and Interference Survey: | | | | | | | | | | | | | | | | Ionospheric Mapping |
| INSTITUTE FOR TELECOMMUNICATION SCIENCES (16) | Origin of Atmospheric Radio Noise - R. DISNEY<br>Interference at Satellite Heights - R. DISNEY<br>Determining the EM Environment of Communication Satellites - D. CROMBIE<br>Satellite Radio Surveillance for Frequency Management - BERGMAN/NEWBERN-SMITH<br>Orbital Power Flux Density Mapping for 100 - 10,000 MHz - R. BERGMAN | | Mapping Tropospheric Radio Ducts - P. RICE<br>Scintillation Observations at VHF/UHF and Microwave Freq. - J. TARY<br>Low Elevation Angle Propagation Tests - G. GIERHART<br>Propagation Char. of the Atmosphere Near the 22 GHz Water Vapor Line - THOMSON<br>Atmospheric Propagation Meas. at 50-75 GHz - LIEBE<br>Spatial and Frequency Coherence of Microwave Signals - D. CROMBIE<br>Phase Synchronization of Remote Oscillators - THOMSON/WOOD<br>Synchronization of Oscillators via Microwave Link - L. WOOD<br>Measuring Tropospheric Characteristics Important to Propagation - P. RICE | | | | | | | | | | | | | | | | ATC Demonstrations and Tests - J. TARY<br>Multiple Frequency Ranging - L. WOOD |
| MITRE CORPORATION (1) | | | | | | | | | | | | Large Passive Array | | | | | | | |
| NATIONAL OCEANIC AND ATMOSPHERIC ADMIN. (1) | | | | | | | | | | | | | | | | | | | Radio Beacon Experiment - K. DAVIES |
| BLUE BOOK VOL. V (13) Jan. -1971 | Terrestrial Noise Measurements<br>Noise Source Identification | Susceptibility of Terrestrial Sources to Satellite-Radiated Energy | Multipath Measurements<br>Tropospheric Propagation Measurements<br>Millimeter Wave Communication System and Propagation Demonstration | | Plasma Propagation Measurement | | Transmitter Breakdown Tests | | Optical Frequency Demonstration | | | | | Surveillance & Search & Rescue Demonstration | | Autonomous Navigation Systems for Space | On-Board Laser Ranging | | Satellite Navigation Techniques for Terrestrial Users |
| **INDUSTRY** | | | | | | | | | | | | | | | | | | | |
| TRW SYSTEMS GROUP (25) | | | Experimental Determination of Max. Bit Rates at VHF and Greater - W. SISCO<br>Propagation Meas. at HF, MF, LF, VLF, and ELF - W. SISCO<br>Pulse Multipath Study - P. KARR<br>Crd Multipath Statistics - J. MALLINCKRODT<br>Multipath Statistical Path Losses - W. SISCO<br>A Possible Method of Alleviating the Interfering Effect of Multipath - P. KARR<br>Depolarization of EM Waves from 0.1-10 GHz - W. SISCO | Atmospheric Effects on Laser Comm. - R. DISHINGTON<br>Laser Beam Uniformity Problems in Space - R. DISHINGTON | | | | On-Board Processing - D. SPENCER<br>Processing Repeater Applications - D. SPENCER<br>Bandwidth Reduction & Error Control Coding - D. SPENCER | Acquisition & Tracking System Exercises - R. DISHINGTON<br>Acquisition & Tracking Parameter Experiments - R. DISHINGTON | Feasibility Long Wire Antennas at VLF - W. SISCO<br>ELF Propagation from within ionosphere - J. MALLINCKRODT | Frequency Reuse and Multiple Shaped Beam Antenna - GALINDO/IMBRIALE<br>Multiple Feed Reflector Antenna - J. DUNCAN<br>Multiple Shaped-Beam Antenna - DUNCAN/GALINDO<br>High Gain Multiple Beam Antenna System J. DUNCAN | | Low Sidelobe Millimeter Wavelength Ant. - J. DUNCAN | | | | Unknown Landmark Tracking J. WILLIAMS<br>Automatic Landmark Tracking Techniques & Sensors | | Horizon Altitude Uncertainty - J. WILLIAMS | Ionospheric Medium Scale Structure - J. MALLINCKRODT |
| McDONNELL-DOUGLAS ASTRONAUTICS (3) | | | | | | | Wideband-Narrow-beam Ant. Acq. and Track - E. PFARR | | | | | | | | | Unknown Landmark Availability Study - R. SEIBERT | | | Low-G Accelerometer Calibration - R. SEIBERT |
| COMSAT CORPORATION (11) | | | Extended Propagation Measurements - D. LIPKE<br>Polarization Perf. of RF Transmission Systems: 2-30 GHz - POLLACK/HYDE<br>Channel Coherent Bandwidth Determination - J. CAMPANELLA | Laser Comm. Transponder - POLLACK/HYDE/BERMAN | | Direct Broadcast Demonstration - D. LIPKE<br>Radio Direct Broadcast - BRISKMAN | | | | | Multiple-Beam Ant. Configuration - LIPKE<br>Phased-Array Ant. R. KREUTEL | | | | Radio Interferometer Position Location - F. KLEIN (Co-Sponsored by U. of Pa.) | | | | Extra Terrestrial Comm. - R. D. BRISKMAN<br>Quasi-Transverse Faraday Effect - J. BEYER |
| BELL LABORATORIES (4) | | | | Evaluation of Transmission Channel for Digital Comm. - T. KINSEL | | | | | Optical PCM Comm. Exp. - T. KINSEL<br>Optical PCM Error Rate Exp. - T. KINSEL | | | | | | | | Precision Ranging Exp. - T. KINSEL | | |
| HONEYWELL (1) | | | | | | | | | | | | | | | | | | | Electrostatic Gyro (ESG) |
| RAYTHEON/ WRIGHT PATTERSON AFB (1) | | | HF/VHF Guided Propagation in the Lower Atmosphere - J. BARKER/M. GROSSI | | | | | | | | | | | | | | | | |
| HUGHES AIRCRAFT (2) | | | | | | High Power, 12 GHz Transmitter - R. WALP | | | Laser Space Comm. Exp. - GOODWIN | | | | | | | | | | |
| GENERAL ELECTRIC SPACE SYSTEMS (1) | | | | | | | | | | | | | | | | Autonomous Navigation Using Coherent Optical Filter Techniques - J. WELCH | | | |
| WESTINGHOUSE SPACE SYSTEMS (2) | | | | | | | Low-Noise 60 GHz Parametric Amplifier - DICKENS | | | | | | | | Interferometric Nav. Tech. - TANKERSLEY | | | | |
| RADIATION SYSTEMS (1) | | | | | | | | | | | | Ku-Band Unfurlable Ant. | | | | | | | |
| NATIONAL SCIENTIFIC LABS (1) | Man-Made Noise Experiment - J. KELLEHER | | | | | | | | | | | | | | | | | | |
| FAIRCHILD HILLER CORP. (1) | | | | | | | | | | | Multiple-Shaped Beam Antenna - H. WARD | | | | | | | | |
| IBM (1) | | | | | | | | | | | | | | | Interferometer Pos. Location - TSITSERA | | | | |
| **UNIVERSITY** | | | | | | | | | | | | | | | | | | | |
| UNIV. OF ILLINOIS (2) | | | | | | | | | | | | | | | | | | | Ion Density Measurements - WEBB<br>Ion Mass Spectra in the Ionospheric E&F Regions - A. DIPERT |
| UNIV. OF PENNSYLVANIA (1) | | | | | | | | | | | | | | | Terrestrial Nav. Tech. Employing a Satellite-Borne Spinning Interferometer - F. HABER | | | | |
| UNIV. OF HOUSTON (3) | | | | | | Amateur Radio Comm. - LINDSEY | | | | | | | | | | | | | Low Frequency Sounding - LINDSEY<br>Medium & High Frequency Radio Astronomy - LINDSEY |
| MASSACHUSETTS INST. OF TECH. (1) | | | | | | | | | | | | | | | | | | | Ejected Satellite Navigation |
| STANFORD UNIVERSITY (1) | | | Microwave Occultation Exp. - LUSIGMAN | | | | | | | | | | | | | | | | |
| **INTERNATIONAL** | | | | | | | | | | | | | | | | | | | |
| HAWKER-SIDDELEY DYNAMICS (1) | | | Atmospheric Attenuation Measurements | | | | | | | | | | | | | | | | |

Figure 8

The first two areas are concerned with measurements relating to the natural environment, while the last two are devoted to measurements associated with demonstrating and testing hardware components and systems. The areas and classes were selected to facilitate the inclusion of new experiments as these are identified and justified.

The 18 experiment classes within these four areas comprise the framework for the Communication/Navigation Research Laboratory experiment program. A point experiment in each of the 18 areas was developed to provide a basis for defining laboratory equipment (see Volume III). The detailed experiment definitions also establish the specific implementation baseline by which the required research and technology investigations for reach of the 18 experiment classes will be pursued.

The grouping by title of the 18 experiment classes within these four areas is shown in Figures 9 and 10.

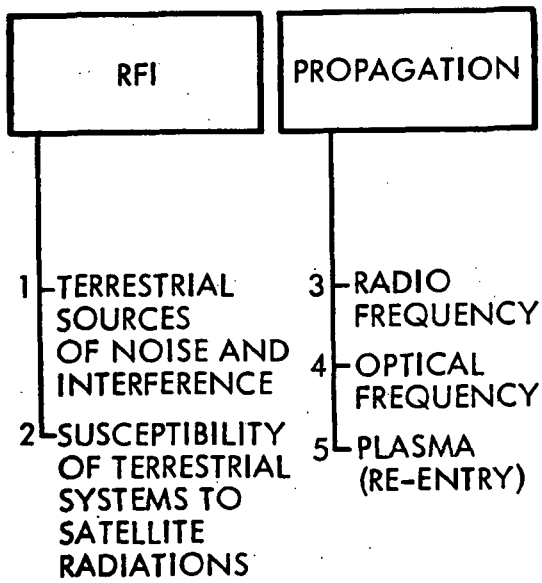



Figure 9. Measurements Related to Natural Environment

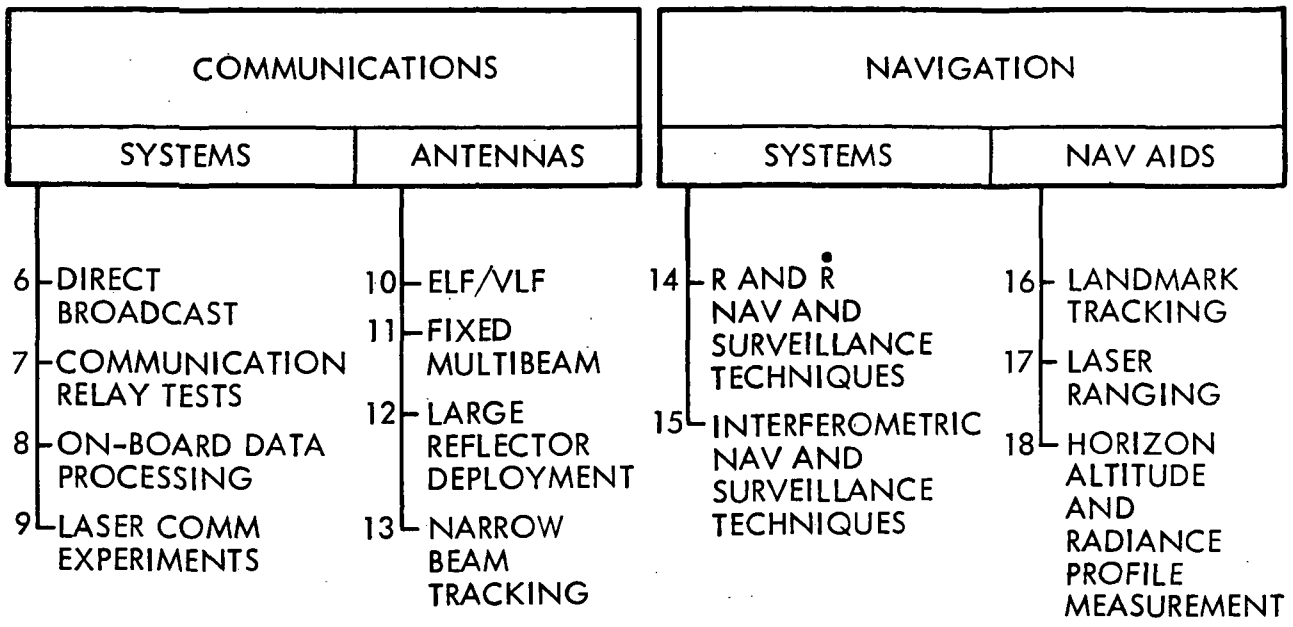



Figure 10. Measurements Related to Demonstration and Test of Comm/Nav Hardware

## D. EXPERIMENT SELECTION CRITERIA FOR THE EARLY LABORATORY

The development of criteria for selecting experiments for the Early Laboratory involves considerable subjective judgement. Program goals and mission constraints are important inputs to criteria definition. Certain criteria (usefulness, timeliness, cost-effectivity) are obviously desirable features for any project. However, there are several aspects of the Sortie laboratory concept which are also of considerable interest.

Shuttle sortie missions, unlike an automated spacecraft mission, are constrained in two key areas: orbital altitude and flight duration. Most of the experiment classes can be structured to exploit the low altitude advantages, but the short mission duration means some experiments will need more than one flight.

One method of minimizing laboratory costs is to select experiments which have a high degree of experiment commonality. While this criteria was not considered as important as usefulness or timeliness, it was evident in the selection of a common frequency regime (UHF) for the terrestrial noise and RF propagation experiments.

The shuttle-supported manned laboratory represents an experiment base in space which is unique. Early experiments should exploit this new

capability, not only to demonstrate its value, but to point the way for future development. The interferometer navigation experiment, for example, requires deployment of a large antenna boom. It requires that this antenna geometry be maintained constant to a high order of precision. It requires, as do the other selected experiments, a fair amount of astronaut participation to insure the successful conduct of the experiment.

In summary, the criteria applied in selecting a candidate experiment payload for the Early laboratory include:

1) Usefulness in solving technological problems related to projected spacecraft Comm/Nav systems

2) Timeliness with respect to other on-going experiment programs and the urgency of the user application needs

3) Cost effectiveness in comparison with accomplishing the objective with an unmanned automated spacecraft experiment

4) Experiment duration – expectation of attaining the objective within the nominal 7-day sortie mission duration.

## E. EXPERIMENT RANKING

Figure 11 summarizes one quantitative approach to evaluating the 18 experiment classes with respect to the criteria developed in the previous section. Each class is graded in a 5-highest, 1-lowest relative ranking in each of the categories. The point total is used in prioritizing the experiments.

Other aspects of time phasing are those associated with inter-experiment priorities, and the escalation of complexity within an experiment, or experiment group. A sequence of experiments can be phased by gradually adding, to equipment used to perform one particular measurement, other equipments required to perform similar or related measurements. Noise source receivers, recorders and analyzers selected for tests in the VHF/UHF band, for example, can be supplemented with receivers for measurements in the microwave or millimeter-wave regions. Transmitters/receivers can be used with added multibeam antennas to perform detailed antenna evaluations and, in turn, the millimeter-wave equipment used for communication relay tests, and so on.

| EXPERIMENT CLASS | EXPERIMENT TITLE | RELATIVE RANKING | | | | | |
|---|---|---|---|---|---|---|---|
| | | USEFULNESS | TIMELINESS | COST EFFECTIVENESS | EXPERIMENT DURATION | POINT TOTAL | PRIORITY RANKING |
| 1 | TERRESTRIAL SOURCES | 5 | 5 | 5 | 3 | 18 | 1* |
| 2 | SUSCEPTIBILITY OF TERR. SOURCES | 3 | 3 | 2 | 3 | 11 | 10 |
| 3 | RF PROPAGATION | 5 | 5 | 5 | 3 | 18 | 2* |
| 4 | OPTICAL PROPAGATION | 3 | 3 | 2 | 2 | 10 | 15 |
| 5 | PLASMA PROPAGATION | 4 | 3 | 2 | 3 | 12 | 9 |
| 6 | DIRECT BROADCAST | 2 | 3 | 2 | 2 | 9 | 16 |
| 7 | COMMUNICATION RELAY | 4 | 4 | 2 | 3 | 13 | 7* |
| 8 | DATA PROCESSING | 3 | 3 | 3 | 2 | 11 | 12 |
| 9 | LASER COMMUNICATIONS | 5 | 4 | 3 | 3 | 15 | 4* |
| 10 | ELF/VLF ANTENNA | 1 | 2 | 3 | 2 | 8 | 18 |
| 11 | MULTIBEAM ANTENNA | 4 | 4 | 4 | 4 | 16 | 3* |
| 12 | LARGE REFLECTOR | 1 | 2 | 4 | 2 | 9 | 17 |
| 13 | NARROW BEAM TRACKING | 4 | 3 | 2 | 3 | 12 | 8 |
| 14 | R&R NAVIGATION & SURVEILLANCE | 3 | 3 | 3 | 2 | 11 | 11 |
| 15 | INTERFEROMETER NAVIGATION | 4 | 4 | 4 | 3 | 15 | 5* |
| 16 | LANDMARK TRACKING | 3 | 4 | 4 | 3 | 14 | 6* |
| 17 | LASER RANGING | 4 | 2 | 2 | 2 | 10 | 14 |
| 18 | HORIZON RADIANCE PROFILE | 3 | 3 | 2 | 2 | 10 | 13 |

* Early Laboratory Selected Payload

Figure 11. Experiment Prioritization – Early Laboratory

A gradual evolution of general purpose test equipment applicable to a wide variety of experiments can thus be economically achieved. Figure 12 illustrates this concept applied to the 18 Comm/Nav investigative areas.

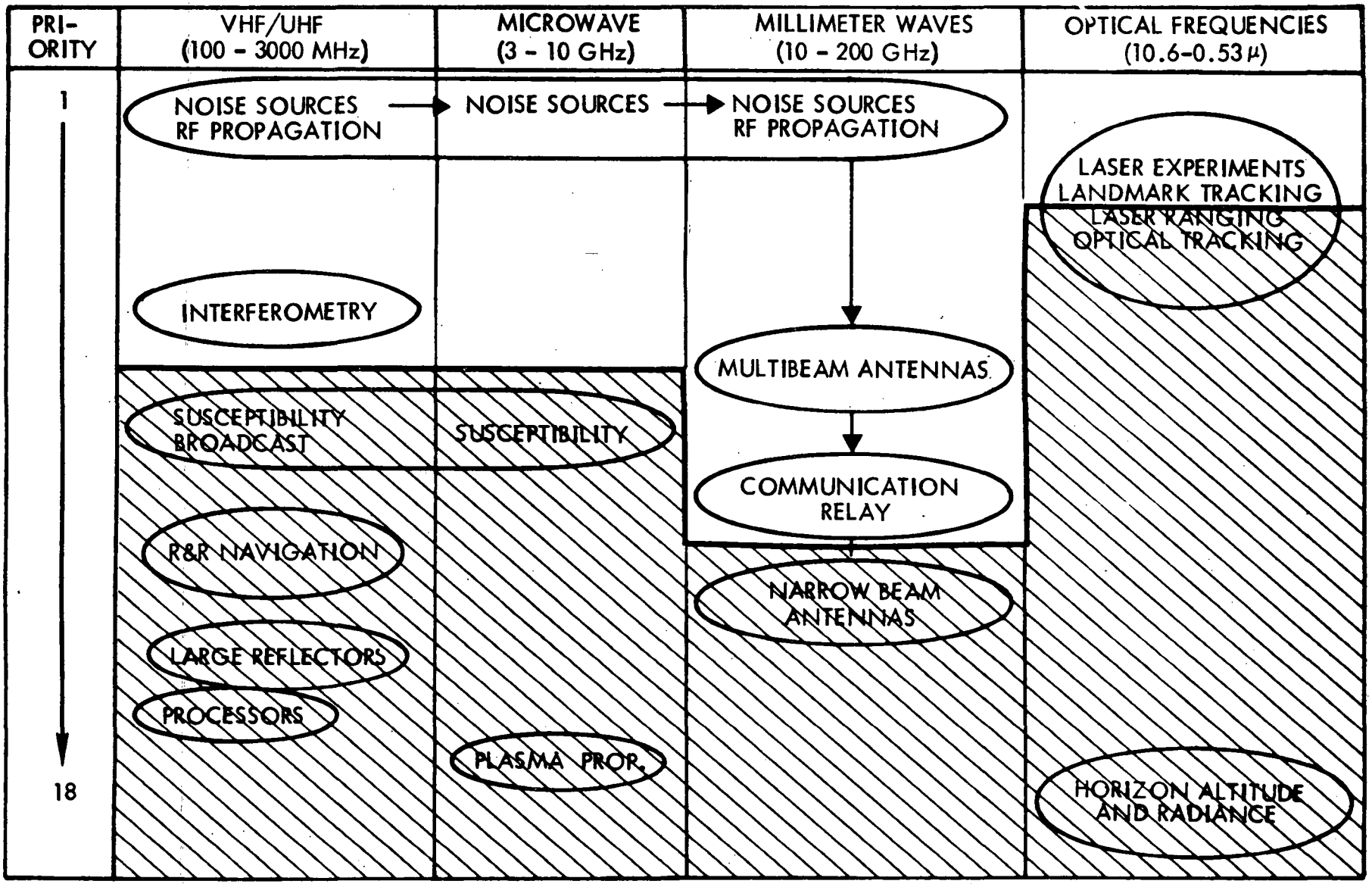
Beyond the initial screening of experiments as candidates for implementation in the Comm/Nav facility, it was essential to evaluate the relationship of each experiment to operational system growth requirements. This, in turn, leads to a clear identification of the supporting data or techniques required before operational capability can be established.

The projected state-of-the-art of components was also considered in deriving the relative time phasing of experiments in order to determine the required supporting research and technology (SR&T) needs. These are discussed in Section 3.8 of Volume III.

Finally, after iteration with the original requirements to determine if alternate approaches are feasible where state-of-the-art techniques are impractical, the availability of platforms for early limited testing was considered. These platforms include aircraft (CV-990 Program), SATS, ATS-F & G, and possibly Skylab B.

The sequence of operations involved in applying the methodology outlined above is illustrated in Figure 13.

Using the basic criteria of usefulness, timeliness, cost effectiveness, advantages for crew participation, ability to accomplish experiment objectives on short duration missions, and expected commonality of equipment, the 18 experiment classes were subjected to a quantitative analysis for priority rating and assignment to Early, Growth, and Total Laboratory flights. Results of this exercise indicated that, for the purposes of laboratory configuration design and equipment layout and mission planning, the following could be representative of experiment class placement:




7 Candidate Experiments for Early Sortie Can Missions

Remainder of 11 Comm/Nav Investigative Areas

Figure 12. Experiment Phasing

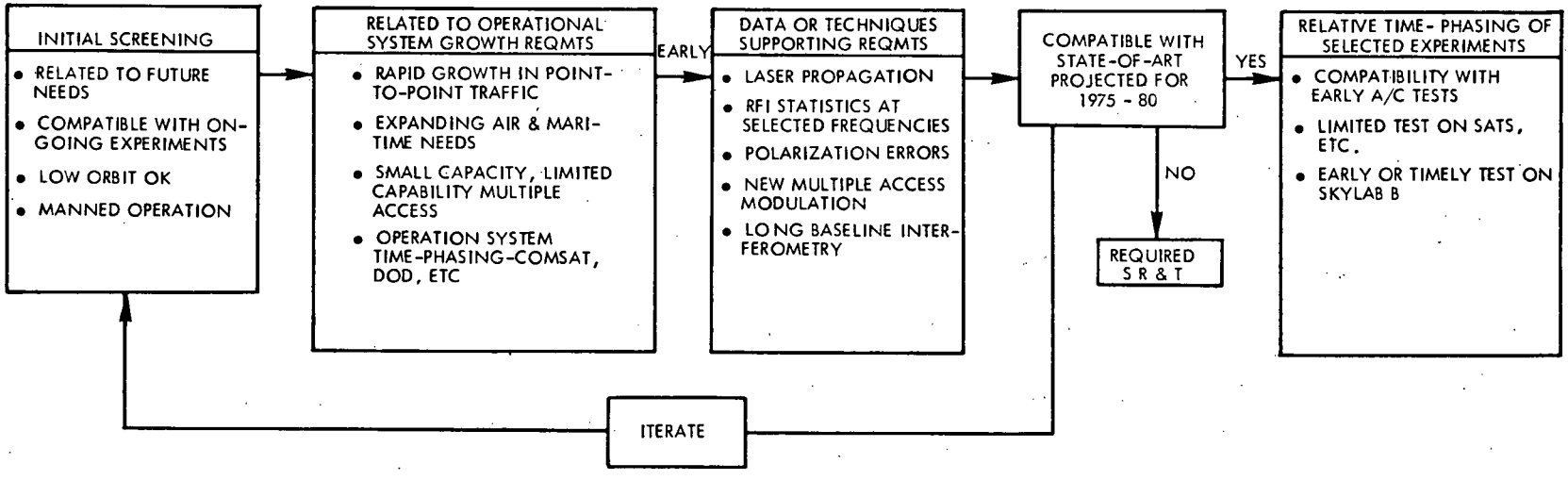



Figure 13. Experiment Time Phasing Criteria and Screening

Experiment Class Time Phasing.

Early Lab (1980 - 1985 Missions) Experiment Classes

- Terrestrial Sources of RF Noise and Interference
- Radio Frequency Propagation
- Communication Relay
- Laser Communication
- Fixed Multibeam Antenna
- Interferometric Navigation and Surveillance Techniques
- Landmark Tracking

Growth Lab (1985 - 1990 Missions) Experiment Classes

Above Early Lab Experiment Classes plus:

- Susceptibility of Terrestrial Systems to Satellite Radiation
- Plasma Propagation
- On-Board Data Processing
- Narrow Beam Tracking
- Range and Range Rate Navigation and Surveillance Techniques
- Horizon Altitude and Radiance Profile Measurement

Total Lab (1990 Missions) Experiment Classes

Above Early and Growth Lab Experiment Classes plus:

- Optical Propagation
- Direct Broadcast
- ELF/VLF Antenna
- Large Reflector Deployment
- Laser Ranging

The selected Early Laboratory experiments are well suited for low-orbit missions. The measurement of terrestrial RFI, for example, is enhanced because of high receiver sensitivity (proximity to earth), the ability to localize sources of interference, and the capability to perform sequential area mapping on a global basis.

Similar remarks pertain to the RF Propagation experiment where multipath phenomena can be measured over varying terrains and elevation angles.

Laser experiments are expedited by the presence of man who can align, adjust, change filters, evaluate performance, etc. and, thereby, perform a large number of related experiments not possible in automated spacecraft.

The equipment required for the performance of these experiments could be used for other experiments with minor modification. For example, the Landmark Tracking experiments can be conveniently performed using portions of the Laser Communications equipment, such as the telescope optical system. This equipment could also be used for Laser Ranging tests.

The derived results from the selected experiments would be useful in solving the most urgent problems relating to many of the projected Comm/Nav systems.

## F. ALTERNATIVE PAYLOADS

In general, the selection of experiments for each of the three laboratory versions was based on a priority rating with the seven highest ranking experiments assigned to the Early Laboratory. Therefore, the experiments associated with the Growth Laboratory may be considered as first alternatives for inclusion in the Early Laboratory.

These alternatives can be used in a variety of ways to supplement and enhance the possibilities of the selected payload group. Three specific possibilities are:

1) Substitution for a selected payload in the event that priorities change or unexpected difficulties arise with the selected experiment, etc.

2) Added to early flight program, expanding the scope of measurements and complexity of equipment payload.

3) Pursued in a serial manner, and considered as a Phase II block, to be added as their separate development (SR&T results) allow and flight schedules permit.

Clearly, the way in which we combine these experiments must hinge on the progress attained in the several related SR&T tasks and, in particular, the difficulties encountered in translating the various commercial equipment designs to a space laboratory compatible form.

# APPENDIX I

# EXPERIMENT SOLICITATION DATA PACKAGE

TRW

8 June 1971

Attention: (Letter Addressed to Interested Individuals, Agencies, Universities, and Industrial Firms)

Subject: Invitation to Submit Candidate Experiments for a Future Manned Space Flight Communications/Navigation Research Laboratory

In support of NASA plans for future manned shuttle/space station activities, the George C. Marshall Space Flight Center, Huntsville, Alabama, has contractually engaged TRW Systems Group to develop conceptual designs for a manned communications/navigation research laboratory. The objective of this study is to conceive laboratory designs capable of supporting a wide variety of experiments leading to the application of space technology to advanced operational systems of direct benefit to mankind. Anticipated operational systems include those planned for multiple access communications, data collection, data relay, direct broadcast TV, and information networking as well as for satellite navigation techniques for terrestrial users, surveillance, search and rescue, air traffic control, position fixing, collision avoidance, and autonomous navigation. The time assumed for an "Initial Operational Capability" of the laboratory is 1980 although interim demonstration of selected experiments and experimental techniques aboard balloon, aircraft and automated (unmanned) satellites are also being considered.

The purpose of the first task of this study is to define applicable experiments and experiment requirements which would take full advantage of man-tended laboratory facilities in low earth orbit to provide useful information concerning needed technological developments in the communications/navigation field. United States and foreign industrial firms, government agencies, and various university communities are being requested to participate in this experiment selection process in order to insure broadly based scientific and engineering contributions to the program objectives.

Individuals and agencies interested in participating in the experiment selection process are encouraged to submit a one-page form (sample attached) for each recommended experiment. A set of reference communications/navigation investigations (NASA "Blue Book," January 15, 1971) is also attached for guidance. Information and reports already published concerning recommended space experiments or technology studies which may lead to such experiments would be most helpful and acceptable in their original form.

The "Principal Investigator" or originator of each recommended experiment, and his associated agency, will be identified with the experiment (see attached form) and may be requested to participate further in later developmental phases of the program. In any event, participants will be sent the list of experiments approved by NASA.

Submittals should be directed to:

TRW Systems Group
One Space Park
Redondo Beach, Calif. 90278
Attention: Dr. R. Y. Huang
Bldg. R6, Room 1587

and should be mailed in time to be delivered to Dr. Huang by 12 July 1971.

TRW Inc.

Jack Kliger

Jack Kliger
Project Office
Comm/Nav Research Lab Study
Space Vehicles Division
TRW Systems Group

JK:we

Attachments:

1) Project Summary
2) C/N RL Candidate Experiment Form
3) Reference Earth Orbital Research and Applications Investigations (Blue Book), Volume V - Communications/Navigation National Aeronautics and Space Administration, January 15, 1971

ATTACHMENT NO. 1

PROJECT TITLE: DEFINITION OF EXPERIMENTS AND INSTRUMENTS FOR A COMMUNICATION/NAVIGATION RESEARCH LABORATORY

## PROJECT SUMMARY

**Purpose:**

Study to develop conceptual designs for a manned communications/navigation research laboratory capable of supporting a wide variety of experiments in the field of communications and navigation.

**Cognizant Agency:**

NASA/Marshall Space Flight Center
Program Development Division
COR: Mr. Charles Quantock
Alternate COR: Mr. Harry Craft

NASA Headquarters Representation:
Gene Ehrlich, OSSA
William Miller, OMSF
John Hammersmith, OMSF

NASA/GSFC Representation: John Flaherty

**Contract Details:**

$300,000, Phase A, Study
FFP, 10 months duration,
Start date 14 June 1971

**Prime Contractor:**

TRW Systems Group
Space Vehicles Division (G. A. Harter, Gen. Mgr.)
Project Management: Don Waltz/Jack Kliger of SVD Advanced Systems (C. D. Graves, Mgr.)

**Subcontractors to TRW:**

- McDonnell Douglas Astronautics Company
- Communications Satellite Corporation (COMSAT)
- Institute for Telecommunication Science

**Consultants to TRW:**

Dr. Robert A. Helliwell, Stanford University
Dr. Albert J. Mallinckrodt, Communications Research Laboratory, Santa Ana, Calif.

**Study Tasks:**

- Define communications and navigation experiments and experiment requirements.
- Identify major laboratory and experiment equipment and instrumentation.
- Develop conceptual designs of major laboratory and experiment equipment and instrumentation.
- Perform systems operations analysis in support of the communications/navigation research laboratory design.
- Develop conceptual designs of the communications/navigation research laboratory.
- Develop cost, schedule and SRT requirements.

ATTACHMENT NO. 2

EXAMPLE OF COMPLETED EXPERIMENT FORM

COMMUNICATION/NAVIGATION RESEARCH LABORATORY CANDIDATE EXPERIMENT

Experiment Title:

Acquisition and Tracking Parameter Experiments for Laser Communication Systems.

Principal Investigator (Originator):

R. Dishington

Principal Investigator Association:

TRW Systems Group

Experiment Objectives/Description:

Introduction: A list of major problem areas in laser acquisition and tracking systems must include:

a. Pointing and control
b. Lock-on and tracking
c. Point ahead
d. Background
e. Atmospheric Effects
f. Beam Uniformity
g. Doppler Shift

The first three items are described in this experiment. The others are either proposed separately or are adequately investigated in other ways.

1. Pointing and Control

Objective: To make a near absolute measurement of the accuracy of competing pointing and control systems of the high precision required for initial acquisition in the optical communication mission.

Description: The laboratory will be equipped with a standard pointing and control system having a $3\sigma$ accuracy of 50 to 100$\mu$ radians. This standard will employ a precision attitude determination system of the "stellar updated inertial" type such as the TRW "PADS" or the Lockheed/Honeywell "SPARS", ground determined ephemeris data, and a high accuracy remote gimbal alignment sensor system to point a dummy telescope package including realistic heat loads, etc.

The performance of various competing operational type pointing and control systems will be measured using the above standard system as a basis for comparison. Evaluations will be made for particular sets of orbital and other operational constraints. It is anticipated that tests will include both intermediate accuracy (350 - 1000μ radian) systems of the earth sensor type as well as the more sophisticated systems.

2. Lock-On and Tracking

Objective: To evaluate the effectiveness and reliability of the stepped field-of-view lock-on sequence employed by the typical laser communication system, with particular reference to problems of "hand-over" from coarse to fine error signal sensor.

Description: The gimballed telescope package employed above will be equipped with a prototype set of lock-on and tracking sequence optics and sensors, and the package will be exercised using stars and ground beacons. Simulate marginal signal-noise ratios with optical attenuators placed in telescope optical chain.

3. Point Ahead

Objective: To first establish that a lead angle between the tracking line of sight and the laser transmitter beam can be set in with the required accuracy, and second to this, determine the accuracy with which this point ahead correction can be made in a test involving ephemeris data and a real target point.

Description: These tests employ a simple, narrowbeam instrumentation laser. The first test uses two stars to represent the set in point ahead angle and compares the image position of one of these to the laser beam position through the built-in boresight optics.

The second, and most difficult test, involves an instrumented target point, such as a high altitude ground station or balloon, and nutation and modulation on the laser beam.

What Comm/Nav Services Will the Experiment Support?:

Space Data Relay Satellite

Proposed Experiment Schedule (Year):

As soon as possible

References and Bibliography:


1. "An Integrated System for Precision Attitude Determination and Control", A.M.Frew, D. K. Kirby, and P. C. Wheeler of TRW Systems and T. C. Huber of NASA Goddard Space Flight Center. AIAA 1971 Guidance, Control and Flight Mechnaics Conference.

2. "SPARS, Space Precision Attitude Reference System," Lockheed/ Honeywell/Control Data papers for the Symposium on Spacecraft Attitude Determination, 30 September 1969.

3. "Program 777's Control System Pointing Accuracy Analysis," TRW 777-F2-265 April 6, 1970 (U)

4. "Space Data Relay Subsystem - Laser Communication Preliminary Subsystem Design" TRW No. 20088, March 1971.

5. "Optical Components and Technology in Laser Space Communications Systems", C. McIntyre, W. M. Peters, C. Chi and H. F. Wischnia, Proc. IEEE, Vol. 58, pp 1491 - 1503, October 1970.

6. "Deep Space Communication and Navigation Study," Volume II, Bell Telephone Laboratoreis, 1 May 1968.

# APPENDIX II

## EXPERIMENT DESCRIPTIONS

Experiment definition detail for each of 18 experiment classes comprising the candidate Comm/Nav experiment program is provided in this section. The chart below illustrates the grouping of the experiments into four major investigative areas:

1) Radio Frequency Interference

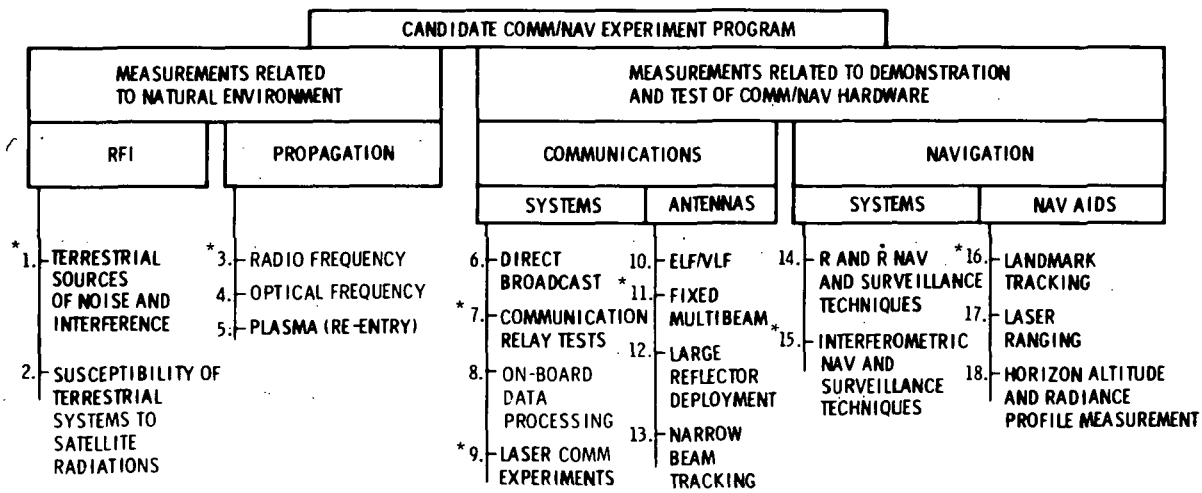
2) Propagation

3) Communications

4) Navigation.

The first two areas include measurements related to the natural environment and are primarily research/technology-oriented. The latter two include measurements related to demonstration and test of hardware components and systems and are application-oriented categories.

INVESTIGATIVE AREA GROUPING




* CANDIDATE EXPERIMENT - EARLY LABORATORY (SORTIE CAN MISSION)

The 18 experiment descriptions, identified by number and title on the chart, are presented in numerical order. Those experiments recommended for early implementation on Shuttle Sortie Can missions are flagged with an asterisk.

## EXPERIMENT DESCRIPTION AUTHORS

The 18 Communication/Navigation Experiment Classes described herein were written by the following TRW personnel:

| Author | Experiment Class |
|---|---|
| Stanley P. Clarke | • Terrestrial RF Sources of Noise and Interference |
| | • Susceptibility of Terrestrial Systems to Satellite Radiation |
| | • Radio Frequency Propagation |
| | • Plasma Propagation |
| | • Direct Broadcast |
| | • On-Board Data Processing |
| James E. Mackey | • ELF/VLF Ionospheric Radiation |
| | • Fixed Multibeam |
| | • Large Reflector Deployment |
| | • Narrow Beam Tracking |
| Wayne A. Massey | • Optical Frequency Propagation |
| | • Laser Communications |
| | • Laser Ranging |
| I. Joseph Williams | • Landmark Tracking |
| | • Horizon Altitude and Radiance Profile Measurement |
| David Brown | • Range and Range Rate Navigation and Surveillance Techniques |
| | • Interferometric Navigation and Surveillance Techniques |
| Geoffrey J. Bonelle | • Communication Relay Tests |

# EXPERIMENT 1

# TERRESTRIAL RF SOURCES

# OF

# NOISE AND INTERFERENCE

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APPENDIX A

APPENDIX B

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# 1. TERRESTRIAL RF SOURCES OF NOISE AND INTERFERENCE

## 1.1 EXPERIMENT CLASSIFICATION

Pursuit of this experiment will involve three phases of space activity. The first is concerned with demonstrating that useful and reliable data pertaining to terrestrial noise level and interference sources can be collected from a low orbit space laboratory. The second phase involves perfecting the collection technique and automating the procedure based on practical experience of its operation in space.

As the instrumentation system is perfected and the results of SRT are embodied, the frequency coverage will be extended from the VHF-UHF region to the microwave and millimeter wave portions of the spectrum.

The final step involves demonstrating, documenting, and supervising a sophisticated data gathering system as a service, and defining its transfer to an unmanned satellite, manned satellite, or assigning the function to the Total Laboratory. The classifications are therefore as follows:

a) Applied research and testing (Early Lab)

b) Development operation (Growth Lab)

c) Operation (Total Lab).

## 1.2 EXPERIMENT OBJECTIVES

The general objective of this experiment is to derive statistically valid data on the spatial and frequency domain distribution of terrestrial noise and terrestrial interference sources as a function of the time of day and season of the year. Initial measurements will be made in the VHF-UHF range from 100 to 1000 MHz.

The program benefits accruing to U.S. communication and navigation activities will be:

a) Permit optimal choice of Comm/Nav frequency assignments, power levels, and modulation schemes.

b) Establish the general levels of unnecessary spaceward radiation produced by terrestrial transmitters.

c) Facilitate technological improvements and legislation to control spaceward radiation patterns and levels.

d) Identify preferred ground sites for space-ground link stations.

e) Enhance fundamental understanding of terrestrial surface reflection of deep space noise sources.

f) Obtain statistics for mobile sources such as aircraft, vessels and wheeled vehicles.

g) Establish criteria for spacecraft antennas to optimize their coverage versus noise and interference immunity.

h) Determine whether a permanent synchronous orbit space spectrum monitoring service (orbital FCC) is desirable and, if so, define its role.

The knowledge gained by pursuing this research will permit more efficient use of the spectrum, will aid in establishing frequency allocations and system standards, and will place the United States in an informed position regarding negotiations for international frequency allocations.

## 1.3 DISCIPLINE BACKGROUND AND STATUS

Data on the levels of terrestrial noise and interference experienced in space have already been evaluated, but only to a limited degree, by a combination of aircraft flights and satellites. While aircraft flights provide useful, high spatial resolution data for small geographic areas, their low altitude ceiling makes this a prohibitively costly means of collection data on a national basis. Most of the satellite-based measurements have been associated with classified military defense programs and the resulting data is not available for civil applications.

Unclassified high quality electronic equipment designed for the type of measurements proposed is readily available from commercial sources.

## 1.4 EXPERIMENT DESCRIPTION

### 1.4.1 Technique

A pictorial sketch of the proposed experiment implementation concept is shown in Figure 1-1. A receiver in the orbiting laboratory sweeps across the frequency band of interest while an associated magnetic tape recorder stores the power density seen. The sweep rate is limited by the reduction in sensitivity, and increase in effective bandwidth which occur when the sweep rate exceeds a critical value, derived in Appendix A.

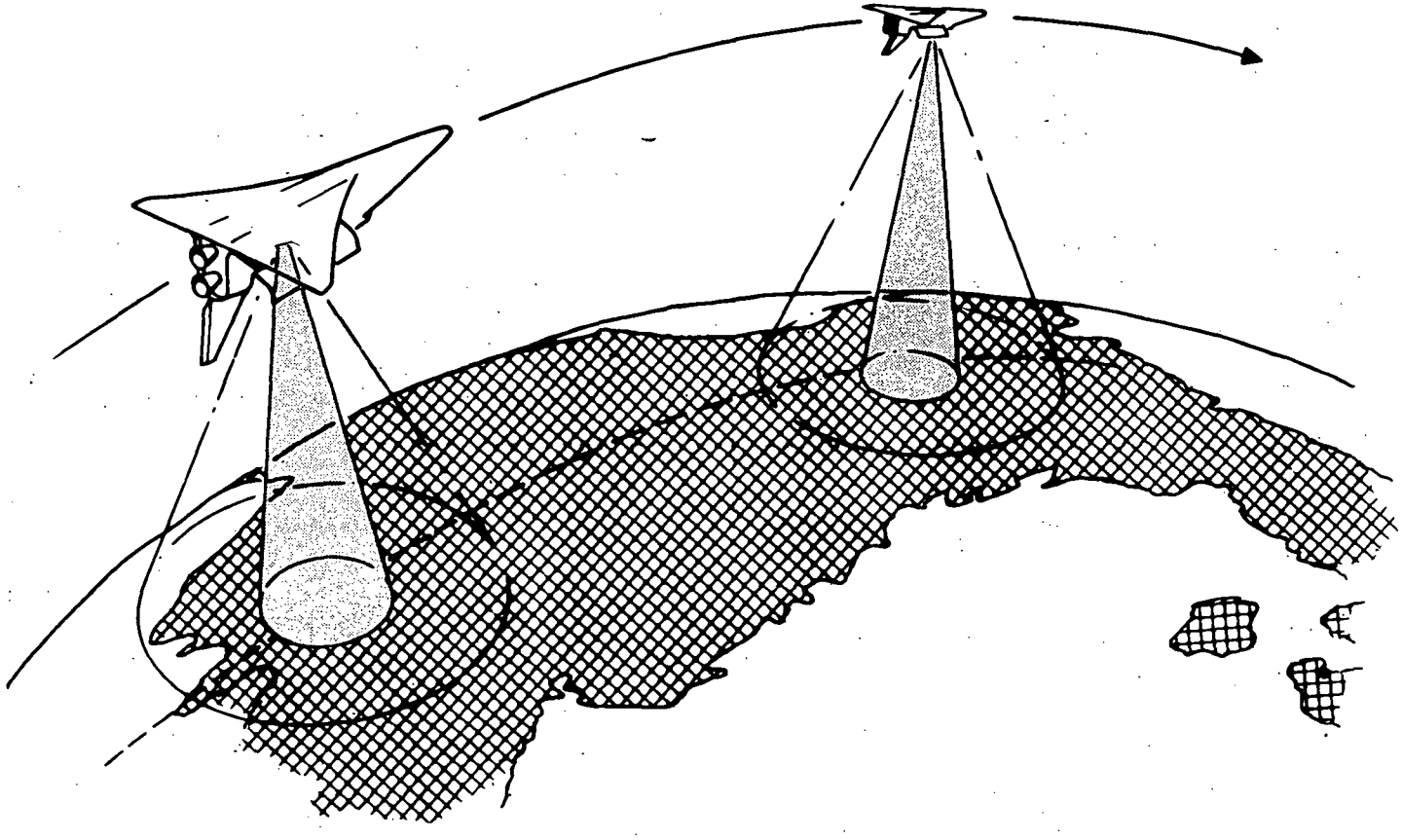

Figure 1-1. Measurement of Terrestrial RF Sources of Noise and Interference

Functional block diagrams of the electronic equipment required to configure the experiment are given in Figures 1-2 and 1-3. The first figure describes the communication equipment and the latter covers the information processing subsystem.

### 1.4.2 Visibility

The visibility time is a function of both the orbit and the selected antenna pattern. The maximum viewing time for any target occurs when that target lies on the laboratory subtrack, and is approximately six minutes for a 200 n. mi. orbit. Signals close to the horizon experience multipath degradation. In general, viewing angles of under 10 degrees are not considered reliable. The maximum slant range distance for a 200 n. mi. orbit altitude, assuming a 10 degree cut-off angle, is about 730 n. mi. The geometric analysis used in deriving visibility time and slant range is given in Appendix B.

### 1.4.3 Features

- Log periodic or helical antenna looks towards earth collecting signals over frequency range of interest.
- Synthesizer receiver sweeps spectrum by stepping 100-1000 MHz and derives power density versus frequency.
- Video display facilitates astronaut-experimenter identification of potentially interesting signals or spectral regions.
- Supplementary signal analysis receiver under control of experimenter has marker on spectrum analyzer which can be tuned to embrace signal of interest.
- 35 mm film camera attached to video display allows experimenter to obtain film record as well as other displays in the field of view (FOV).
- Manual control keyboard allows experimenter to establish start, stop and increment frequencies and dwell time.
- Output from sweep receiver recorded on magnetic tape unit. Test conditions from data header.
- Signal analysis receiver has multiple parallel detectors for AM, FM, SSB, PSK, FSK feeding operator speaker, phones, and CRT.

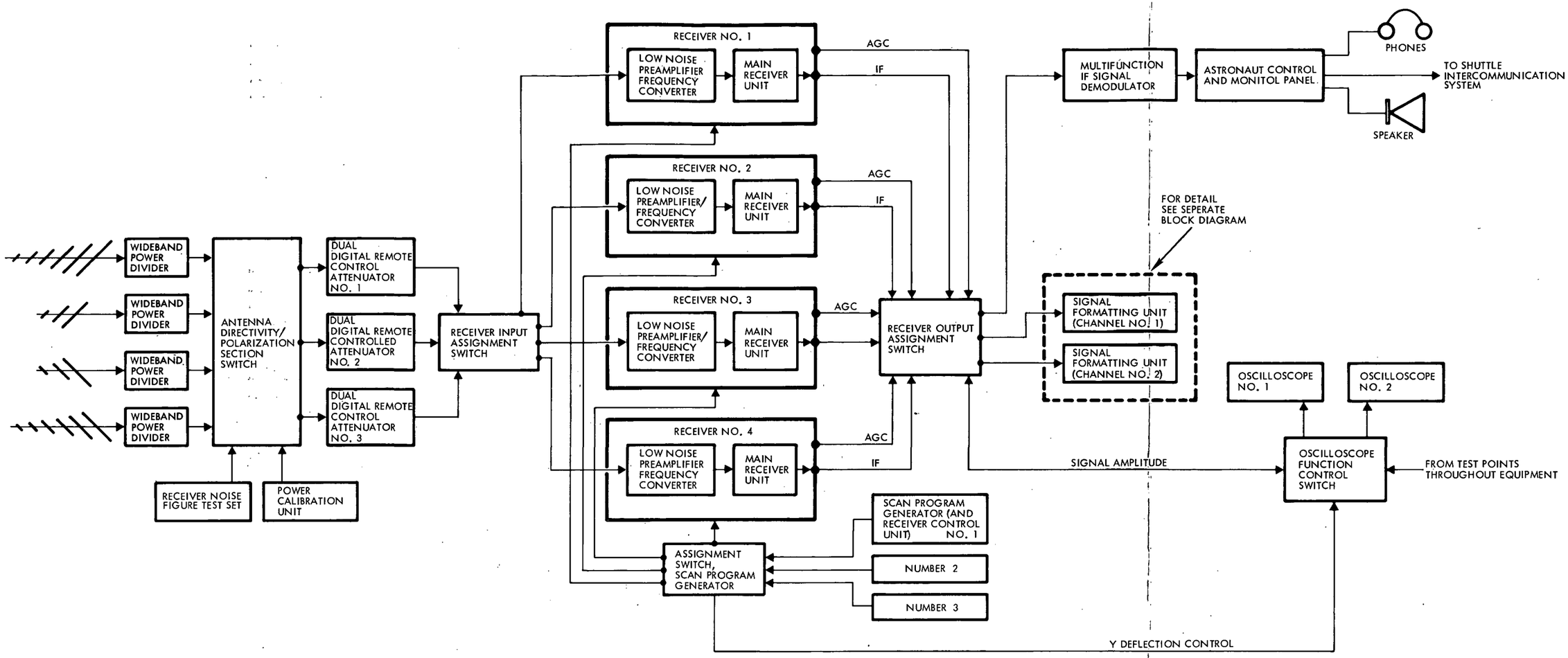


Figure 1-2. Functional Block Diagram - Terrestrial RF Sources of Noise Interference (Communication Subsystem)

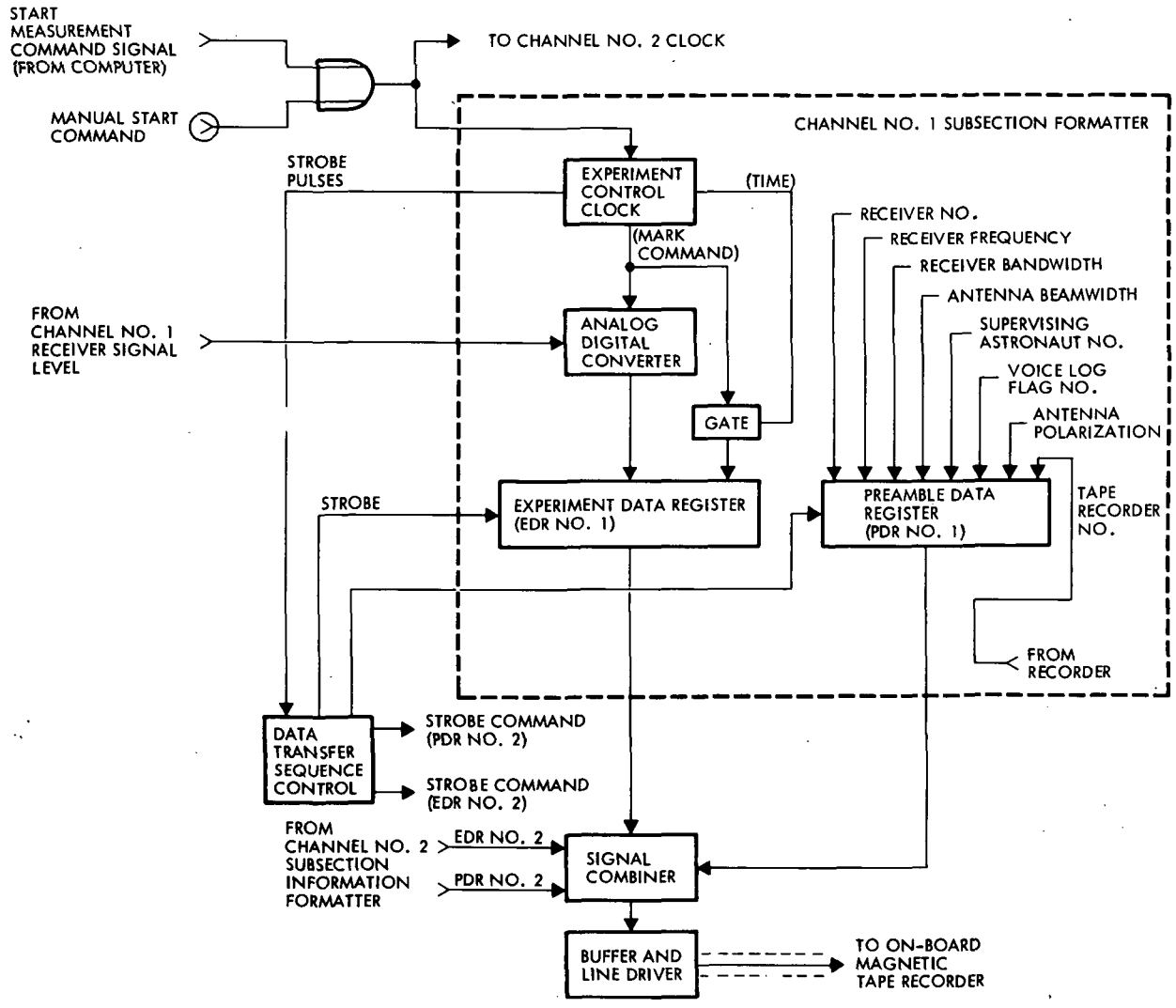


Figure 1-3. Functional Block Diagram – Terrestrial RF Sources of Noise and Interference (Information Processing Subsystem)

- Reference signal generator derives power level calibration for in-flight astronaut use.
- Predetermined programs of spectrum analysis can be invoked using on-board computer to establish sweep parameters.
- Duplication of sweep receiver and switched attenuators will extend dynamic range.

### 1.4.4 Experiment Parameters

The parameters and constraints adopted for this experiment and the rationale for their selection are shown in the following table:

| Parameter | Value or Constraints | Justification |
|---|---|---|
| Geographic Coverage | CONUS only | • Permission for data collection over foreign countries would involve protracted negotiations.<br>• May infringe on role of DOD. |
| Frequency Coverage | 100-1000 MHz | • Ready availability and modest cost of equipment maximizes chance of useful data for early flights.<br>• Selected region has very high user density, providing excellent target.<br>• These lower frequencies pose greatest design challenge to implementing adequate spatial resolution antenna.<br>• Domestic TV has established designs for single antennas which operate over selected range. |

### 1.4.5 Measurements Defined

The overall experiment involves making a series of measurements under selected combinations of different test conditions. The variables under control of the experimenter are as follows:

- Field of view: Broad
  Narrow
- Frequency: Sweep 100-1000 MHz
  Sweep selected segment
  Fixed
- Time: Night
  Day
- Signal sensitivity: Threshold
  Low.

### 1.4.6 Sensitivity and Resolution

The sensitivity of the proposed system is directly related to the selected receiver IF bandwidth, the aperture through which the total spectrum is viewed. A narrow bandwidth reduces the thermal noise base and enhances signal separation but limits the sweep speed.

Assuming perfect experiment timing and a target on subtrack, the available sweep time is six minutes, the minimum IF bandwidth is about 12 kHz, and the expected noise base is of the order of -158 dBw. For the initial measurements a hemispherical earth coverage antenna will provide no more than 6 dB gain. The resulting signal detector threshold (unity SNR) is about -164 dBw (shaded by galactic and terrestrial noise across the band).

Since the propagation loss for the signals being appraised depends on both their particular slant range and operating frequency, the minimum detectable signal is a function of both these variables. In general, the threshold, in terms of earth surface transmitter power level, will range from a mean* of -40 dBw (100 MHz) to a mean* of -16.5 dBw (900 MHz). A preliminary analysis of this topic is given in Appendix C. A discussion of the expected signal levels emanating in the 100 - 1000 MHz region of the spectrum due to terrestrial services is presented in Appendix C.

The sensitivity is a function of several variables and is, therefore, best expressed parametrically. The most significant variables are:

- Frequency of signal
- Location of signal source
- Selected sweep width.

The frequency of the signal determines the value of the frequency dependent term in the free-space loss equation for the link power budget. The equipment is designed to allow operation over a range of 100 to 1000 MHz, producing a variation 20 dB in threshold.

---

* The values are more exactly arithmetic averages of nadir and slant range value (both reference to unity SNR).

The location of the signal source establishes the slant range and determines the range dependent loss term in the free-space loss equation. For a 200 n. mi. orbit altitude and a 10 degree above the horizon assumed cut-off angle, the range varies from 200 to 730 n. mi., corresponding to an 11 dB change in range loss.

Lesser variables include the following:

- Receiver noise figure
- Antenna gain
- Off-boresight loss.

The receiver noise figure (~4 dB) does vary with frequency, so that the basic receiver threshold is not constant but degrades with increasing frequency. Fortunately for modern high quality receivers, this variation is small, perhaps 2 dB, and not too important in relation to the other factors.

The antenna gain depends on both the signal frequency and the direction of signal arrival. The variation in gain with frequency is partially under the control of the antenna designer. For the suggested dual log periodic unit, a 6 dB variation is assumed.

The direction of the signal source in relation to the direction in which the antenna points establishes the misalignment, or pointing loss. For the wide beam dual log periodic antenna with a 140 degree beamwidth, the worst case loss due to this effect will be -3 dB.

The magnitudes of the factors reviewed above are shown in Figure 1-4. The expected sensitivity at the upper and lower frequency limits, and both nadir and limit range conditions, is developed in the link power budgets shown in Table 1-1.

The foregoing limits assume that the sweep speed is slow in relation to the selected receiver bandwidth. If the sweep speed is reduced to meet this requirement, insufficient "samples" of each source may be obtained to provide confidence in the data. The effect of performing multiple sweeps during the approximately six minutes visibility time over a particular target is to increase the rate of sweep, which can degrade the system sensitivity. For the particular values of six minutes

Table 1-1. Sensitivity Link Budgets for Limiting Conditions

| FREQUENCY | LOW LIMIT = 100 MHz | | HIGH LIMIT = 1000 MHz | |
|---|---|---|---|---|
| SLANT RANGE VALUE | Min = 200 n. mi. | Max = 730 n. mi. | Min = 200 n. mi. | Max = 730 n. mi. |
| Noise Base (Bw = $10^3$ Hz) | -174.0 Bw | -174.0 dBw | -174.0 dBw | -174.0 dBw |
| Receiver Noise Factor | 2.0 dB | 2.0 dB | 4.0 dB | 4.0 dB |
| Space Loss | 126.6 | 135.5 | 146.6 | 155.5 |
| Laboratory Antenna Gain | 1.0 dB | -2.0 dB | -1.0 dB | -4.0 dB |
| Sensitivity Limit (Unity SNR) | -46.0 dBw | -34.5 dBw | -22.4 dBw | -10.5 dBw |

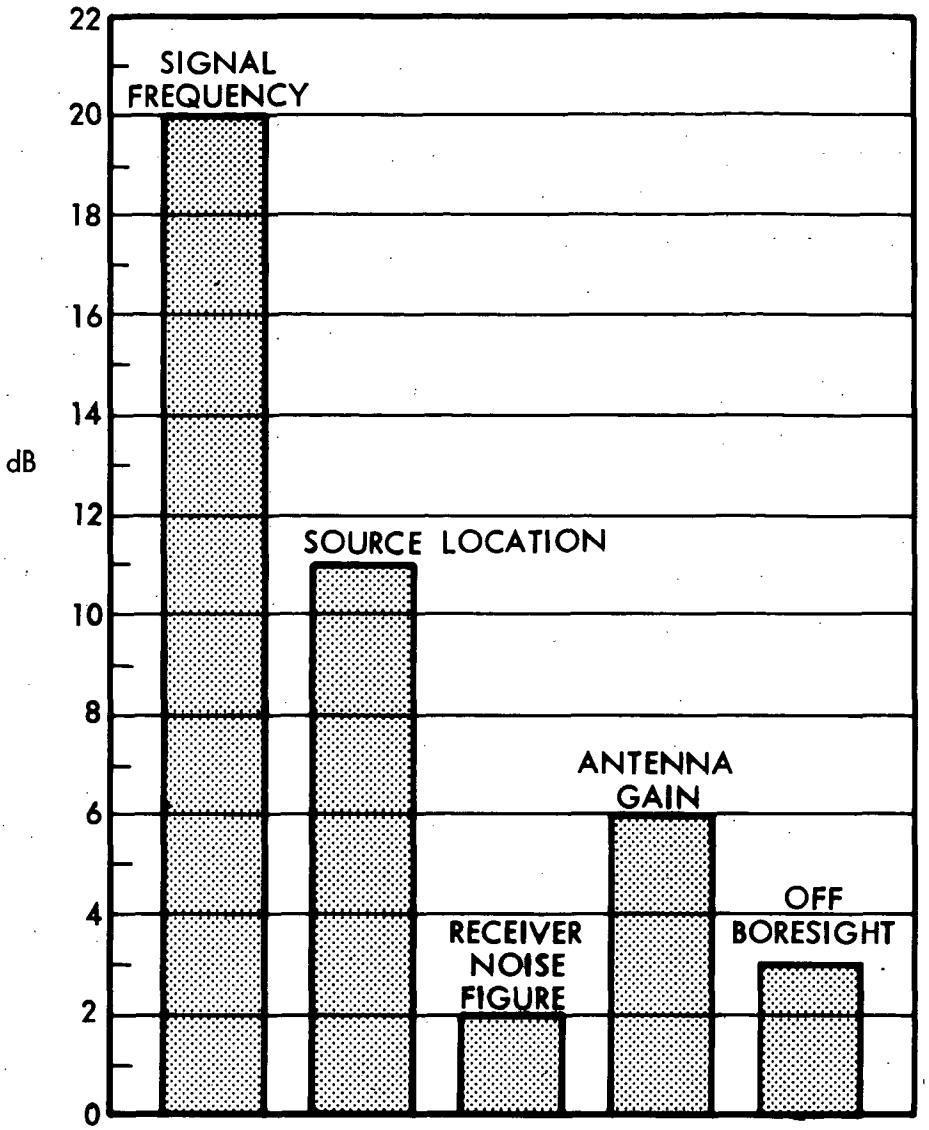


Figure 1-4. Magnitudes of Factors Affecting Sensitivity Threshold of Power Spectral Density Measurement

and a 1 kHz bandwidth, the effect on threshold is shown in Figure 1-5. For a further discussion, refer to Appendix C. If the receiver bandwidth is increased to avoid the sweep rate induced sensitivity loss, the thermal noise (KTB) is proportionately increased, negating the desired improvement.

The unity signal-to-noise ration (SNR) factor, used in deriving the absolute sensitivity is arbitrary; in practice a positive SNR will be required. The required SNR depends on the statistical detection performance desired. The noise level obtained from the formula $P_n = KTB$ yields the magnitude of the rms value of noise power. Thus, if the signal has the same value as the rms noise, an ideal detector would detect the signal only 50 percent of the time.

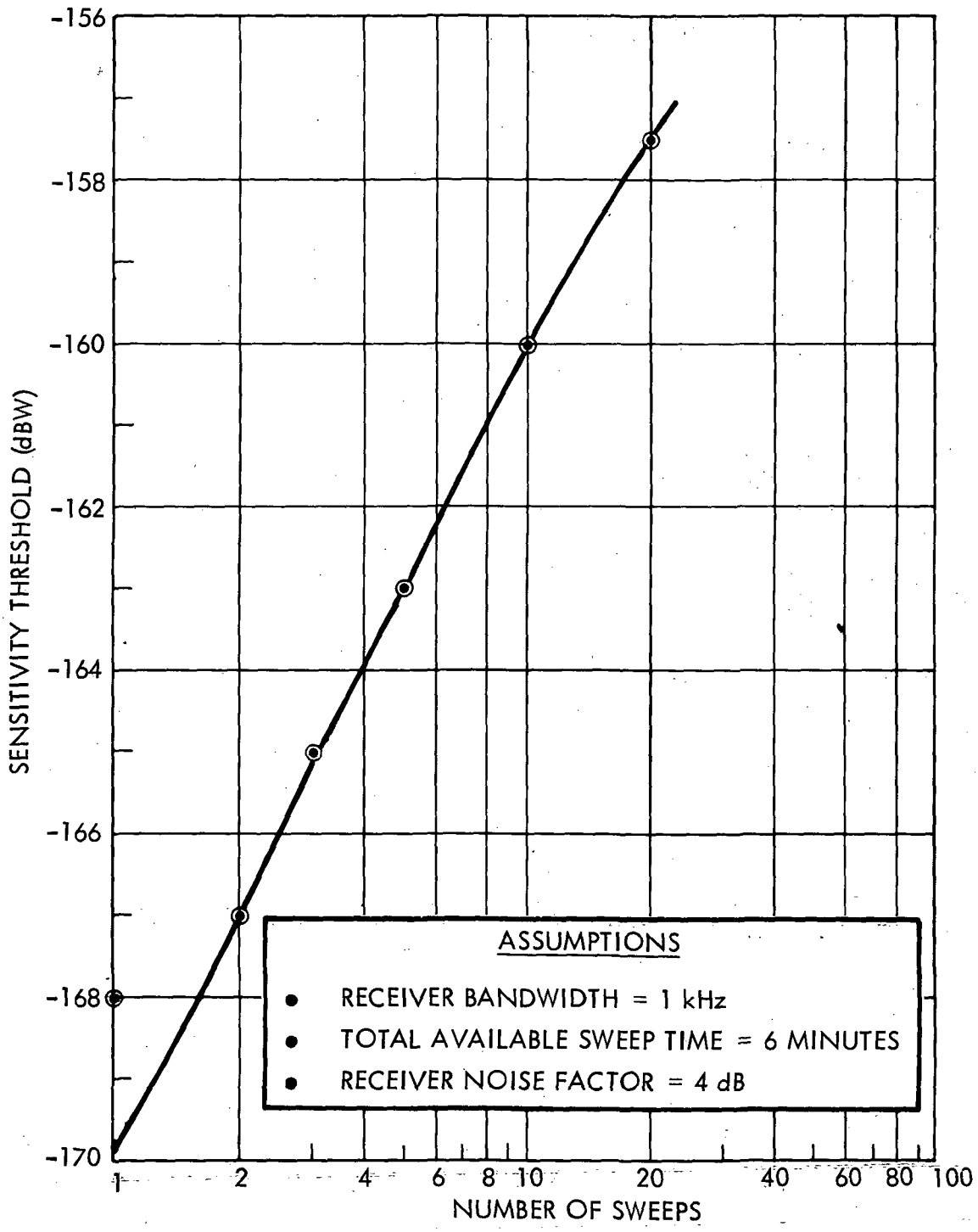


Figure 1-5. Sensitivity Threshold versus Number of Total Spectrum Sweeps

## 1.4.7 Signal Processing and Data Storage

The power of the ground station target transmitters varies from about 100 milliwatts to 1 megawatt, a power range of $10^7$:1. The dynamic signal range of any radio receiver is quite small. Large signals result in circuit overloading and non-linearity, while very small signals can become lost in the noise.

Modern amplitude modulation (AM) receivers incorporate automatic gain control (AGC) which regulates the signal amplification provided by the receiver in accordance with the magnitude of the actual received signal. The actual implementation involves peak rectifying the IF signal, filtering it to remove the modulation and obtain an average, and using the resulting signal to control the gain of the RF and IF amplifying devices. The foregoing circuit arrangements convert the receiver into a logarithmic device as far as the average signal is concerned, but preserve its linearity for modulation. The key parameter is the AGC time constant of the filter network. This filter establishes the highest signal rate of change that the AGC loop can follow. If the time constant is made too short, modulation components are transferred to the control devices and both instability and modulation "wipe-off" can occur. If the time constant is made excessively long, the AGC action is so slow that it cannot respond to level variations and overloading or noise masking of the signal results. It is usual to provide differing time constants for reducing and for increasing the receiver gain. The reduction is usually fast, typically 10-50 milliseconds and is termed the "attack" constant, while recovery to the full gain condition, termed "decay," is two orders of magnitude greater, typically 0.1-10 seconds.

The required time constant depends on the expected rate of change of signal level during spectrum scanning. As an example, consider the avionic communication band, where signals are spaced 25 kHz apart. To resolve the power of two adjacent signals, the AGC time constant must allow the signal to change between viewing any adjacent pair of channels. If 100-1000 MHz is scanned in two minutes, then the effective linear rate is $900/2 \times 60 = 7.5$ MHz per second and the interchannel time is $25 \times 10^3 / 7.5 \times 10^6 = 3.3$ milliseconds. The AGC loop response is seen to be an important factor in determining the maximum sweep rate.

An alternative approach is to use a true logarithmic amplifier in which non-linear devices provide a real-time log characteristic without recourse to a gain regulation loop.

For a sweep receiver employing AGC, the magnitude of any input signal is indicated by the level of the AGC signal. The estimated range of signal powers of the ground target transmitters is 100 milliwatts to 1 megawatt or a ratio of about $10^7$:1. A typical AGC circuit will provide a control signal that holds the output signal voltage within 10 dB for an input signal range of 3 microvolts to 1 volt or a power ratio of about $10^9$:1.

For an approximately logarithmic control characteristic the AGC voltage will vary by about 6:1 over a six decade range of input voltage, assuming a 10 volt maximum value, from 1.6 - 10 volts. A variation of 1.6 volts implies a 10:1 change in input voltage and a 20 dB power increment. To resolve a 1 dB power increment will require quantizing to within 1/20 of 1.6 volts or $\pm$0.08 volt. The corresponding fractional quantization is 1 part in 10/0.08 or 1 in 125, for which the closest binary code is 7 bits (128 levels).

As a first approximation to the expected data output, a uniform signal density of 1 signal per 25 kHz, or $36 \times 10^3$ in the 100-1000 MHz band, is assumed. Assuming sampling at twice the implied signal rate, i.e., $72 \times 10^3$ values per scan, the total data generated is:

$\Sigma$(orbit) = $72 \times 10^3$ (values) x 7 (bits per word x 2 (sweeps per orbit) $\approx 10^6$ bits

$\Sigma$(mission) = $36 \times 10^6$

From the foregoing figures the astronaut "quick look" replay data storage requirements are $10^6$ bits, and the seven day mission storage requirements are $36 \times 10^6$ bits.

In addition to the above quantized spectral power density values, it is required to record certain facts concerning the equipment configuration, so that the quantitative data can be correctly interpreted on the ground. This ancillary data should include the following elements:

| Item | Purpose | Discrete Levels Required | Binary Coding (Bits) |
|---|---|---|---|
| Astronaut identifier | Which astronaut | 2 | 1 |
| Antenna gain beamwidth | Select FOV | 2 | 1 |
| Polarization unit | Test freq. A, B, or C | 3 | 2 |
| Receiver (Channel #1) | Main or spare | 2 | 1 |
| Receiver (Channel #2) | Main or spare | 2 | 1 |
| Astronauts monitor receiver | Main or spare | 2 | 1 |
| Frequency converter range | What frequency range | 5 | 3 |
| Frequency | Present value (F) | 7000 | 13 |
| Attenuator setting | Present value (dB) | 60+60 | 6 + 6 |
| Orbit time | Ephemeris correlation | day, hr, min, sec | 12+8+8+8 = 36 (BCD) |
| Calibration level | Injection power (dB) | 60 | 6 |
| Voice commentary flag | Correlates astro log | 8 | 3 |

## 1.5 EXPERIMENT MEASUREMENT PROGRAM

This experiment includes measurements on three classes of radio frequency signal interference; namely, discrete radio transmitters, man-made electrical noise and natural electrical noise. The initial activities involve calibrating the sensitivity of the receiving equipment and recording the electrical noise spectrum due to the laboratory itself.

After the calibration and checkout activities have been completed, data collection starts. The proposed equipment provides two independent and simultaneous recording channels and permits a choice of broad or narrow antenna beamwidth, with either E or H polarization. It is anticipated that data from the first few Early Laboratory flights will be collected for several combinations of these variables.

Although a full frequency sweep of the whole VHF-UHF spectrum will be instructive, major interest will center on restricted sweeps of specific areas of the spectrum of interest for current programs and topical problems at the time of the laboratory flights.

### 1.5.1 Preliminary Observation Plan

Table 1-2 presents a preliminary plan for the initial observations and measurements to be performed by the astronauts in the Early Labora-

# Table 1-2. Model Observation and Measurement Program

| Ref. No. | Measurements | Sensitivity | Orbit | Beamwidth CH #1 | Beamwidth CH #2 | Polarization CH #1 | Polarization CH #2 | Sweep Freq. Range Channel #1 | Sweep Freq. Range Channel #2 | Comments/Rationale |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Laboratory Signature | H | Any | - | - | - | - | 100 - 1000 | 100 - 1000 | Requires Subtraction from Measured Signatures |
| 2 | Sensitivity Calibration | Var | Any | - | - | - | - | 100 - 1000 | 100 - 1000 | Passive Atten. & Local Osc of Known Power |
| 3 | VHF-UHF Overview | L | CONUS | W | W | V | H | 100 - 1000 | 100 - 1000 | Gross VHF-UHF Data |
| 4 | NASA Communication Links | M | CONUS | W | W | V | H | 135 - 139 and<br>147 - 151<br>399 - 407 | 135 - 139<br>147 - 151<br>399 - 407 | STADAN Down Link<br>STADAN Up Link<br>Meteorological and MetSats |
| 5 | Spectral Power Density | L | CONUS + Atlantic + Pacific | W | W | V | H | 107 - 119<br>120 - 121<br>242 - 244<br>327 - 337 | 107 - 119<br>120 - 121<br>242 - 244<br>327 - 337 | Aeronautical Comm. & Navigation Aids Bands and Distress Frequencies |
| 6 | Man Made Noise * | M | CONUS + Atlantic + Pacific | N | N | V | H | 100 - 1000 | 100 - 1000 | Establish Actual Levels for Statistically Significant Number of Tests |
| 7 | Natural Noise ** | H | CONUS + Atlantic + Pacific | N | N | V | H | 100 - 1000 | 100 - 1000 | Establish Actual Levels for Statistically Significant Number of Tests |
| 8 | TV Signals & Harmonics | L & M | CONUS | N | N | H | H | 173 - 217 | 346 - 434 | Synchronized 2nd Harmonic Analysis |
| 9 | TV Signals & Harmonics | L & M | CONUS | N | N | H | H | 173 - 217 | 519 - 651 | Synchronized 3rd Harmonic Analysis |
| 10 | Doppler Location | L | CONUS | W | W | H | H | Fixed<br>TV Channel<br>7, 8, 9, 10, 11 or 12 | Fixed<br>Any Other<br>TV Channel 7-12 | Initial Experiment for Doppler Source Location Technique |

Key - Sensitivity Level: H = High; M = Medium; L = Low.

* Will include both day and night-time orbits, representative seasons of year, weekdays and weekends.

** Will include both day and night-time orbits, representative seasons of year.

tory. This test group is offered as a model only and will require tempering with the specific requirements of the user Comm/Nav programs as they evolve.

A key activity will be the evolution of the Doppler source location technique as an alternative to the very large antenna structures needed to obtain a pencil beam with sufficient spatial discrimination for source location.

## 1.6 INTERFACE, SUPPORT, AND PERFORMANCE REQUIREMENTS

The proposed series of experiments is substantially self-supporting. However, they do impose the following requirements on the support vehicles:

| Support Item | Classification | Description |
|---|---|---|
| Electrical Power | Essential | 28 V DC or 400 Hz |
| Temperature | Trade Off | $71^{\circ}F + 3^{\circ}F/76^{\circ}F \pm 116^{\circ}F$ |
| Pressure | Trade Off | 28-31" Hg/0-31" Hg |
| Vehicle Ephemeris | Essential | 3-Axis Continuous History |
| Orbit | Trade Off | 200 N. Mi. /600/Elliptical |
| Time Std. | Trade Off | Day, Hour, Minute & Second |

## 1.7 ROLE OF MAN

### 1.7.1 Calibration

Equipment calibration for this experiment will be performed by the astronaut during the orbit immediately preceding the first useful (CONUS coverage) orbit. This involves a routine check to ensure that all equipment is powered and functional. The astronaut will then perform the power level calibration, followed by the vehicle EMI/RFI baseline signature recording procedure. The first of these involves injecting known levels of RF signal power into the sweep receiver using the multifrequency calibration oscillator and verifying that all five signals appear on the panoramic display. The astronaut then initiates the calibration recording run during which an attenuator increments the test output level applied to the sweep receiver, while the receiver output is recorded on magnetic tape. All receivers are calibrated this way.

The second test involves obtaining a spectrum sweep record of each receiver, with the antenna disconnected from it, to obtain data on the residual background power density characteristic of the vehicle itself.

Following the calibration phase, the astronaut returns the system to the program clock control.

### 1.7.2 Initial Data Acquisition

During the remaining useful CONUS orbits, the system collects data during the overpass segments of each orbit. The data is recorded on the magnetic tape recorder.

A stored voice message alerts the astronaut at selected intervals prior to each CONUS overpass to allow him to make use of the sweep panoramic display in realtime and/or the operator's monitor receiver and waveform display units.

### 1.7.3 Astronaut Evaluation and Equipment Adjustment

At a convenient time during the 18 hours immediately following the initial data acquisition, the astronaut returns to the Comm/Nav control panel and replays the magnetic tape records, monitoring their outputs on the panoramic display. The program clock control limits the recording period to a little in excess of the coverage time, so that the adjacent orbit records have been compacted and are conveniently adjacent for astronaut evaluation. The total replay time is only about 30 minutes at regular speed.

As a result of this record evaluation, the astronaut is able to optimize the equipment control parameters on the basis of the actual signal levels and distribution observed. The astronaut selects the apparently optimum spectrum segments, sweep rates, bandwidth, etc., and then returns the system to the record standby mode under control of the program clock control unit.

### 1.7.4 Semi-Automatic Data Acquisition

During this final phase the equipment collects data on terrestrial noise and power spectral density over CONUS during five groups of six

orbits. This covers a period of six days and provides data for test periods dispersed over the full 24-hour period, including workdays and a weekend.

The recorded data is stored on magnetic tape for later analysis at NASA ground facilities.

## 1.8 EXPERIMENT EVOLUTION

The experiment has been divided into three phases reflecting the projected time span, permissible equipment payload, and increasing understanding of the problem. The key hardware development required is an ultranarrow beam antenna. A parallel supporting research and technology (SRT) program is recommended on this topic.

### 1.8.1 Phase I

This first phase is based on obtaining gross geographic data over CONUS using commercially available antennas. These will provide broad (horizon-horizon) coverage and a modestly narrow pencil beam (approximately 25 degrees). Flights will yield night and day data over the frequency band from 100 to 1000 MHz or selected segments. During Phase I, an SRT effort will be pursued to develop a highly directive multi element static array with a minimum ground trace footprint of approximately one mile.

### 1.8.2 Phase II

The equipment configuration for Phase II will be expanded to incorporate the new antenna array for UHF/VHF, plus additional antennas and receiving equipment to cover the microwave region from 1-1- GHz. During Phase II the antenna SRT will be continued to develop an improved steerable UHF/VHF antenna for extra-vehicular activity (EVA) assembly plus improved antennas for microwave bands.

### 1.8.3 Phase III

Phase III will incorporate full frequency analysis capability covering VHF, UHF, microwaves, and millimeter wave regions.

The pointing arrays for VHF/UHF and the higher band will be installed with multiple receiving equipment and recording channels.

Substantial automation is assumed with crew providing supervisory control and performing unique analyses.

### 1.8.4 Experiment Plan for Early Laboratory

This experiment involves four phases, namely:

- Preliminary Calibration
- Initial Data Acquisition
- Astronaut Evaluation and Equipment Adjustment
- Semi-Automatic Data Accumulation.

Evaluation of the ground trace geometry for 200 mile altitude inclined orbits indicated CONUS coverage would be available during six consecutive orbits out of each group of 18. This format provides six blocks of six useful (CONUS) orbits during a seven day mission.

The proposed timing for this experiment within a seven day Early Lab mission is illustrated in Figure 1-6.

## 1.9 SRT REQUIREMENTS

Four SRT tasks have been identified in connection with the experiment:

- Antenna integration
- Pencil beam antenna development
- Improvements to Doppler position location
- Receiver frequency extension

### 1.9.1 Antenna Integration

The proposed laboratory antenna for use with all VHF/UHF experiments is a log periodic design because it provides the widest possible bandwidth in a single structure. Multiple discrete radiators with a frequency crossover network are not considered because of the very large area needed at these low frequencies and the high cost of the associated deployment structure.

The log period antenna is also required to provide a choice of E or H linear polarization. This need is readily met by using two separate orthogonally aligned, linearly polarized, log periodic structures. If these two antennas are structurally integrated, the result would be a

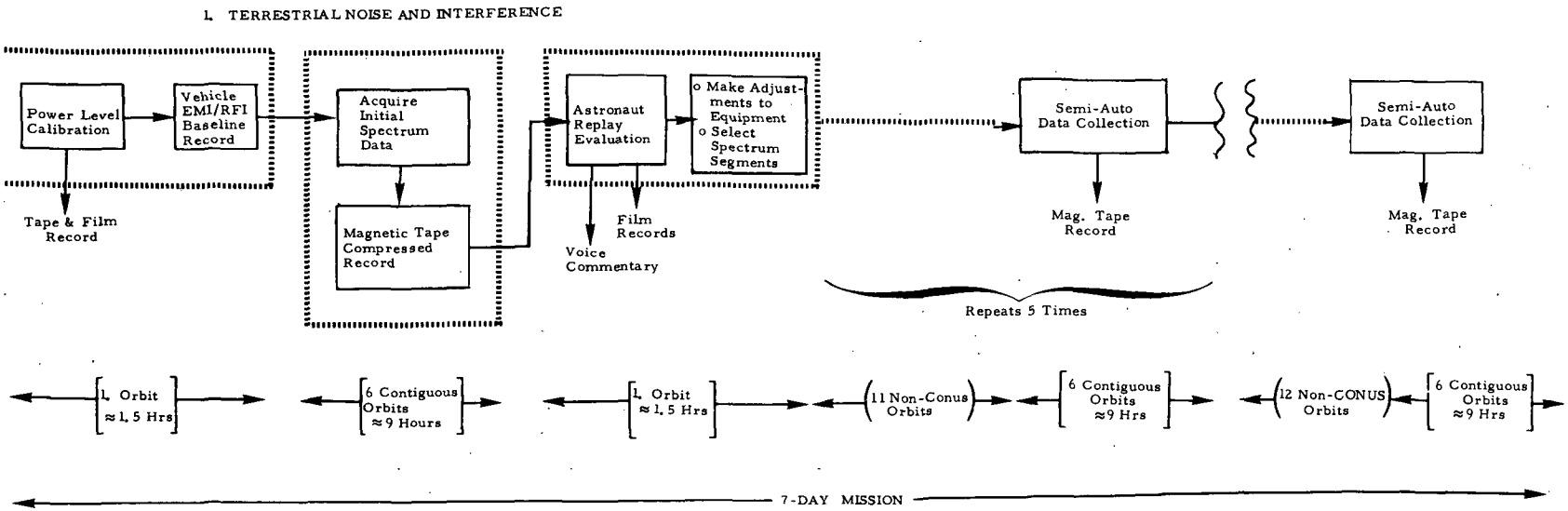


Figure 1-6. Experiment Plan for Early Laboratory for 7-Day Mission

single coaxial structure with cruciform elements and, hopefully, a common boresight. Fortunately, the orthogonal alignment minimizes mutual interaction between the separate radiation patterns.

In addition to the dual polarization, it is also highly desirable to provide a choice of beamwidth. The widest beamwidth needed is about 140 degrees. This allows full coverage out to slant ranges involving a 10 degree horizon angle of view. The minimum beamwidth is limited by a combination of the desired 10:1 bandwidth and the practical problems of element spacing, tolerance, and length. The latter pair appear to increase rapidly for beamwidth angles of less than about 45 degrees.

It appears potentially feasible to combine two different beamwidth cruciform arrays, of the type just outlined, into a single structure providing a choice of beamwidths and choice of two polarization planes. The first SRT task is to investigate in detail the feasibility of this concept and recommend the most appropriate solution.

### 1.9.2 Pencil Beam Antenna Development

Two methods of locating the approximate position of a ground interference transmitter have been discussed. The ultra narrow beam (pencil) antenna is the more obvious method and can be used for noise as well as coherent signals; however, it presents serious technical problems. To locate a source within 100 feet requires an antenna beamwidth that subtends a 1/50 n. mi. diameter footprint from 200 n. mi. altitude, i. e., under 1/10 of a degree.

Clearly a compromise is necessary between extreme antenna size, cost, and deployment problems on the one hand, and poor spatial resolution on the other. It appears that a combination of antenna design and ingenious measurement schemes may be needed to arrive at an effective solution. The proposed SRT task involves investigating this problem.

### 1.9.3 Improvements to Doppler Measurement

An interesting alternative to a very narrow beam antenna, for locating the position of a terrestrial source, is a signal processing scheme called Doppler Time History Analysis (DTHA), mentioned earlier. In this scheme the laboratory records the value of the Doppler shift experienced by the signal of interest during an orbit. The individual Doppler

shifts and the associated laboratory orbital positions are then processed in a computer to determine the location of the source.

This technique was brought to our attention by Dr. Charles Laughlin of GSFC and had been proposed as a means of tracking pressure sensing meteorological balloons (Reference 19). Implementation of this method hinges on the accuracy of position determination it can provide, which in turn depends on the sophistication of the laboratory equipment and the short-term stability of the target transmitter.

It is proposed that an SRT task be initiated to perform the required analyses, define the preferred equipment configuration, investigate the impact of this feature on the proposed scanning receiver and integrate the solution into the Early Laboratory equipment configuration.

### 1.9.4 Receiver Frequency Extensions

Since our long term interests in efficient spectrum use encompass the complete range of frequencies from VLF through millimeter waves, it is necessary to ensure that equipment appropriate to the proposed experiment measurement plan is available, or will be available within the desired time frame.

Although specific hardware items have been identified for the immediate measurement needs, the criticality of this aspect suggests a separate SRT task be initiated with the objective of ensuring timely hardware availability of scanning receivers.

Two topics requiring attention are:

a) Extension of coverage per band

b) Development of receivers for new bands.

The first requirement is concerned with extending the sweep range of the receiver from the present value of 10:1 in frequency so as to provide enhanced continuity and reduce cross-band correlation of results.

The second task involves ensuring that additional receiver models or frequency converters will be available to cover the higher frequency bands between 10 GHz and 100 GHz, and in the long term bridge the gap between millimeter waves and optical transmission frequencies.

In the past, receivers of the type desired have been developed almost exclusively for military intelligence and electronic warfare applications. With the reduced emphasis of military research and development, it appears unlikely that the required equipment will be developed as a product line, while equipment developed for a specific military program will in all likelihood be classified and not generally available.

It is, therefore, proposed that an SRT task be instituted to investigate the availability of sweep receivers over the complete spectrum range and assemble a hardware availability calendar. This will allow identification of gaps in the desired frequency coverage. The same SRT task will then allow evaluation of the technical requirements for each of these gaps to determine the most cost effective solution. The options at this point would probably comprise the following:

a) Fund a new receiver development.

b) Develop a frequency conversion adapter.

c) Combine a number of available elements to produce a temporary (brass board) receiver.

d) Negotiate with DOD on a joint funding.

e) Defer the laboratory measurements in this region.

It is proposed that the SRT contractor would evaluate the relative merits of these approaches and present a final report fully documenting the facts.

## 1.10 ACKNOWLEDGEMENTS

### 1.10.1 Related Experiments

The following candidate experiments were submitted in response to a solicitation made during the Communication/Navigation Research Laboratory Study:

| Experiment | Principal Investigator and Association |
|---|---|
| 1. RFI Measurement | V. Henry, Goddard Space Flight Center<br>H. Weinberger, Hughes Aircraft |
| 2. Origin of Atmospheric Radio Noise | R. Disney, Inst. for Telecommunication Sciences |
| 3. Interference at Satellite Heights | R. Disney, Inst. for Telecommunication Sciences |
| 4. Determining the EM Environment of Communication Satellites | D. Crombie, Inst. for Telecommunication Sciences |
| 5. Satellite Radio Surveillance | Bergman/Newbern-Smith Inst. for Telecommunication Sciences |
| 6. Orbital Power Flux Density Mapping for 100 - 10,000 MHz | R. Bergman, Inst. for Telecommunication Sciences |
| 7. Terrestrial Noise Measurement | Blue Book, Vol. V, Jan. -1971 |
| 8. Noise Source Identification | Blue Book, Vol. V, Jan. -1971 |
| 9. Man-Made Noise Experiment | J. Kelleher, National Scientific Laboratories |

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# APPENDIX A

## BANDWIDTH EXPANSION AND SENSITIVITY REDUCTION AT HIGH SWEEP RATES

In the discussion of power spectral density data acquisition we mentioned that if the sweep receiver is swept too rapidly the effective IF bandwidth is increased and the sensitivity reduced. These effects place an upper limit on the sensitivity sweep time product and are, therefore, important.

The following analysis, taken from Reference 1, assumes a Gaussian IF response and establishes the magnitude of these effects.

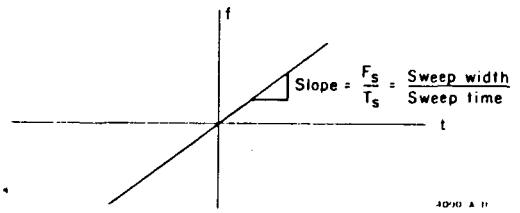



Figure A-1

A sweep frequency signal as illustrated in Figure A-1 can be represented by:

$$s(t) = e^{j\pi(F_s/T_s)\,t^2} \quad ,$$

which can be transformed to the form:

$$S(\omega) = \tau\sqrt{2\pi}\, e^{-1/2\,(\tau\omega)^2} \qquad \left[\text{where } \tau = \sqrt{(jT_s)/(2\pi F_s)}\ .\right]$$

If we assume a Gaussian response $H(\omega) = e^{-1/2\,(\omega/\delta)^2}$ ,

The product of $S(\omega)\,H(\omega)$ is:

$$Y(\omega) = S(\omega)\,H(\omega) = \tau\sqrt{2\pi}\exp\left[-\frac{1}{2}\left(\tau^2 + \frac{1}{\delta^2}\right)\omega^2\right].$$

The output transient is the inverse transform of the above product, i.e.,

$$y(t) = \frac{\tau}{\sqrt{\tau^2 + \frac{1}{\delta^2}}}\exp\left[-\frac{1}{2}\left(\frac{t^2}{\tau^2 + \frac{1}{\delta^2}}\right)\right].$$

and substituting for $\tau$,

$$y(t) = \frac{1}{\left[1 - j\frac{2\pi F_S}{T_S\delta^2}\right]^{1/2}} \exp\left[-\frac{1 - j\frac{\delta^2 T_S}{2\pi F_S}}{1 + \left(\frac{T_S\delta^2}{2\pi F_S}\right)^2}\right] \frac{\delta^2 t^2}{2}$$

The envelope of $y(\tau)$ is then:

$$y(t) = \frac{1}{\left[1 + \left(\frac{2\pi F_S}{T_S\delta^2}\right)^2\right]^{1/4}} \exp\left[-\frac{\frac{\delta^2 t^2}{2}}{1 + \left(\frac{T_S\delta^2}{2\pi F_S}\right)^2}\right] \quad (1)$$

For slow sweep rates the inequality $\frac{T_S}{2\pi F_S} \gg \frac{1}{\delta^2}$

applies, and the envelope becomes simply:

$$y(t) = \exp\left[-\frac{1}{2}\left(\frac{2\pi F_S}{\delta T_S}\right)^2 t^2\right] \quad (2)$$

The above response is, of course, just that of the IF amplifier. If the stated inequality is not met, then both the duration and amplitude of the output signal are modified. The amplitude will be reduced by a factor ($\alpha$) given by the expression:

$$\alpha = \frac{1}{\left[1 + \left(\frac{2\pi F_S}{T_S\delta^2}\right)^2\right]^{1/4}} \quad (3)$$

Since $\delta = \frac{\pi . \Delta f}{\sqrt{\ell n 2}}$, where $\Delta f$ = -3 dB bandwidth, we can rewrite (3) above as follows:

$$\alpha = \frac{1}{\left[1 + \left(\frac{2\ln 2}{\pi}\right)^2 \left(\frac{F_S}{T_S \Delta F 2}\right)^2\right]^{1/4}}$$

The expected reduction in sensitivity (in dB) expressed as a function of the normalized sweep rate factor (K) is shown in Figure A-2, where K is defined as:

$$K = \frac{F_s}{(T_s \cdot \Delta F^2)} \tag{4}$$

We can also solve to find the time separation between the 3 dB points in the output by using equations (1) and (2) and setting the value of y(t) to a magnitude of $1/\sqrt{2}$. This yields

$$\Delta t' = \frac{2\sqrt{\ln 2}}{\delta\pi}\left[1+\left(\frac{T_s\delta}{2\pi F_s}\right)^2\right]^{1/2}$$

for equation (1), and

$$\Delta t = \frac{2\sqrt{\ln 2}\,\delta T}{2\pi F_s}$$

for equation (2). The normalized degradation in time is the ratio of the above two expressions; i. e., $\frac{\Delta t'}{\Delta t}$ which simplifies to the following expression,

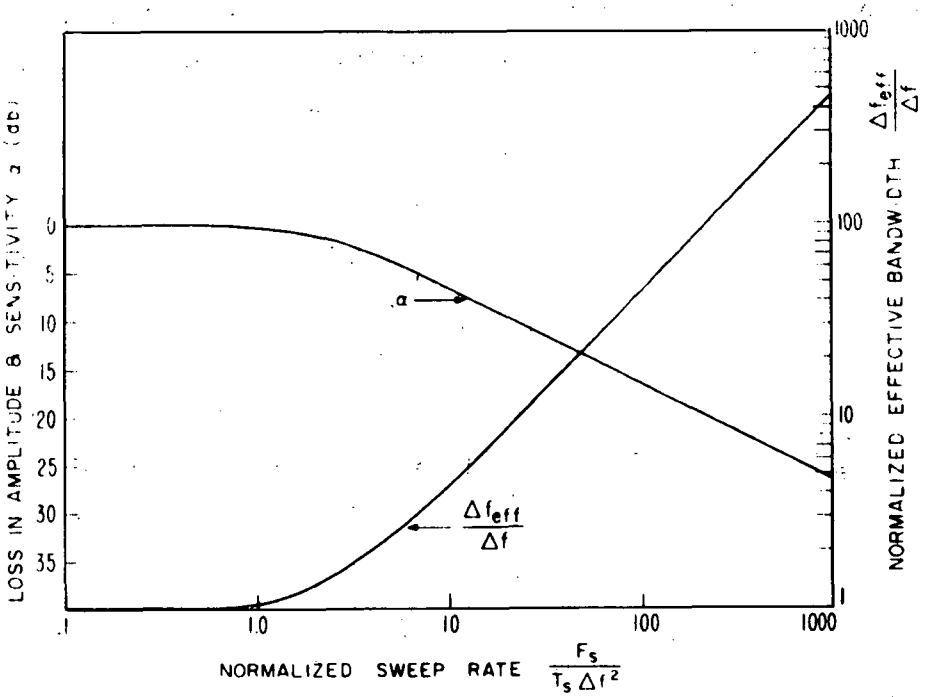
$$\frac{\Delta t'}{\Delta t} = \left[1+\left(\frac{2\pi F_s}{T_s\delta^2}\right)^2\right]^{1/2} \tag{5}$$

In terms of the 3 dB IF bandwidth, the normalized resolving bandwidth is given by the following expression:

$$\frac{\Delta f_{eff}}{\Delta f} = \left[1+\left(\frac{2\ln 2}{\pi}\right)^2\left(\frac{F_s}{T_s\Delta f^2}\right)^2\right]^{1/2}$$

This expansion factor is plotted with the sensitivity degradation in Figure A-2.

Reference -1 Technical Appendix to Application Note #63 by Hewlett-Packard Company, August 1968.




$F_s$ = Sweep Width

$T_s$ = Sweep Time

$\Delta f$ = 3 db IF Bandwidth

$\Delta f_{eff}$ = Impulse Bandwidth

Figure A-2. Sensitivity Loss and Normalized Effective Bandwidth versus Normalized Sweep Rate

# APPENDIX B

## VISIBILITY TIME AND SLANT RANGE ANALYSIS

### GEOMETRY

The general geometric situation involving the orbiting space laboratory and a transmitter located on the earth surface is illustrated in Figure B-1. From this model, a maximum visibility time is derived for a station located on the laboratory subtrack. Using this value, the slant range for a "10 degree to earth tangent" viewing limit is derived.

### ANALYSIS

In the triangle OBD

$$\frac{OB}{\text{Sin} \angle BDO} = \frac{OD}{\text{Sin} \angle OBD} = \frac{R}{\text{Sin} \angle BDO} = \frac{R \text{ and } L}{\text{Sin} \angle 90 + 10}$$

ie $$\frac{3.444 \times 10^3}{\text{Sin} \angle BDO} = \frac{3.644 \times 10^3}{\text{Sin } (100^\circ)} = \frac{3.644 \times 10^3}{\text{Sin } (80^\circ)}$$

whence $$\text{Sin} \angle BDO = \frac{3.444 \times \cancel{10^3} \times \text{Sin } (80^\circ)}{3.644 \times \cancel{10^3}}$$

$$\text{Sin} \angle BDO = \frac{3.444}{3.644} \times 0.9848 = 0.9451 \times 0.9848 = 0.9308$$

$$\text{Sin}^{-1} \; 0.9308 = \underline{68.55^\circ}$$

$$\therefore \angle DOB = 180 - [68.55 + 100] = 180 - 168.55 = \underline{11.45 \text{ degrees}}$$

$$\text{Fractional Visibility} = \frac{\angle COD}{360} = \frac{22.9}{360} = \underline{0.06362}$$

Orbit Period (200 nmi) = 0.06386 days

Orbit Time = $24 \times 0.6386$ = <u>1.5326 hours</u>

Target Visibility Time = $0.06362 \times 1.5326 \times 60$ = <u>5.85 minutes</u>

Maximum slant range = BD

$$\frac{BD}{\text{Sin } (11.5)} = \frac{OD}{\text{Sin } (100)} \quad \therefore \frac{BD}{0.2} = \frac{3.644 \times 10^3}{0.9848}$$

$$\therefore BD \approx 0.2 \times 3.644 \times 10^3 = 0.7288 \times 10^3 = \underline{729 \text{ nmi}}$$

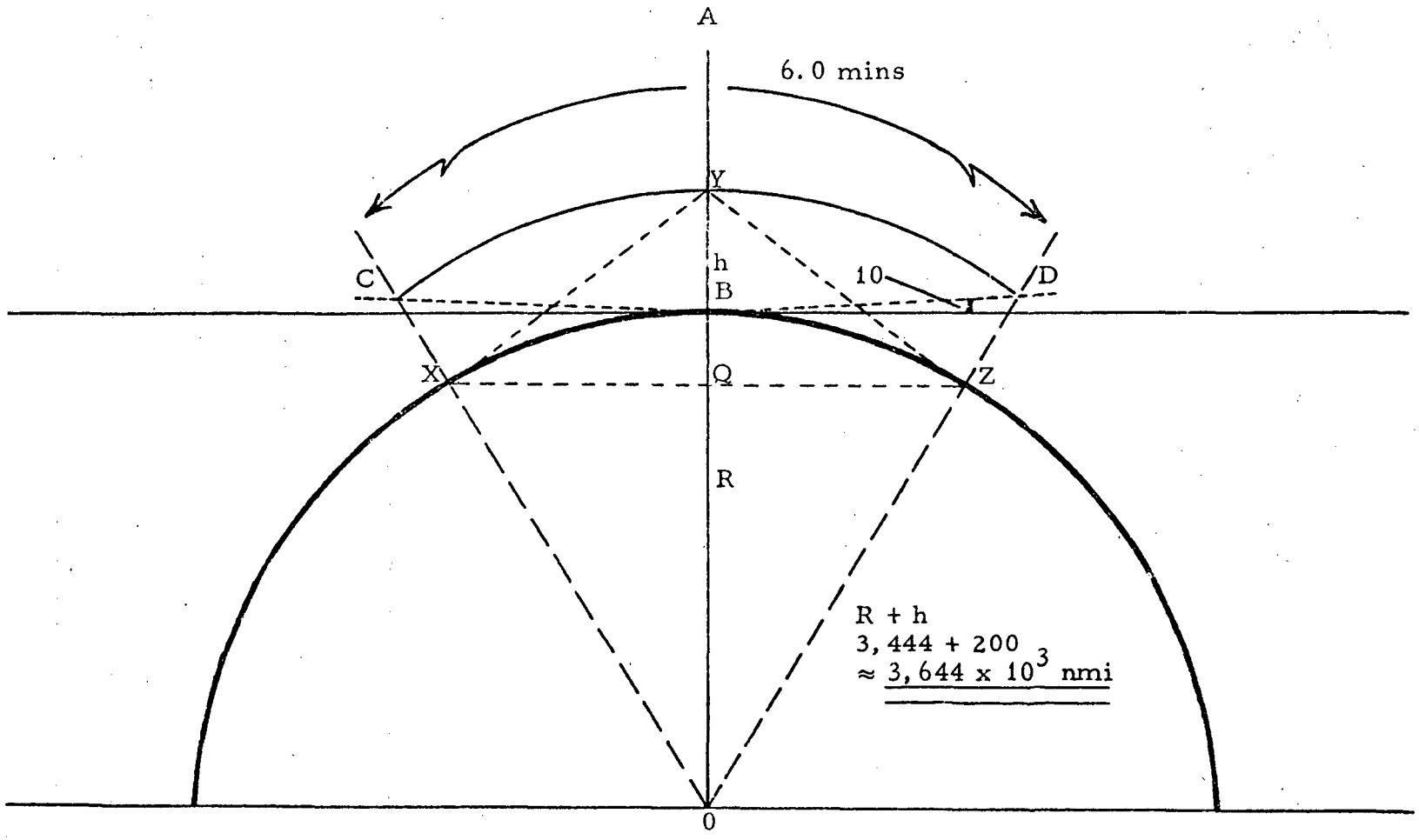



Figure B-1

ANTENNA BEAMWIDTH

The broad beam antenna must have sufficient beamwidth so that the antenna coverage does not reduce the available visibility time. Referring to Figure B-1, this entails a laboratory antenna with a beam angle XYZ.

ANALYSIS

Join points X-Z to form the chord XZ. Since the figure is laterally symetrical, the radius line O B bisects the chord at point Q

In the triangle OXQ, $\angle OQX = 90^{\circ}$, and $\angle XOQ$ has already been established ($11.45^{\circ}$), therefore

$$\frac{XQ}{\text{Sin } (11.45)} = \frac{OX}{\text{Sin } (90)} \quad \text{or} \quad \frac{XQ}{0.2} = \frac{3,444}{1}$$

$\therefore$ XQ = 688.8 nmi

In the triangle XQY,

$$\text{Sin } \angle QYX = QX/XY = \frac{688.8}{729} = 0.9449$$

$\therefore \angle QYX = 70.9^{\circ}$, and the required antenna beamwidth ($\angle XYZ$) 142 Degrees

# APPENDIX C

## ANTICIPATED LEVELS

## FOR TERRESTRIAL SOURCES OF RF INTERFERENCE

The anticipated signal power levels due to the several terrestrial sources that occupy the spectral region of 50 MHz to 1 GHz are shown in Figure C-1.

In the description for this experiment, it was shown that the average expected sensitivity threshold, for unity SNR, referenced to the earth surface, was between -40 dBw (100 MHz) and -16.5 dBw (1000 MHz) with the exact value depending on the slant range value, etc. Clearly, such values assure entirely adequate SNR and detection statistics using the suggested configuration and operational procedures.

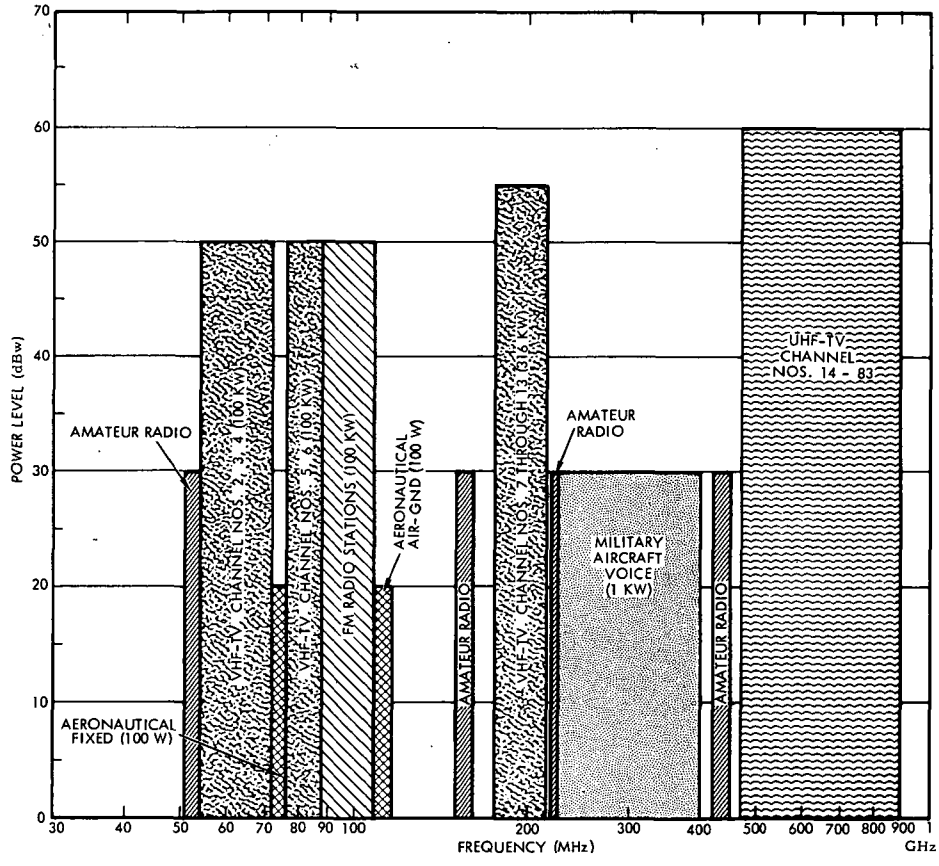



Figure C-1. Levels of Terrestrial Signals Anticipated in the Range 50 MHz to 1 GHz

# EXPERIMENT 2

# SUSCEPTIBILITY OF TERRESTRIAL SYSTEMS TO SATELLITE RADIATION

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APPENDIX A

# 2. SUSCEPTIBILITY OF TERRESTRIAL SYSTEMS TO SATELLITE RADIATION

## 2.1 EXPERIMENT CLASSIFICATION

There are four phases in the proposed susceptibility experiment. The first phase involves operating with various combinations of transmitter power, frequency, modulation, and antenna polarization, while the effects are monitored at terrestrial test sites. This phase is classified as applied research.

The second phase involves a combination of computer analysis and interpretation of the data collected to abstract information on the relative susceptibility of various parameter combinations. This phase will be performed entirely on the ground and is also classified as applied research.

The third phase entails evaluating the results of the data analyses and preparing specific recommendations for the optimum parameter combinations that should be used by satellite communication/navigation space links to minimize terrestrial interference effects. Once again the appropriate description is applied research.

The fourth phase involves operating an orbiting transmitter under the recommended conditions and collecting statistical data on the susceptibility effects.

## 2.2 DISCIPLINE BACKGROUND AND STATUS

The radiated RF power levels and types of modulation used by satellites are limited by international agreement and specified in CCIR regulations (Reference 1). The regulations were framed with a view to minimizing disruptive satellite interference with existing ground and avionic communication services.

The initial application for communication satellites has been in the role of an orbiting communication repeater, which provides an alternative to submarine cables. A key feature of such links is that they provide a connection between two geographically remote but known and fixed

locations. Because the terminal sites are fixed, high gain directional antennas can be used so that only low power transmitters are needed to assure an acceptable signal-to-noise ratio. Single terminals allow ideal sites to be selected that minimize interference with other terrestrial sources.

Future communication and navigation systems will require satellites to provide links between a multiplicity of points on the earth's surface, and with all types of moving vehicles. These developments can be expected to require significantly higher satellite transmitter power and to preclude selection of optimum terminal sites.

Direct TV transmission from a satellite to the home at a frequency compatible with existing TV receivers or a low cost converter-antenna combination would require a very high power transmitter. It seems more likely that CATV networks will provide distribution (References 2, 3, 4).

The expansion of the Comm/Nav services it is proposed to implement will require the use of a larger portion of the radio spectrum. It may necessitate rearrangement of existing frequency allocations. These changes can be expected to give rise to additional forms of interference.

Primary interference problems are expected in three regions:

- UHF Television, 620 - 790 MHz (Channels 39 - 67)
- Instructional TV Fixed Services, 2.5 - 2.686 GHz
- Common Carrier Microwave Links (TV, telephone, etc.) 3.7 - 4.2 GHz.

The 3.7 - 4.2 GHz band has been shared, between high power space communication systems and terrestrial point-to-point microwave links, for several years. The other two bands were recently allocated for Space TV broadcast purposes.

The effect of an interfering signal, emanating from a spacecraft, on terrestrial TV services is a function of a number of factors including the following:

- Relative power levels of desired and interference signals
- Frequency separation and signal formats
- Types of modulation used by each service
- Antenna patterns of satellite and ground stations.

In order to understand the relative importance of these factors and to define a meaningful experiment, we have to quantify the performance of an existing commercial service. We have chosen domestic TV.

### 2.2.1 Characteristics of Regular UHF Television

Current U.S. television services are provided primarily by means of wide band amplitude modulated radio signals in the VHF and UHF bands. At these frequencies transmission is essentially on a line-of-sight basis. The transmitter and antenna of the TV station are located at a site having the highest elevation practicable, with the actual antenna mounted to a tower from 100 to 1000 ft. above ground. The net effect is to provide substantially unobscured line-of-sight signal paths to a large fraction of the viewers in the surrounding area.

The signal power level radiated by the television transmitter depends on both the characteristics of the transmitter antenna and the power of the final output stage of the transmitter.

The most common antenna is the so called "Supergain" design (Reference 5) which, when properly configured, provides omni-directional coverage in the azimuth plane, combined with a relatively narrow vertical beam, and provides a power gain of about 10 dB.

The combined transmitter power and antenna gain determine the effective radiated power (ERP), the maximum value of which is regulated by the Federal Communications Commission (FCC). Each license granted to a TV station specifies the maximum permitted ERP, which is dependent on the local terrain, and computed to minimize mutual interference while providing adequate viewer signal levels. As examples of the order of magnitudes involved, Table 2-1 presents details on those television stations which serve the Los Angeles area (Reference 6).

The FCC, which regulates all U.S. commercial television activity, has defined three grades of service based on the electrical field strength levels: They are shown in Table 2-2.

## Table 2-1. Summary of Characteristics for Serving the Los Angeles Area

| Ch. # | Call Sign | Antenna Location | Visual Power (KW) | | Aural Power (KW) | | Tower Height (Ft.) | Height ASL (Ft.) | Frequency (MHz) | Notes |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Max. | Hor. | Max. | Hor. | | | | |
| 24 | KMJ | Bear Mtn | 1600 | 190 | 153 | 38 | 321 | 3713 | 530-536 | |
| 7 | KABC | Mt Wilson | -- | 166 | -- | 25.7 | 234 | 5940 | 174-180 | 3° Electrical Tilt |
| 13 | KCOP | Mt Wilson | -- | 170 | -- | 32.4 | 200 | 5880 | 210-216 | |
| 9 | KHJ | Mt Wilson | -- | 162 | -- | 22.9 | 199 | 5929 | 186-192 | |
| 34 | KMEX | Mt Wilson | 810 | 182 | 160 | 36.3 | 170 | 5876 | 590-596 | |
| 4 | KNBC | Mt Wilson | -- | 42.7 | -- | 7.41 | 490 | 6170 | 66-72 | Nondirectional; 2.5° Tilted |
| 2 | KNXT | Mt Wilson | -- | 46.8 | -- | 9.33 | 466 | 6126 | 54-60 | |
| 5 | KTLA | Mt Wilson | -- | 50.1 | | 10 | 240 | 5936 | 77-82 | |
| 11 | LTTV | Mt Wilson | -- | 135 | -- | 20 | 237 | 5907 | 198-204 | |
| 22 | KWHY | Mt Wilson | -- | 64.6 | -- | 9.12 | 146 | 5846 | 518-524 | |
| 52 | KBSC | Mt Wilson | -- | 69.2 | -- | 9.33 | 82 | 5752 | 698-704 | |
| 40 | KLXA | Mt Wilson | 622 | 260 | 123 | 52 | 200 | 5863 | 626-632 | |
| 28 | KCET (NON COMM EDVC) | Mt Wilson | 1200 | 45.7 | 240 | 9.12 | 363 | 6022 | 554-560 | Directional |

Table 2-2. Median Field Strength versus Service Grade

| Grade of Service | Field Strength |
|---|---|
| Principal Cities | 5mV/m |
| Urban Areas | 1mV/m |
| Rural Areas | 50$\mu$V/m |

The foregoing figures are based on interference-free reception conditions where the magnitude of the signal at the viewer's receiver need only comfortably exceed the thermal and galactic noise levels. In practical situations, some degree of man made interference exists. To accommodate this environment, the FCC has established Technical Standards (Ref. 7) that specify the higher levels of field strength shown in Table 2-3 below:

Table 2-3. FCC Technical Standards for Service Grades

| | VHF | VHF | UHF |
|---|---|---|---|
| Grade of Service | Channels 2-6 (mV/m) | Channels 7-13 (mV/m) | Channels 14-83 (mV/m) |
| Principal Cities | 5.0 | 7.0 | 10.0 |
| Grade "A" Region | 2.5 | 3.5 | 5.0 |
| Grade "B" Region | 0.25 | 0.63 | 1.6 |

The site of the transmitting tower, the choice of antenna, and local terrain factors are taken into account in optimizing the station's performance. The overall performance in terms of radiated signal level is presented in the form of a map of the service region on which semi-concentric contour lines are drawn to indicate the boundaries for Grade "A" and "B" service levels. An example of such a map is shown in Figure 2-1.

It is important to note that the FCC technical standards define the grade of service in terms of field strength rather than signal power. The signal power available at the actual receiver terminals depends, of

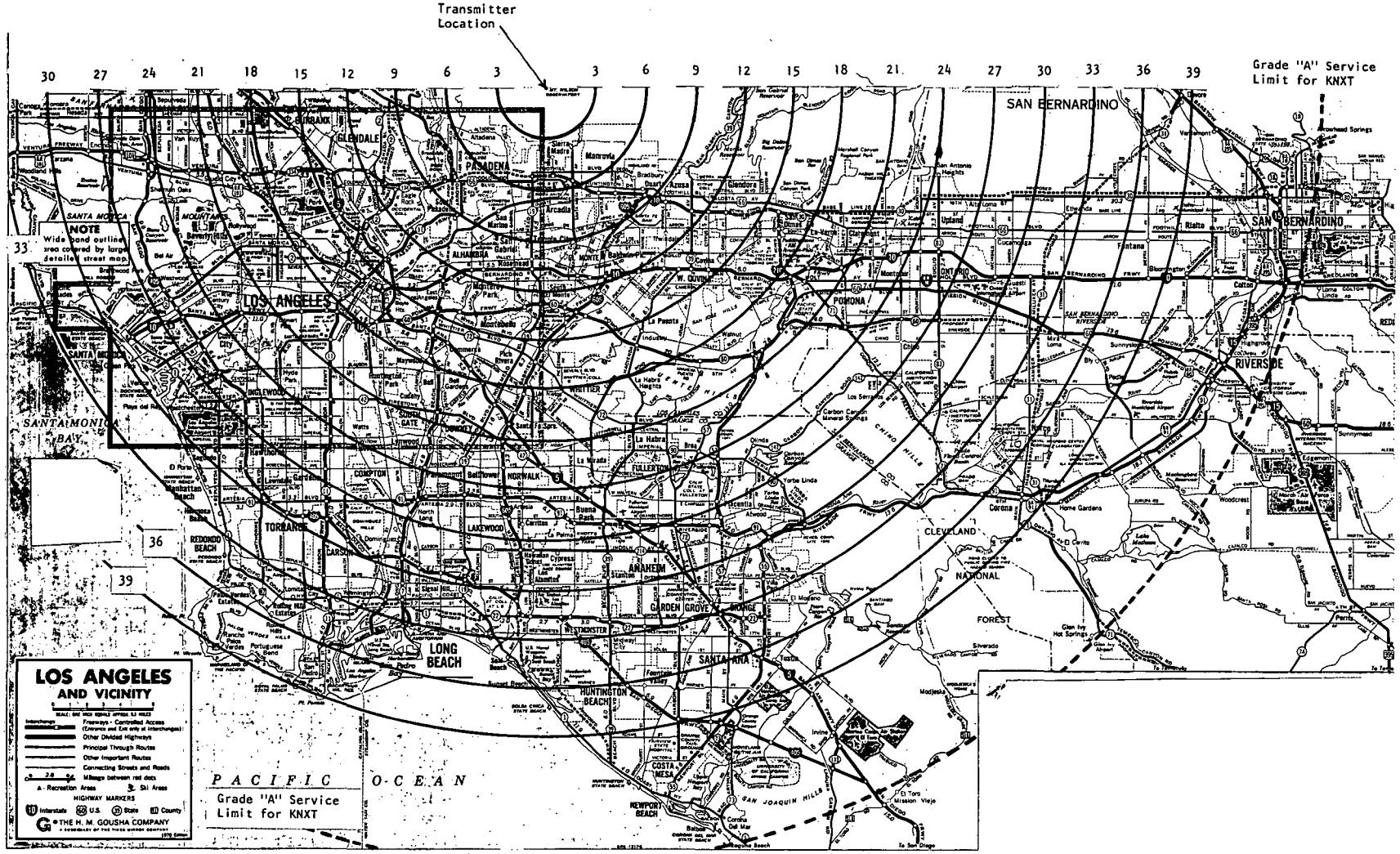



Figure 2-1. Map of Los Angeles Area Showing Range in Miles from Mount Wilson Transmitter Site, and Nominal Grade "A" Service Contour

course, on both its antenna gain and feeder loss, however. For good domestic installations with short feeders, the feeder loss can usually be neglected.

The signal power level expected at a receiver connected to a simple dipole can be readily derived from the field strength values. Such a calculation leads to a value of -82 dBw (See Appendix A).

### 2.2.2 Quantitative Analysis

#### 2.2.2.1 TV Receiving Antennas

In general, TV station antennas have circular radiation patterns, so that the magnitude of signal available at any location away from the immediate vicinity of the antenna (near field region), is inversely proportional to the square of the distance. The magnitude of signal available at the viewer's receiver will depend on the associated antenna's gain, orientation, and directivity pattern.

A wide range of TV antenna designs is now manufactured in large quantities. Early VHF television receivers used a simple "H" type dipole and reflector. This quickly led to multi-element Yagi arrays for extended range. With the advent of UHF television came the higher gain directional "dish" type antennas, possible at these smaller wavelengths. The VHF Yagi developed into a dual band assembly for VHF and UHF, and finally into the now popular log periodic design (References 8, 9). The characteristics of these antennas are summarized in Table 2-4.

Because of its directivity, the receiving antenna can provide a useful degree of discrimination against interference sources, so that the effect of a satellite interference source depends on the viewing angles to the desired terrestrial TV station and to the satellite.

#### 2.2.2.2 Expected Signal Level

For roof or tower-mounted receiving antennas, with an assumed clear view of the TV transmitter, the propagation (free space) loss is given by the relationship:

$$\alpha\ (\text{dB}) = 36.6 + 20 \log f\ (\text{MHz}) + 20 \log d(\text{st. miles}),$$

where f is the operating frequency and d is the communications distance.

Table 2-4. Representative UHF Television Antenna Performance

| Type of Antenna | Gain Over Isotropic (dB) | Gain Over Dipole (dB) | Front-to-Back Ratio (dB) | Comments |
|---|---|---|---|---|
| 1/2 wave dipole | 2.15 | Zero | Zero | Poor for location with reflections. |
| Dipole and screen | 6.25 | ~4 | <20 | Slight reflection aid. |
| Bow-tie and screen | 6.25 | ~4 | <20 | Similar to above but broader bandwidth. |
| Two bow-ties and screen | 9.0 | ~7 | <20 | Gain advantage of 3 dB. |
| Corner reflector | 11.0 | ~9 | =20 | More gain but narrow bandwidth. |
| Periodic | 10-11 | 8-9 | >25 | Good front-back ration for reflection flat gain and VSWR over entire band. |
| Stacked array Two periodics | 13-14 | 11-12 | >25 | Gain advantage of 3 dB. |
| Log periodic (1.5 elements) | 10-15 | 8-13 | >20 | Uniform gain and VSWR over band slightly poorer front-back ratio. |
| Yagi array | 7-17 | 5-15 | >20 | Higher gain possible but relatively narrowband. |
| Arrays of bow-ties | 10-17 | 8-15 | =20 | High gain but relatively narrow bandwidth. |
| Dipole parabolic dish | 16-21 | 14-19 | >20 | Very high gain, difficult to align. Narrow bandwidth. |
| Broadband Antenna and Parabolic Dish | 16-21 | 14-19 | >20 | As above, but broad frequency coverage. |

Fairly extensive tests have been carried out to establish the actual signal strengths obtained under practical terrain conditions. In Reference 10, for example, the TASO Working Group determined that the above theoretical free space equation was reasonably accurate at VHF, although about 1 to 4 dB optimistic at the high end of the band (Channel 13). At UHF the presence of local terrain undulation and foliage absorption results in a substantial error. They concluded that in the UHF band, propagation loss exceeds the theoretical free-space value by as much as 22 dB average, in hilly areas. Clearly, this is very important since it is a discriminatory loss attenuating the desired terrestrial signal, but having little effect on the undesired satellite interence signal.

Since each TV transmitter operates on a different channel and has a different authorized maximum horizontal power, the expected signal level versus distance will be different for each TV station. In order to arrive at quasi-quantitative answers, specific situations must be treated. Accordingly, as an example, the nominal distance from Mount Wilson to downtown Los Angeles is approximately 15 miles, so that the nominal range dependent loss (20 log d) is 23.5 dB. Table 2-5 combines the transmitted power and range loss to develop estimated received signal levels at downtown Los Angeles locations for all 13 local TV stations.

Table 2-5. TV Signal Level Estimates – Los Angeles

| Channel | Call Sign | Power (dBW) | Median Frequency (MHz) | Frequency Dependent Loss (dB) | Propagation Loss (Excluding Range Term) (dB) | Expected Signal Level Excluding Range Loss (dBW) | Expected Signal Level at Nominal 15 Miles (dBW) |
|---|---|---|---|---|---|---|---|
| 2 | KNXT | 46.7 | 57 | 35.1 | 71.7 | -25.0 | -48.5 |
| 4 | KNBC | 46.3 | 69 | 36.8 | 73.4 | -27.1 | -50.6 |
| 5 | KTLA | 47.0 | 79 | 37.9 | 74.5 | -27.5 | -51.0 |
| 7 | KABC | 52.2 | 177 | 45.0 | 81.6 | -29.4 | -52.9 |
| 9 | KHJ | 52.1 | 189 | 45.6 | 82.2 | -30.1 | -53.6 |
| 11 | KTTV | 51.3 | 201 | 46.0 | 82.6 | -31.3 | -54.8 |
| 13 | KCOP | 52.3 | 213 | 46.6 | 83.2 | -30.9 | -54.4 |
| 22 | KWHY | 48.1 | 521 | 54.3 | 90.9 | -42.8 | -66.3 |
| 24 | KMJ | 52.7 | 533 | 54.5 | 91.1 | -38.4 | -61.9 |
| 28 | KCET | 46.6 | 557 | 55.0 | 91.6 | -45.0 | -68.5 |
| 34 | KMEX | 52.6 | 593 | 55.4 | 92.0 | -39.4 | -62.9 |
| 40 | KLXA | 63.1 | 629 | 56.0 | 92.6 | -29.5 | -53.0 |
| 52 | KBSC | 48.4 | 701 | 56.9 | 93.5 | -45.1 | -68.6 |

2.2.2.3 Noise

In the absence of interference signals or man-made noise, the useful reception range is limited by thermal noise and the noise performance of the VHF front-end circuits of the viewer's receiver. The thermal noise level can be calculated from the relationship $P_n = k\,T\,B$, where

$k = 1.38 \times 10^{-23}$ joules

$T = 308^{\circ}K$ (corresponding to $35^{\circ}C$ cabinet temp.)

$B = 6 \times 10^{6}$ (6 MHz IF bandwidth for vestigial sideband)

therefore

$$P_n = 1.38 \times 10^{-23} \times 308 \times 6 \times 10^{6} = -136 \text{ dBW}$$

In practice, a combination of galactic and man-made noise appreciably exceeds the thermal noise level and is the limiting factor where no discrete interfering signals exist. The level of man-made noise is appreciably higher in urban locations than in suburban. In rural regions, the man-made noise is generally low, and can approach that of galactic noise. In general, suburban noise levels have been found to be about 18 dB above rural, and urban levels an additional 16 dB above suburban. The actual differences depend on frequency, terrain and the nature of the local industries.

Figures 2-2 and 2-3 show the median expected levels for galactic and man-made noise, in rural, suburban, and urban locations as a function of operating frequency. These characteristics are based on data provided by A. D. Spaulding of the Dept. of Commerce (Reference 11). The dotted characteristics parallel to the median lines indicate the root-mean-square value of variation about the mean ($\pm 1\sigma$ values).

2.2.3 Expected Signal-to-Noise Ratios

The principal concern is with urban and suburban locations, since these involve the greatest fraction of the viewing population, where any interference would constitute a major nuisance. The expected signal-to-noise ratio at any particular location, can be derived by combining the expected signal level with the expected level of noise. Since the expected level of noise is a location-dependent variable, it is necessary to treat this element as a statistical variable.

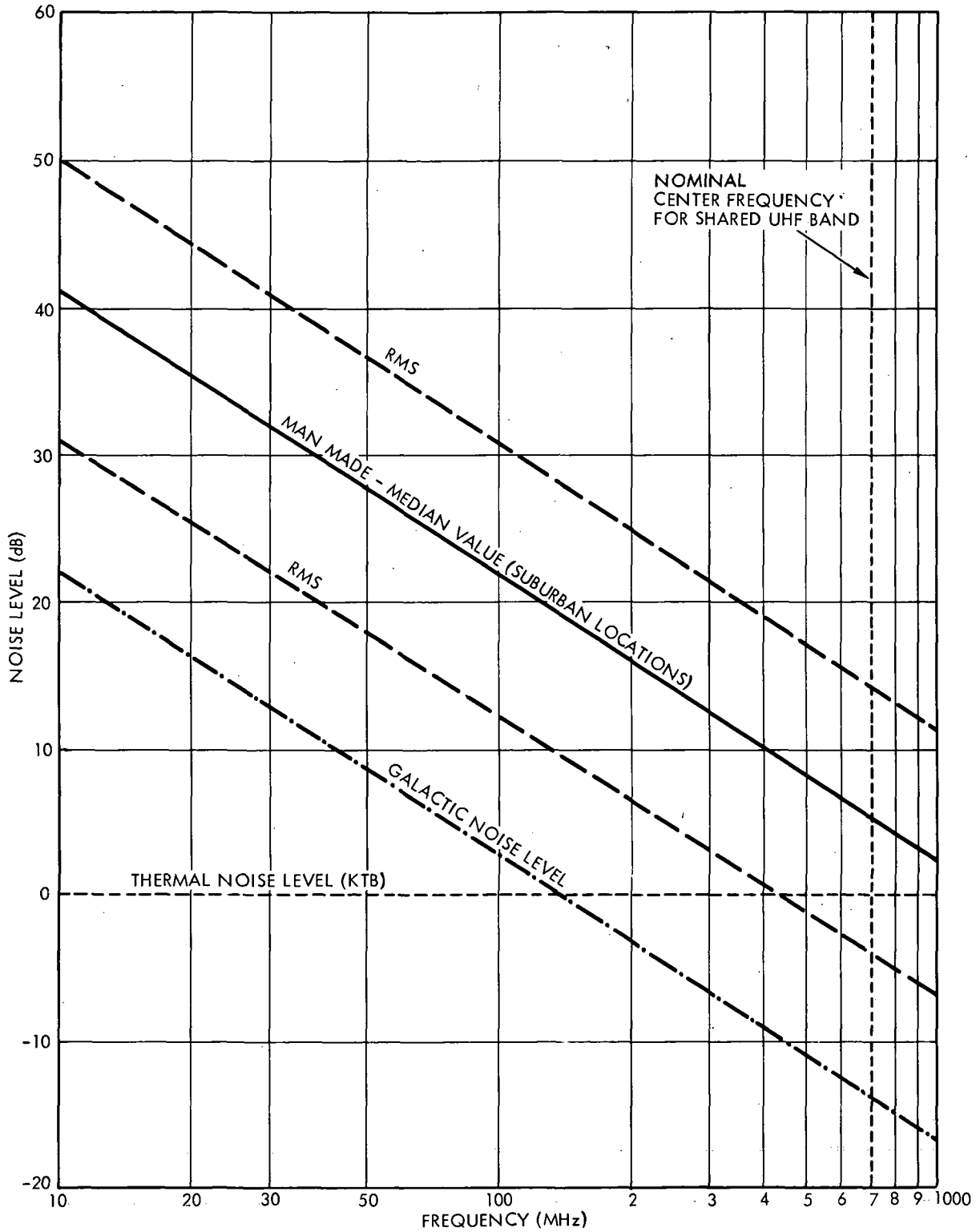



Figure 2-2 Median and RMS Values for Man-Made Noise in Suburban Locations, and Galactic Noise, Versus Frequency. Noise Shown in dB Relative to KTB.

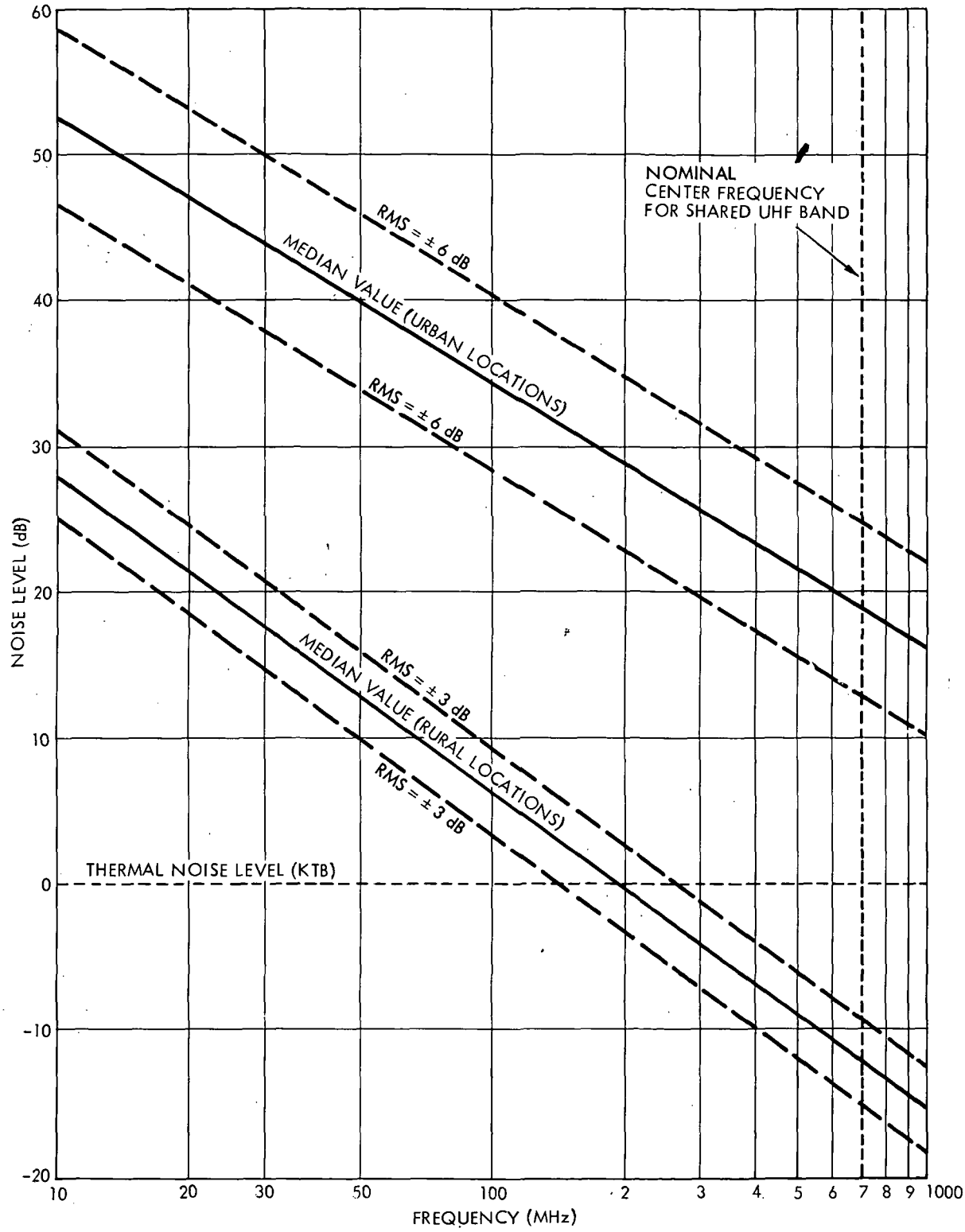



Figure 2-3. Median and RMS Values for Man-Made Noise Levels Relative to Thermal (KTB) Versus Frequency.

In the noise data presented, A. D. Spaulding derived the RMS value for the variation in the expected noise power. Lacking detailed information of the exact statistical distribution, we shall assume a Gaussian form, with the RMS value corresponding to $1\sigma$.

The cumulative Gaussian distribution has the following implication in terms of viewer noise levels, as shown in Table 2-6.

Table 2-6. SNR Degradation Statistics

| REGION | | URBAN | SUBURBAN |
|---|---|---|---|
| % of Viewers | Noise Level Experienced | SNR Degrad. (dB) | SNR Degrad. (dB) |
| 50% | Median | - | - |
| 84 | Median + RMS | 6 | 10 |
| 93.3 | Median + 1.5 (RMS) | 9 | 15 |
| 97.7 | Median + 2 (RMS) | 12 | 20 |
| 99.4 | Median + 2.5 (RMS) | 15 | 25 |
| 99.86 | Median + 3 (RMS) | 18 | 30 |

The expected values for SNR at receiving locations experiencing median levels of man-made noise are developed in Table 2-7.

### 2.2.4 TV Performance Requirements

Determining what level of picture quality is needed to satisfy user demands is a complex and difficult task, because it entails a highly subjective evaluation of quality and because it also is dependent on the nature of the transmitted material.

A number of studies have been made, in which the organizers have sought to generate statistical data from actual tests with multiple observers; examples are References 10, 12, 13 and 15 which report on some 38,000 ratings obtained from 200 observers aged 18 - 65 years.

As a result of these tests the authors developed a series of curves that illustrated how viewers rated various scenes as a function of superimposed interference levels. Five curves were developed to show percent voting by quality assessment in grades ranging from excellent, through passable, to inferior on the following basis: (Table 2-8)

Table 2-7. Estimated Receiver SNR

| Channel | Median Frequency | Median Noise (dB above KTB) | Median Absolute Noise (dBW) | Expected SNR (dB) |
|---|---|---|---|---|
| 2 | 57 | 38.8 | -97.2 | 48.7 |
| 4 | 69 | 37.4 | -98.6 | 48.0 |
| 5 | 79 | 36.2 | -99.8 | 48.8 |
| 7 | 177 | 29.6 | -106.8 | 53.5 |
| 9 | 189 | 29.2 | -106.8 | 53.2 |
| 11 | 201 | 28.8 | -107.2 | 52.4 |
| 13 | 213 | 28.2 | -107.8 | 53.4 |
| 22 | 521 | 21.2 | -114.8 | 48.5 |
| 24 | 533 | 21.0 | -115 | 53.1 |
| 28 | 557 | 20.6 | -115.4 | 46.9 |
| 34 | 593 | 20.2 | -115.8 | 52.9 |
| 40 | 629 | 19.8 | -116.2 | 63.2 |
| 52 | 701 | 18.8 | -117.2 | 48.6 |

Table 2-8. TV Picture Quality Ratings

| Rating | Assigned Adjective | Description |
|---|---|---|
| 1 | Excellent | Extremely high quality, as good as could be desired. |
| 2 | Fine | High quality, providing enjoyable viewing; perceptible interference. |
| 3 | Passable | Acceptable quality; interference not objectionable. |
| 4 | Marginal | Poor quality, improvement desirable; interference somewhat objectionable. |
| 5 | Inferior | Very poor; tolerable viewing; definitely objectionable interference present |

Under adjacent channel interference conditions, 50 percent of the viewers found that reception was acceptable for a signal-to-interference ratio of 27 dB. For random noise, 50 percent found the picture of passable quality for an RMS noise to RMS synchronizer signal ratio of 27 dB.

Co-channel interference between two TV signals can cause annoying "beat" effects when the carriers of the wanted and unwanted signals are located close together. The required signal-to-interference ratio (S/I) as a function of the carrier separation for 50 percent of the observers to rate the picture as passable is tablulated below. Note that the required S/I ratio varies in a cyclic manner.

Table 2-9. Required S/I in Presence of Co-Channel Interference

| Carrier Offset (Hertz) | Required Signal/ Interference Ratio (dB) |
|---|---|
| 360 | 22 |
| 604 | 41 |
| 9, 985 | 24 |
| 10, 010 | 17 |
| 19, 995 | 29 |
| 20, 020 | 17 |

This cyclic phenomena occurs because for 360 Hz, 20, 000 and 20, 020 values of carrier frequency offset, a visual interlace effect occurs which results in a finer bar structure, alleviating the annoyance value of the interference. A study of the optimum offset values to minimize co-channel interference between TV stations was made by W. L. Behrend, and the FCC, and reported back in 1956 (Reference 14).

## 2.2.5 Satellite Transmission Levels

When a satellite-to-ground link is operated in a frequency band shared by other services, the maximum power radiated must be limited to avoid interference. The actual levels that can be tolerated depend on many factors of which one of the most important is the power levels used by the other terrestrial systems.

The International Radio Consultative Committees (CCIR) have examined the technical problems of interference and issued preliminary recommendations in 1963. These suggested the following maximum limits for the flux density produced at the earth's surface:

Table 2-10. Permissible Satellite Radiation Flux Densities

| Type of Modulation | Max. Flux Density (DBW/sq/meter) | Restrictions |
|---|---|---|
| Wideband FM | -130 | All Arrival Angles |
| Wideband FM | -149 | Per 4 kHz BW, All Arrival Angles |
| Other Than FM | -152 | Per 4 kHz BW, All Arrival Angles |

The above limitations were developed for channels shared between satellites and terrestrial line-of-sight radio relay systems.

Tests on the ground, involving interference between regular VSB/AM television station signals have led to a general rule that about a 30 dB signal to interfering signal ratio is required to provide acceptable performance. This criterion is used in the re-allocation of domestic TV channels in contiguous regions across the United States. This ratio assumes a small but significant carrier separation to preclude "beat" (heterodyne) pattern inteference effects. In the case of a non-synchronous satellite, additional separation is necessary to accommodate the Doppler frequency shift.

In 1966 the CCIR established a revised recommendation for satellite power which took into account the fact that most terrestrial antennas were directed towards the horizon and would tolerate a greater incident interference signals at angles near the vertical (Reference 16). To allow for

this effect, they suggested increasing the specified flux levels by $\theta/15$ dBW where $\theta$ is the angle between the satellite and horizon at the receiving point. This allows 6 dB more power under nadir conditions.

In the case of satellite transmitted TV signals, the concern is with reception by domestic TV receivers. These antennas range from dipoles to fairly complex log periodic and parabolic reflector arrays. For the case of the dipole we can convert the CCIR recommendation from a flux density to an absolute power level by correcting for the effective collecting area of the antenna. The effective area (A) is given by the expression (Reference 17).

$$A = \frac{G(\lambda)^2}{4\pi}$$

For the case of a half wave dipole (G = 1.64), and the UHF band 620 - 790 MHz (average f = 700 MHz), the area is:

$$A(\text{dipole}) = \frac{1.64 \times \left[\frac{300}{700}\right]^2}{4\pi} = 0.058 \text{ sq. meters}$$

This is about 1/17 meter and, therefore, amounts to about 12.4 dB relative to a unit area. The expected interference signal at a TV receiver due to a satellite complying with the CCIR flux density specification will be 12.4 dB below -152 dBW or -164.4 dBW max., in any 4 KHz bandwidth.

If all the 4 KHz segments comprising the TV signal bandwidth of say 6 MHz were uniformly loaded to this level, the total interference power level ($P_{(TOT)}$ would be:

$$P_{(TOT)} = -164\,\text{dBW} + 10\log\left[\frac{6 \times 10^6}{4 \times 10^3}\right]$$

$$= -164.4 + 31.8 \quad -132 \text{ dBW}$$

Appendix A shows that the same simple dipole would receive a useful TV signal of about -82 dBW. This would be in a major city and corresponds to a field intensity of 10 mV/meter. Outside the city the FCC has stipulated 5 mV/m for "A" quality reception, and 1.6 mV/m for "B", so the expected signal levels are:

- Major City (10 mV/m) = -82 dBW
- "A" Regions (5 mV/m) = -85 dBW
- "B" Regions (1.6 mV/m = -90 dBW

With the assumption that approximately 30 dB of signal to-interference ratio is necessary under "B" grade service conditions, a nominal satellite power limit of -120 dBW (total) is indicated. This is at least 12 dB above the recommended CCIR level derived above. The levels of TV signals, noise and interference are illustrated in the combined chart, Figure 2-4.

These preliminary calculations indicate that actual test results will verify the feasibility of operating satellite downlinks at appreciably higher levels than the CCIR recommendation. A further improvement is expected by optimizing the form of modulation used by the satellite.

### 2.2.6 Energy Dispersal Modulation

A major factor in the magnitude of interference produced by a television signal is the non-uniform energy distribution in the frequency domain. A significant amount of energy is located in the line structure associated with the scanning frequencies, but additional energy concentration results from certain scene characteristics; for example, when a picture has large areas of the same brightness.

Members of a CCIR study group have suggested that this could be alleviated by modulating the TV carrier with an additional signal, termed a "dispersal waveform". The proposed signal waveform would be added to the regular video waveform prior to the carrier modulation process. The dispersed waveform would be extracted at the receiver, to yield the regular video signal (Reference 18).

Symmetrical and saw tooth waves were evaluated as candidates, with repetition frequencies in the range of 12.5 - 50 Hertz.

Preliminary experiments by the CCIR team indicated a clear performance advantage when the new waveform was synchronized with the field rate. The peak-to-peak level of dispersal wave amplitude used in the tests was in the range 10 - 50 percent of the peak-to-peak video amplitude (before pre-emphasis). Two methods for the removal of the energy dispersal waveform at the receiver were studied, namely:

- Local waveform cancellation
- Black Level clamping.

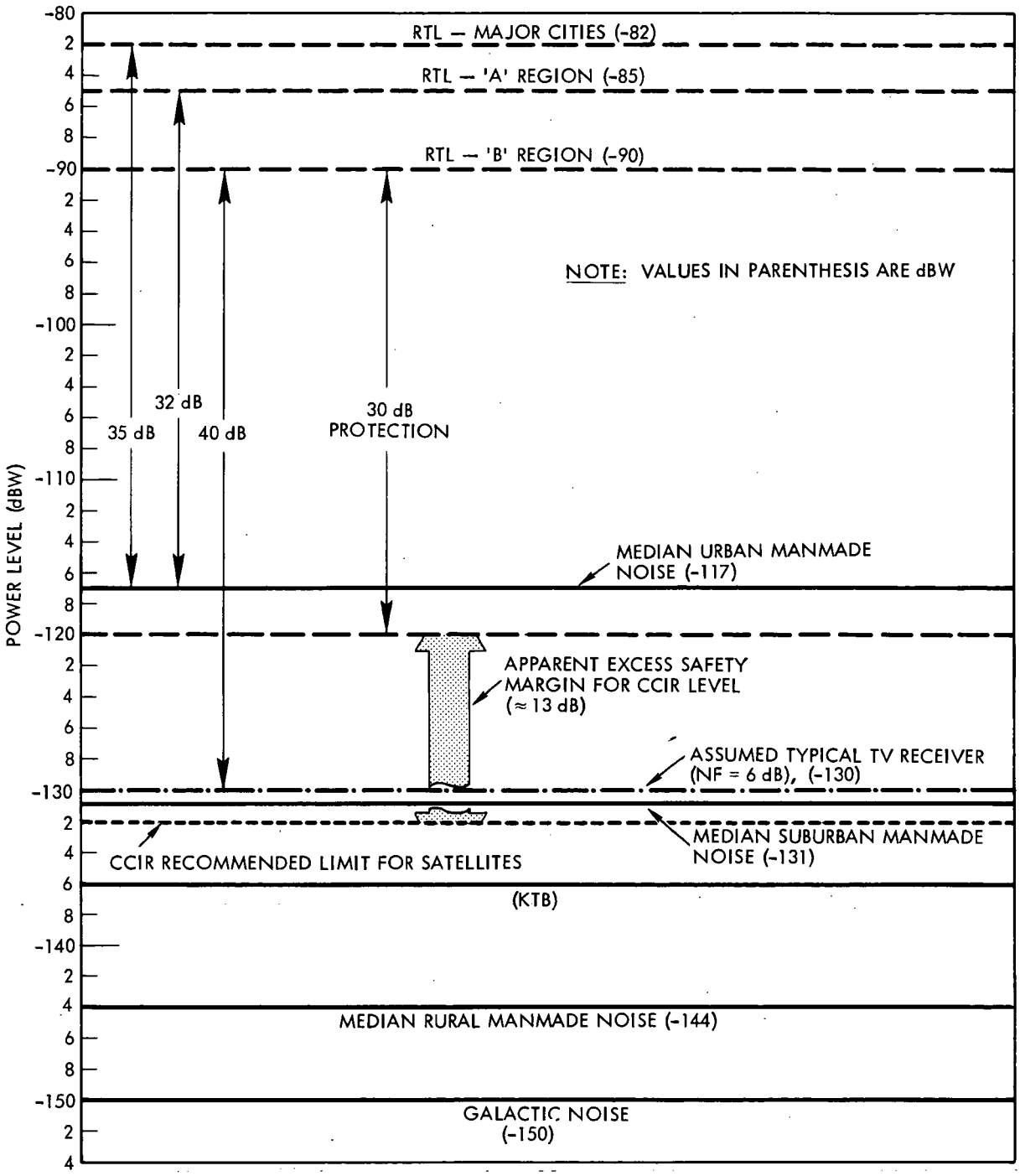



Figure 2-4. Signal, Noise and Derived Levels for UHF TV at a Nominal Frequency of 700 MHz (Note: Values in Parenthesis are dBW).

The first method involves generating a local sawtooth replica and subtracting this from the received "dispersed video" signal. The circuitry implementation proved somewhat complex compared with the second approach.

Black level clamping involves the use of a circuit element already present in the receiver, called the "DC restorer". It serves to hold the brightness level over long periods and prevents level drifting which would otherwise arise because of the lack of DC coupling between camera and CRT and the finite time constant of the coupling components (see Reference 19). Because the dispersal waveform has a very slow rate of change, the resulting clamped video exhibits only a slight shading of the intensity across the picture.

The results are summarized in Table 2-11.

Table 2-11. Performance Comparison of Sawtooth and Symmetrical Triangle Dispersal Waveforms

| Type of Waveform | Picture Impairment | Synchronization Impairment | Dispersal Waveform Rate Effects | |
|---|---|---|---|---|
| | | | 12.5 or 25 Hz | 50 Hz |
| Sawtooth | Barely Perceptible Shading of Intensity | Serious Distortion During Field Blanking Interval Upsets Synch. | Negligible Flicker | Perceptible |
| Symmetrical Triangle | Still Impaired After Single Clamp Stage | No Impairment | Annoying Flicker Cured with 2 Clamps | Gradation Across Middle of Picture |

Although these tests were based on the European synchronization frequencies, it seems likely that the results would have been quite similar had values of 15, 30 and 60 Hertz (appropriate to U.S. systems) been used.

Energy dispersal is clearly an interesting technique which could allow higher power to be used for space TV transmission without increasing the interference with terrestrial systems in shared bands. The simplicity of the dual clamp needed for a signal extraction is compatible with the concept of low cost domestic receivers. The small required modification is well within the ability of any amateur electronics enthusiast who might participate in the experiment evaluation.

## 2.3 EXPERIMENT OBJECTIVES

The basic objective of this experiment is to obtain substantial additional data on the magnitude of interference experienced by terrestrial communication systems from the transmissions of orbiting communication/navigation satellites. Its pracitcal implementation, however, is complex because of the several variables involved and resulting large combination of conditions.

Since the terrestrial services involved in this investigation are presently providing useful and important services to the community, a very important objective is to obtain the desired data with a minimum of interruption to these terrestrial systems. This objective will be attained by a combination of two methods. First, only the minimum power necessary to produce perceptible and measurable interference shall be used, rather than use extreme levels that obliterate the terrestrial services. Second, the interference source shall be activated for a minimum time, sufficient to obtain reliable measurements.

## 2.4 EXPERIMENT DESCRIPTION

An orbiting experiment module will be equipped with a relatively high power tunable transmitter and facilities for implementing a wide variety of combinations of modulation schemes, antenna polarizations and operating frequencies. Figure 2-5 illustrates the conceptual configuration of the experiment. The general arrangement of the equipment needed to perform the susceptibility tests described is shown in Figures 2-6 and 2-7. Figure 2-6 depicts the equipment arrangement used in the orbiting experiment module, while Figure 2-7 shows a ground receiving station.

For the initial implementation of this experiment, it is proposed to restrict activities to the 620 - 790 MHz UHF band that is now shared between space TV and terrestrial TV (Channels 39 to 67). This will facilitate the common use of a quantity of VHF-UHF equipment already specified for other experiments. The coverage will be extended to the microwave region after initial results have been obtained and the data collection method has been optimized.

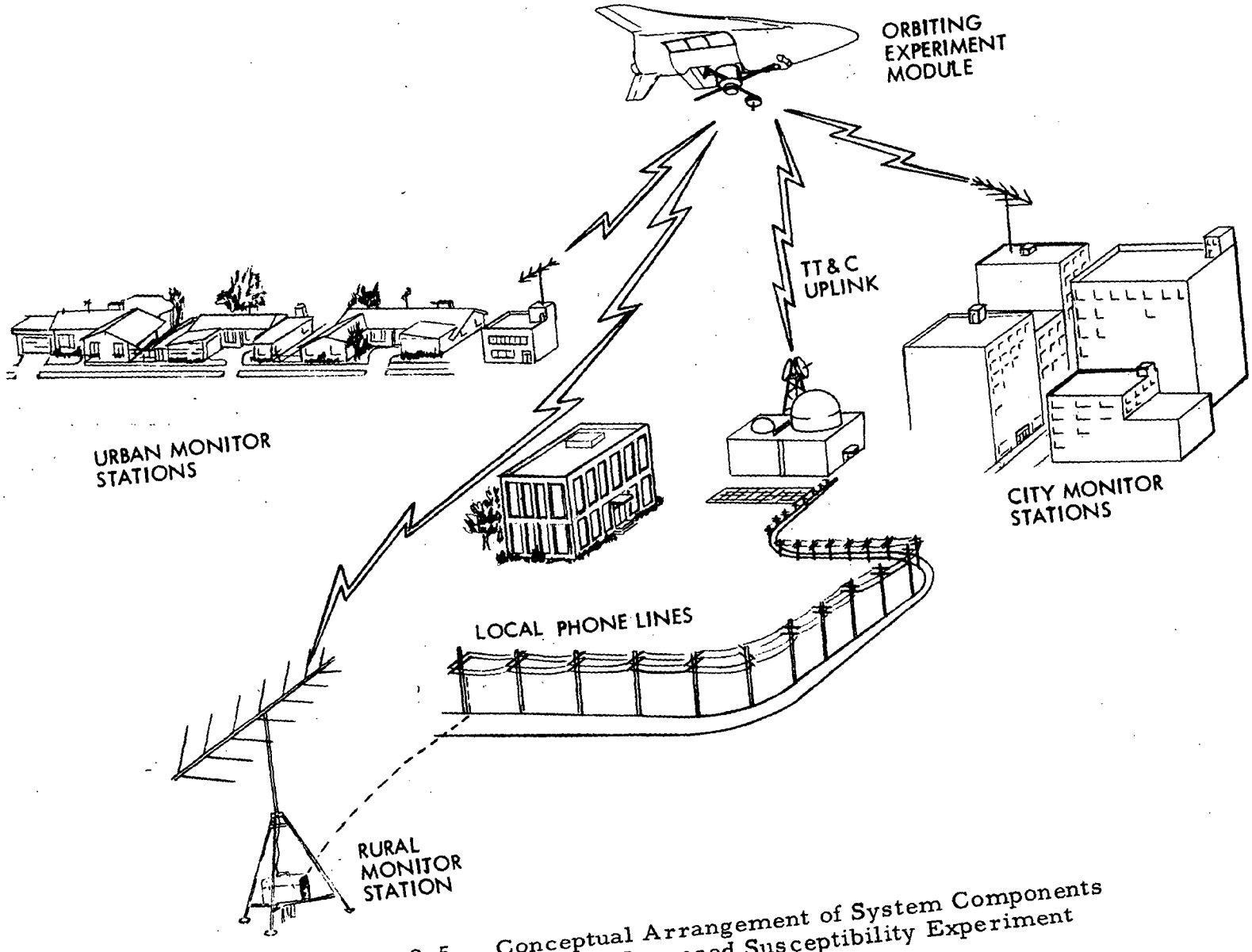



Figure 2-5. Conceptual Arrangement of System Components Used for Proposed Susceptibility Experiment

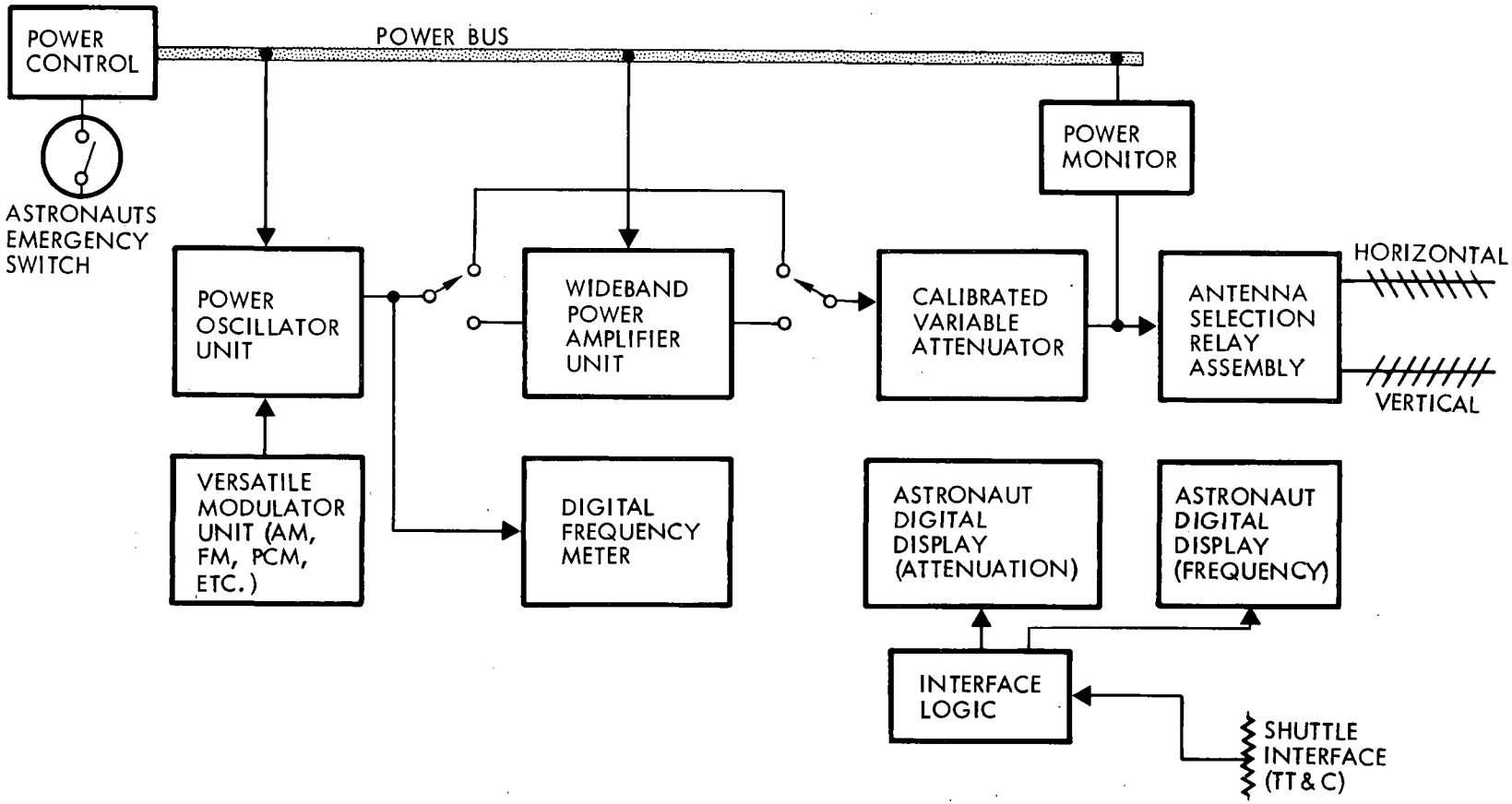
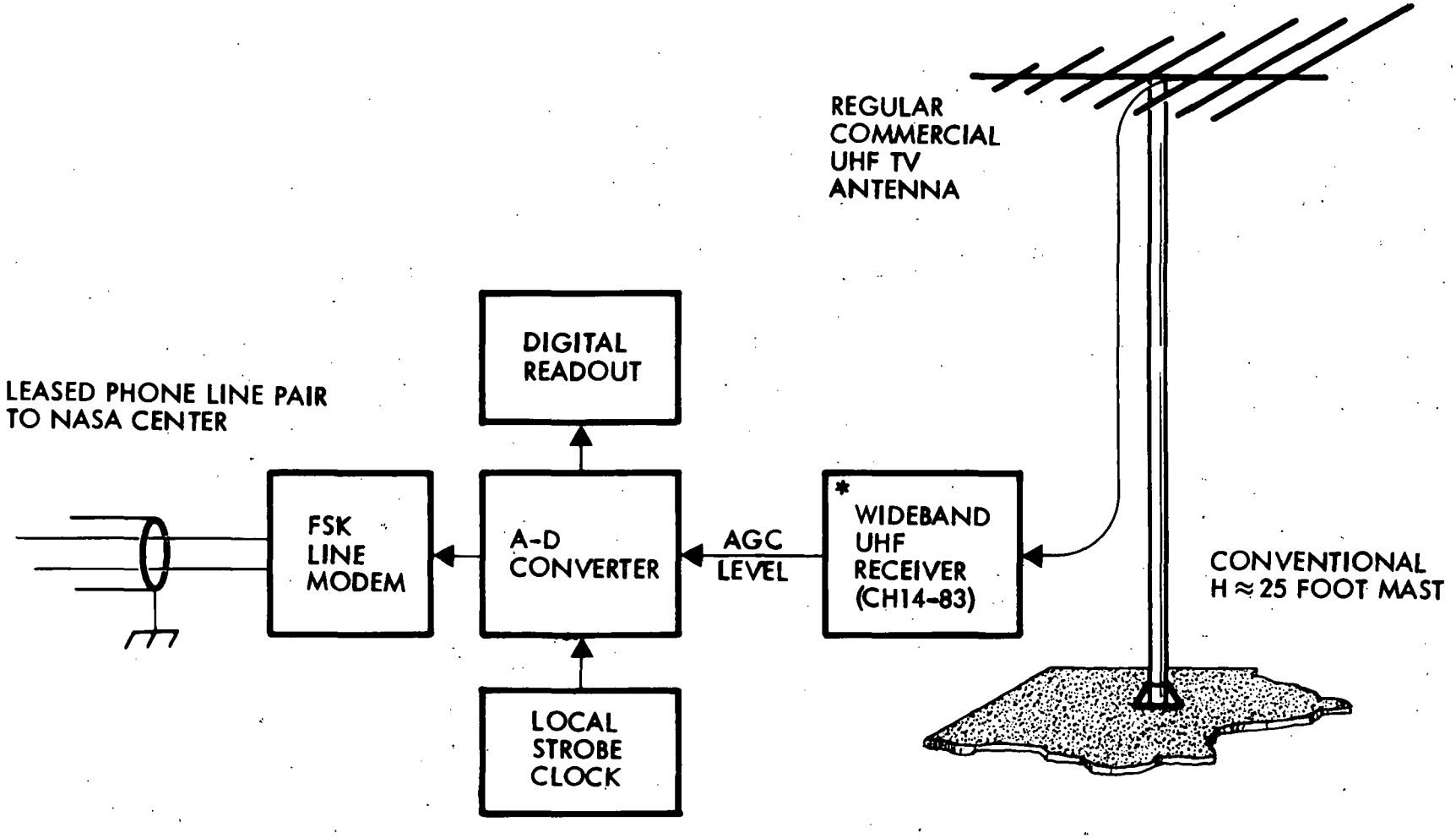



Figure 2-6. Experiment Module Subsystem




* PROPOSE USING REGULAR COMMERCIAL SOLID STATE TV RECEIVER

Figure 2-7. Receiving Station Subsystem

The proposed method of measurement will involve monitoring the signal levels obtained within UHF/TV channels 39 through 67 at ground sites with regular horizontal commercial antennas, oriented toward relevant local stations (e.g., Mount Wilson in the Los Angeles area).

The separate monitor stations will be connected to a convenient NASA tracking station by leased telephone lines. The received signal level, due to the orbiting transmitter, will be quantized by an analog-to-digital converter and the value transmitted over the leased lines as FSK binary words. At the NASA tracking station these signals will be converted back to binary words and fed to a general purpose computer. The computer will utilize a software algorithm to combine the many received signal samples and determine what adjustment should be made to the ERP of the orbiting experiment transmitter to minimize interference while collecting useful data. The appropriate command words will be generated and sent via the command uplink to the experiment module where they will be implemented by the astronaut. For later flights it is proposed to operate this power regulation arrangement on a closed loop basis.

The signal level output from the transmitter in the orbiting experiment module will be standardized (calibrated) by the astronaut so that the initial power is accurately known.

## 2.5 OBSERVATION/MEASUREMENT PROGRAM

The initial phase of this experiment involves measuring the interference levels experienced by ground receiving systems operating in the UHF television band. Since these tests are at UHF, it is proposed that common RF equipment be shared with other experiments. Because the tests will result in finite deliberate interference with existing terrestrial communications and require a multiplicity of cooperating ground stations, the experiment will be restricted to those portions of the vehicle orbit that provide continental United States (CONUS) coverage.

In view of the foregoing orbital restriction, it seems highly desirable to combine this susceptibility experiment with that for Terrestrial RF Sources of Noise and Interference, which also entails CONUS cover-

age. This is particularly attractive since the susceptibility tests require only brief periodic transmission between which it will be possible and convenient to gather incident spectral power density data.

The initial activity in space will consist of checking out the transmitter, modulator and associated equipment and then standardizing the power output. An essential feature of this calibration phase will be testing the main power control attenuator and the associated command uplink interface unit and astronaut display. The RF system must be tested in space to ensure that no breakdown occurs due to ionization effects associated with the combination of high RF power level and the zero-pressure external environment. These checks involve testing through all combinations of antenna beamwidth and polarization to ensure that no breakdown results for any combination of switch positions.

Following the source related checkout, the astronaut will transfer control of the transmitter to the onboard master experiment clock. Just prior to the onset of visibility on the CONUS portion of the orbit, the experiment clock will activate the transmitter and the desired level will be determined via ground commands over the command uplink. The astronaut will receive the desired power reduction commands via a digital display, and will manually adjust the transmitter output. A similar display will indicate the required experiment frequency. When a change of frequency is indicated, the display will alert the astronaut.

Table 2-12 shows the preliminary recommendations for an experimental measurement program. The group of tests described will require refining when the payload has been defined to integrate the several experiments and further examine equipment commonality.

## Table 2-12. Proposed Measurement Plan for Initial Tests

| ACTIVITY | CONDITIONS | ORBIT | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | PRE-CONUS | CONUS #1 | PRE-CONUS | CONUS #2 | PRE-CONUS | CONUS #3 | PRE-CONUS | CONUS #4 | PRE-CONUS | CONUS #5 |
| INITIAL EQUIPMENT CHECKOUT AND CALIBRATION | Frequency Ch. Seq. | 39 | | 39 | | 39 | | 39 | | 39 | |
| | Antenna Polarization | - | | | | | | | | | |
| | Modulation | DSBAM | | VSBAM | | FM | | PPM | | PCM | |
| SUSCEPTIBILITY MEASUREMENTS | Frequency Ch. Seq. | | 39 | | 39 | | 39 | | 39 | | 39 |
| | Antenna Polarization | | H, V, CPRM, CPLH | | * | | * | | * | | * |
| | Modulation | | DSBAM | | VSBAM | | FM | | PPM | | PCM |

* Selected on basis of data from Orbits #1

## 2.6 INTERFACE, SUPPORT, AND PERFORMANCE REQUIREMENTS

The support requirements for the terrestrial services susceptibility experiment are summarized in Table 2-12.

Table 2-12. Support Requirements

| Item | Classification | Description |
|---|---|---|
| Electrical Power | Essential | 28 V DC or 400 Hz |
| Temperature | Trade Off | $71^{\circ}F \pm 3^{\circ}F$ to $76^{\circ}F \pm 116^{\circ}F$ |
| Pressure | Trade Off | 28" - 31" or 0 - 31" Hg |
| Vehicle Ephemeris | Essential | Three-Axis History |
| Low Orbit | Trade Off | ≈200 N. Mi. to Minimize Power |
| Time | Trade Off* | Day, Hour, Minute, Second |
| Communications (Data) | Essential | TT&C Up-Link |
| Communications (Voice) | Essential | Up and Down Link |

* Experiment-peculiar equipment or joint unit for all Comm/Nav experiments could be used instead.

## 2.7 POTENTIAL ROLE OF MAN

This experiment requires the services of an astronaut to calibrate the equipment and to operate it during the proposed susceptibility tests.

### 2.7.1 Calibration

Equipment calibration involves checking out the transmitter and modulator to ensure that they are operating correctly, to standardize the output power level, and set the frequency to the desired value.

These activities are scheduled during the non-CONUS portion of the first CONUS coverage orbit to avoid impacting the short period of CONUS overflight visibility.

Operation of high power transmitters in space vehicles is subject to problems from corona breakdown due to the reduced pressure. An operator, monitoring the equipment operation, is able to take prompt action in the event of a failure.

### 2.7.2 Initial Susceptibility Tests

During the susceptibility tests the astronaut responds to power control instructions shown on a digital display. He effects adjustment to the transmitted power level by means of calibrated manual attenuators, that are equipped with a digital readout so that the actual value in use at any time is recorded and can be correlated with the other data during post-mission analyses.

The astronaut is also provided with a real time voice link that allows the NASA ground station to request a shut-down of the transmitter in the event that unexpectedly serious interference is caused to ground services.

### 2.7.3 Data Evaluation

Since the results of the susceptibility tests are available at the ground, it is proposed to perform the data evaluation at an established NASA computer facility rather than transfer this data back up to the astronauts for analysis in the experiment module.

Because the conceptual implementation of the experiment is adaptive (the power level is adjusted to a compromise between detectability and destructive interference), it is not expected that the unprocessed (raw) data

from each orbital test will be needed by the operating astronaut. However, the final outputs from the ground computer will be needed, since these will indicate the effect of changing the several control variables (e.g., frequency, polarization, etc.). For these reasons, no on-board processing or astronaut analysis is proposed.

## 2.8 EXPERIMENT EVOLUTION

Once the basic system has been demonstrated with the astronaut in-the-loop, the emphasis will shift to improving and automating the measurement system. The key change will be replacement of the manual attenuator that controls the transmitter power output with an electrically operated equivalent. A simple interface unit will then permit direct control of the transmitter from the ground using the up-down digital command signals that are already applied to the astronaut's digital readout. Subsequent extensions will involve remote control of the modulation form, carrier frequency, and antenna selection.

During this phase, data will be collected in a basically similar manner, but with different terrestrial test receiver sites. For these activities the astronaut will occupy a low duty cycle supervisory role, but is able to seize control in the event of any emergency and, more importantly, provide a means of interrupting and revising the experiment plan and procedure if necessary.

## 2.9 SRT REQUIREMENTS.

None required.

## 2.10 ACKNOWLEDGEMENTS

Portions of the following references were used in the preparation of this experiment description:

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APPENDIX A

## SIGNAL POWER AVAILABLE FROM A SIMPLE DIPOLE FOR UHF FIELD STRENGTH SPECIFIED IN FCC TECHNICAL STANDARD

The current and voltage amplitude distributions along a simple dipole are of nearly sinusoidal shape. (For a rigorous treatment, see Reference 12).

$$e = \frac{1}{\Pi}\int_{o}^{\Pi} \text{Sin}\,\theta \;.\; d\theta \;.\; Em = \frac{2}{\Pi} \;.\; Em$$

The maximum value of induced voltage (Em) is simply the product of the value of the field strength (E) and electrical length of the dipole. Thus, for a half wave dipole ($l = \lambda/2$) the maximum value is

$$Em = E.\ \lambda/2$$

The receiver represents a matched load for the antenna and thus obtains exactly half of the open circuit voltage value just derived. Combining these expressions we obtain the receiver voltage ($e_r$.) thus:

$$e_r = 1/2.\ \frac{2}{\Pi}\,E.\ \lambda/2 = \frac{E.\lambda}{2}$$

For a representative principal city location, the technical standard specifies a field of 10 millivolts/meter for UHF channels. The average frequency is 1/2 (620 + 790) or 705 MHz, which corresponds to a wavelength of 300/705 or approximately 0.425 meters, so that the receiver voltage will be:

$$e_r = \frac{10 \times 10^{-3} \times 0.425}{2\Pi} = 0.68 \times 10^{-3}\ \text{V, or } \approx 0.7\ \text{mV}$$

The signal power (Pr) will be simply $(e_r)^2/75$, therefore,

$$Pr = \left[6.8 \times 10^{-4}\right]^2 \times \frac{1}{75} \approx \frac{46 \times 10^{-8}}{75} \approx 6.15 \times 10^{9}\ \text{watts or } \underline{-82\ \text{dBW}}$$

This is the level expected in a simple dipole. Multi-element arrays can provide a useful gain of between 3 and 10 dB depending on the design sophistication and signal frequency. These aspects are discussed in Section 2.2.3.

# EXPERIMENT 3

# RADIO FREQUENCY PROPAGATION

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APPENDIX A

# 3. RADIO FREQUENCY PROPAGATION

## 3.1 EXPERIMENT

This experiment starts as an applied research task involving substantial astronaut participation. As the work proceeds and initial data from the VHF and UHF tests are analyzed, the experimental methods will be refined and become more routine. Practical experience with astronaut involvements will provide valuable inputs to equipment refinement.

During the intermediate phase, improved equipment and methods will be developed and the measurements will be automated insofar as proves feasible. During this period the astronaut will be mainly concerned with using the microwave equipment and performing novel special purpose experiments; the automation will permit his participation in the VHF UHF area to be reduced to one of supervision.

In the final phase the complete radio frequency propagation measurement equipment will be heavily automated and the results of the various SRT tasks embodied so that these data collection functions can be accomplished by an unmanned satellite, a laboratory sub-satellite, or supervised at a low level by the final laboratory staff. The relevant classifications are, therefore:

- Early Lab — Applied research and equipment testing.
- Growth Lab — Equipment development, automation and operation.
- Total Lab — Routine operation with low level supervision of the experiment.

## 3.2 EXPERIMENT OBJECTIVES

The objectives of this class of experiments are to establish high confidence level statistics on specific RF propagation effects, including multipath, ionospheric scintillation, and Faraday rotation. Further, it is desired to extend these investigations from the initial VHF and UHF region to the shorter wavelengths and to supplement these tests with absolute path loss and phase coherence tests in the microwave and millimeter wave bands. Finally, absolute path loss data for a 60 GHz milli-

meter wave test link between the laboratory and one or more satellites will be obtained.

These statistics will provide insight into the manner in which the propagation parameters vary as a function of latitude, longitude, time of day, season and year, weather conditions, sunspot activity and selected frequency. The end application of the resulting data will provide substantial benefits to communication and navigation systems. Examples of their useful application are as follows:

- Establish the magnitude of multipath effect to be expected as a function of terrain, altitude, frequency, and path geometry essential to the design of air-to-air, air-to-satellite, and air-to-ground links.

- Provide system design reference data on the expected excess communication link loss due to ionospheric scintillation effects, as a function of latitude, longitude, time of day and year, frequency used, path geometry, and beam cross section. This data avoids assigning arbitrary power margins for miscellaneous effects and will quantify the statistics for excess loss.

- Polarization data is of considerable importance in allowing the system designer to make tradeoffs between circularly polarized, linearly polarized, and polarization tracking antenna systems.

- The measurement of absolute path loss when combined with the specific loss phenomena already enumerated will close the link calculation loop.

- Detailed phase coherency measurements over a wide frequency range will yield data of initial importance for the early implementation of ultrawide bandwidth data transmission systems, urgently needed for an increasing range of information collection/user systems, from avionics and navigation to earth resources and pollution control satellites.

- The 60 GHz tests are intended to provide data on the feasibility of low orbit to synchronous orbit, and low orbit to low orbit satellite communication systems. In particular, the tests will establish the extent to which the communications path may intercept the earth's ionosphere before the losses make the link unfeasible.

## 3.3 DISCIPLINE BACKGROUND AND STATUS

Currently available information on multipath, atmospheric scintillation and polarization rotation phenomena is not statistically adequate to allow satisfactorily reliable space communication and navigation systems to be designed.

There has been a significant investigation of multipath effects, particularly as they related to aircraft-to-ground communication. Unfortunately much of this data is of doubtful utility because little is known of the terrain, weather conditions and similar factors. The newer aircraft in the 1980s are expected to operate under sufficiently different communications conditions that appropriate propagation data will be essential. The following changes are expected:

- Appreciably higher altitudes for supersonic planes
- Greatly increased use of ground reaction vehicles such as hovercraft having zero altitude
- Significantly higher velocities (>Mach 2) with the attendant higher Doppler
- Significantly greater aircraft traffic density
- Institution of air-to-air and air-to-ground telephone, teletype, TV and data services for passengers
- Adaptive flight plans resulting in large changes in air corridor usage depending on weather.

In order to provide the drastically improved avionic communication and navigation services needed to support these developments, we shall require an abundance of statistically valid data on radio propagation covering the complete RF and optical spectrum. Without this, data systems will be designed on a brute force basis and fail to meet the 1980 needs.

## 3.4 EXPERIMENT DESCRIPTION

The experiment involves investigation of five separate phenomena which will be pursued as two sub-groups. Initial tests will be restricted to the VHF-UHF frequency regions. This simplifies the measurement, maximizes commonality of equipment, and permits a wide choice of proven off-the-shelf equipment. On the foregoing basis, it is recommended that initial measurements be made of multipath, scintillation and polarization rotation in the VHF and UHF frequency range, followed by absolute path loss and correlation bandwidth in the microwave and millimeter wave regions. Figure 3-1 illustrates the three propagation phenomena to be investigated.

### 3.4.1 VHF and UHF Tests

The following sub-sections discuss each phenomena and describe the proposed measurement technique, equipment requirements resulting data outputs and allied topics.

#### 3.4.1.1 Features of VHF-UHF Test Group

- Involves operating an aircraft (or sub-satellite) -to-laboratory communication link at VHF and UHF frequencies in the frequency range 100-700 MHz.
- High altitude aircraft (>50,000 ft.) minimizes meteorological effects associated with surface weather.
- High altitude maximizes time difference for earth-bounce multipath signals, easing separation of variables.
- Laboratory orbit altitude ideal for measuring ionosphere characteristics (Reference Figure 3-3).
- Log periodic or helical narrow beam antenna looks earthward while collecting signal from cooperating transmitter.
- Broad band receiver allows choice of test frequency in the range 100-1000 MHz.
- Initial use of sweep receiver mode allows rapid astronaut check on signal level and adjacent interference, using display.
- 35 mm film camera attached to panoramic display lets astronaut record adjacent signal environment.
- Predetermined programs of multipath and scintillation tests can be called up from the on-board computer by the astronaut.

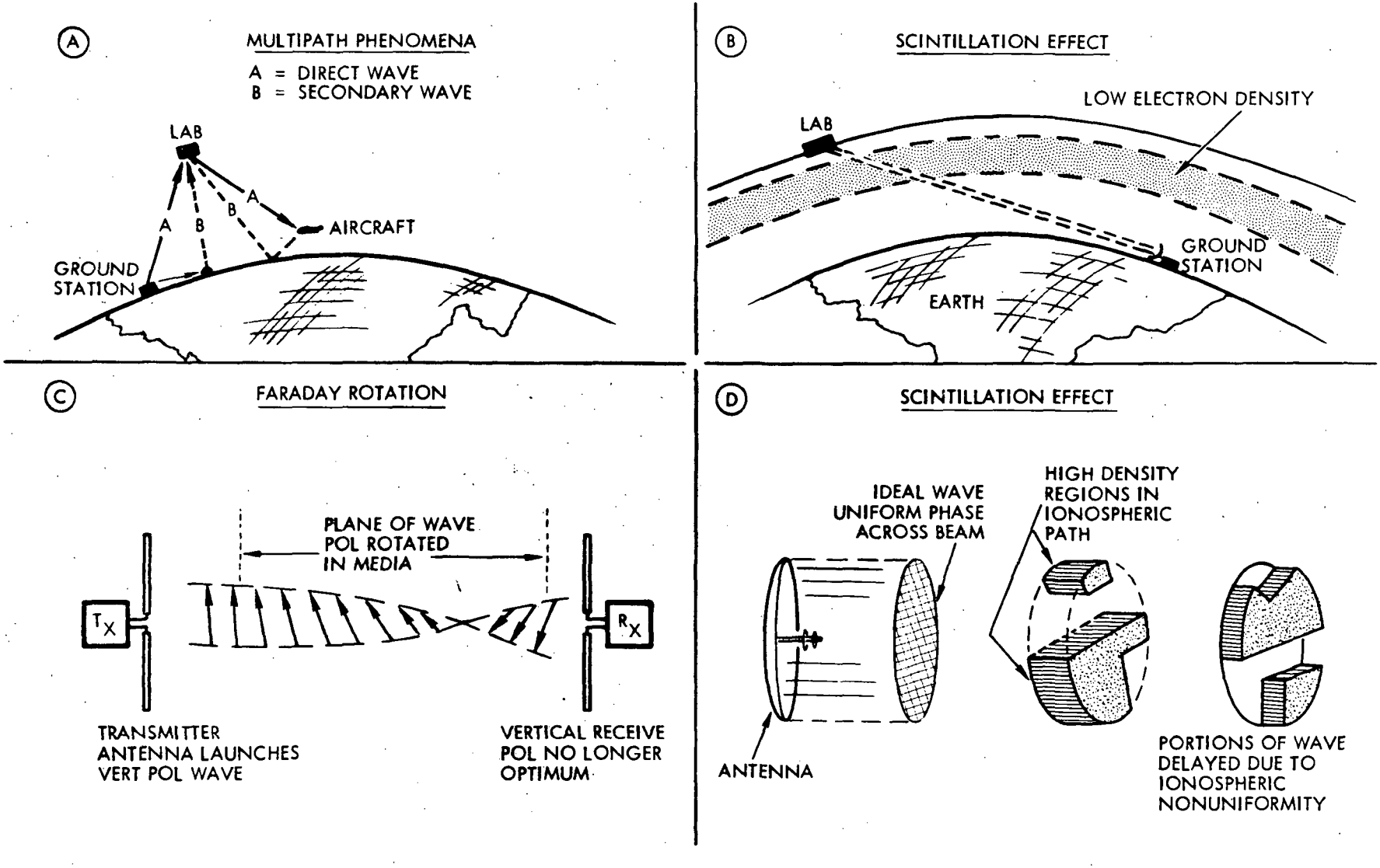



Figure 3-1. RF Propagation Effects

### 3.4.1.2 Candidate Cooperating Sources

Both the multipath and scintillation experiments entail the use of a test transmitter remote from the orbiting laboratory. There is a wide range of candidate methods of providing this source. Table 3-1 identifies these candidates and compares them from a standpoint of applicability.

Of the options available, a dedicated NASA high altitude aircraft, or a shuttle deployed sub-satellite appear to be the most attractive approaches. Implementation of these methods is, therefore, assumed in the further definition of the multipath and scintillation experiments.

### 3.4.1.3 Experiment Parameters

The parameter value and constraints selected for the multipath and scintillation tests are shown in the following table:

| Parameter | Test Application | Value or Constraint | Justification/Comments |
|---|---|---|---|
| Geographic Coverage | Scintillation | Worldwide to $\pm 50^{\circ}$ Lat. | Limited by permissible orbit for shuttle. Varies with latitude. |
| | Multipath | CONUS only | • Adequate variety of terrain in N. America.<br>• Need low/med altitude flight path; easiest in CONUS. |
| Frequency Range | Scintillation & Multipath | 100 - 1000 MHz | • Ready availability and modest cost of equipment maximizes probability of obtaining useful data from early flights.<br>• Can use common equipment of terrestrial noise and power density experiment.<br>• Major problem is antenna with adequate directivity at low end VHF band. |
| Time of Day | Scintillation | 24 Hr. Period | • State of ionosphere related to incident solar radiation (including sporadic-E patches).<br>• Also seasonal and sun spot cycle dependent. |
| | Multipath | No Constraint | • Multipath effects independent of time of day except indirectly EG increased soil conductivity from dew. |

# Table 3-1. Candidate Cooperating Targets for VHF-UHF Multipath/Scintillation Experiments

| BASIC TARGET CLASS | SUB-CLASS OPTIONS | SPECIFIC EXAMPLES | APPLICABILITY OF SERVICE | | | | COMMENTS |
|---|---|---|---|---|---|---|---|
| | | | FREQ. | CONTI-NUITY | Geographic Availability | ERP | |
| GROUND SURFACE TRANSMITTING STATION | CIVIL/COMMERCIAL STATION | Commercial TV Stations | 54-88, 174-216 470-890 | Good | Excellent | 0.1-1 MW | |
| | | Commercial FM Stations | 88-108 MHz | Good | Excellent | ? | |
| | | National Time Standards | 20-25 MHz | Excellent | Acceptable | 0.1-1 KW | |
| | | Police, Taxi, Amateur | VHF | No | Good | Low | |
| | | Navigation Aids & Beacons | See Comments Col. | Excellent | Fair | Low | 75, 108-118, 328-335, 960-1215 |
| | NASA GROUND TRACKING STATION | Goldstone, Calif. (DSIF & MSFN) | up 2.1 GHz dwn 2.3 GHz | | | | 85 ft. dish; USB; Lat. 35° 20.5', Long. 243° 7.5' |
| | | Madrid, Spain (MSFN) | " | | | | 85 ft. dish; USB; Lat. 40° 20.3', Long. 355° 50' |
| | | Honeysuckle, Austrailia (DSIF) | | | | | |
| | | Rosman, N. Carolina (STADAN) | 137, 400 & 1700 MHz | | | | 85 ft. dish Lat. 35° 12'N, Long. 85° 52'W |
| | | Fairbanks, Alaska (STADAN) | | | | | 85 ft. dish Lat. 64° 59'N, Long. 147° 31'W |
| VESSEL AT SEA | NASA TRACKING SHIP | USNS - VANGUARD | | | | | |
| | US AIR FORCE TELEMETRY TRACKING SHIPS | | | | | | |
| | US NAVY FLEET SHIP | | | | | | |
| AIRCRAFT IN FLIGHT | CIVIL AIRLINERS ON REGULAR SCHEDULED FLIGHTS | AIRLINE COY / Flights: Domestic / Internat. | | | | | |
| | | American: x / | 108-132 | Poor | Fair | ≈0.1 KW | |
| | | National: x / | | | | | |
| | | United: x / x | | | | | |
| | | Eastern: x / | | | | | |
| | | Pan. Am. / x | | | | | |
| | | Western: x / | | | | | |
| | | Braniff: x / | | | | | |
| | | Allegheny: x / | | | | | |
| | NASA DEDICATED RESEARCH HIGH ALTITUDE AIRCRAFT | CONVAIR MODEL 990 | | | | | |
| | | NASA U-2 HIGH ALTITUDE | | | | | |
| | MILITARY AIRCRAFT | ROUTINE FLIGHTS? | 225-400 | Poor | Fair | 0.1-1 KW | |
| ORBITING SATELLITE OR JETTISONED SPACE PACKAGE | CURRENT CIVIL SATELLITE (1980 T. F.) | ERTS-X | | | | | |
| | | NIMBUS-X | | | | | |
| | | EOS | | | | | |
| | | ATS-X | | | | | |
| | | SKYLAB-A/B | | | | | |
| | | HEAO | | | | | |
| | | NAVSAT | | | | | |
| | | TDRS | | | | | |
| | EXPERIMENT PECULIAR SATELLITE/PACKAGE | SHUTTLE DEPLOYED SUB-SATELLITE (See "Blue Book") | | | | | |

### 3.4.1.4 Multipath

#### Phenomena

When radio signals propagate from a transmitter to a receiver by more than one path, the receiver senses a composite signal which can result in degraded reception. Degradation results because, in general, the signals arriving by the various routes experience different propagation delays and, as a result, partially cancel at the receiver terminals reducing the available signal-to-noise ratio. When one signal is very small compared with the other, the cancellation is minimal; but, when the paths are similar and the amplitudes comparable, the net signal level can fall 10 to 20 dB under antiphase conditions. Multipath becomes particularly troublesome for moving vehicles, for which the signal amplitude is modulated by the vehicle motion. In a practical situation, there are usually multiple paths rather than just two as discussed above. For multiple paths the phasing becomes more random.

Multipath is a major source of communication impairment for aircraft because at VHF/UHF frequencies the ground acts as a reasonably effective reflector. For communication between satellites and fixed ground stations it has been necessary to develop antennas with specially tailored side lobes to avoid spurious returns from adjacent terrain. Aerodynamic factors preclude the use of these ground antennas on aircraft. Compounding the problem are the various reflective surfaces of the aircraft structure itself and their motion.

#### Techniques

There are two commonly used techniques for measuring multipath, namely,

a) Spatial modulation extraction, and
b) Burst echo comparison.

In the first method, an aircraft-to-ground communication link is established and a signal level recorder installed at one terminal. A permanent record of the signal level versus time is obtained by connecting this recorder to the receiver. The amplitude vs time characteristic incorporates three separate loss characteristics:

a) Range dependent loss

b) Multipath cancellation loss

c) Antenna misalignment loss.

The range dependent term, under far-field conditions, will generally be in accordance with the expression:

$$\alpha \text{ (dB)} \propto 20 \text{ Log}_{10} \text{ Range (miles)}$$

The multipath cancellation effect causes a cyclic amplitude modulation. Antenna misalignment loss can occur if the aircraft banks or turns etc., and is a rapid effect. Misalignment loss also occurs, to a lesser extent, as the aircraft flight path progresses and varies the viewing angle, but this is a slowly varying effect. Figure 3-2 shows how these separate effects combine to yield the overall signal flight history characteristic.

The burst echo comparison method uses a quite different approach. It is based on the assumption that the separate multiple paths responsible for signal degradation involve substantially different physical lengths and transmission delays. When this is true, a short bust transmission results in the reception of a main signal followed by one or more replicas. If the received signals are stored, in an appropriate media, they can be recalled for leisurely analysis. Comparison of the amplitude and time delays exhibited by the replicas allows the multipath effect to be quantified and often correlated with specific terrain features or path geometry.

The key parameter for the burst echo method is the length of burst signal used. If a long burst is used the secondary multipath signals will arrive during the receipt of the primary signal. If the burst is too short the available processing time for signal integration and phase and level measurement is too small, the SNR is poor, and the measured data is uncertain. The periodic nature of the burst method results in a discontinuous set of data points rather than a continuous but possibly ambiguous record.

The foregoing discussion covers the basic technique; the actual implementation involves a number of refinements and computer analysis for variable extraction.

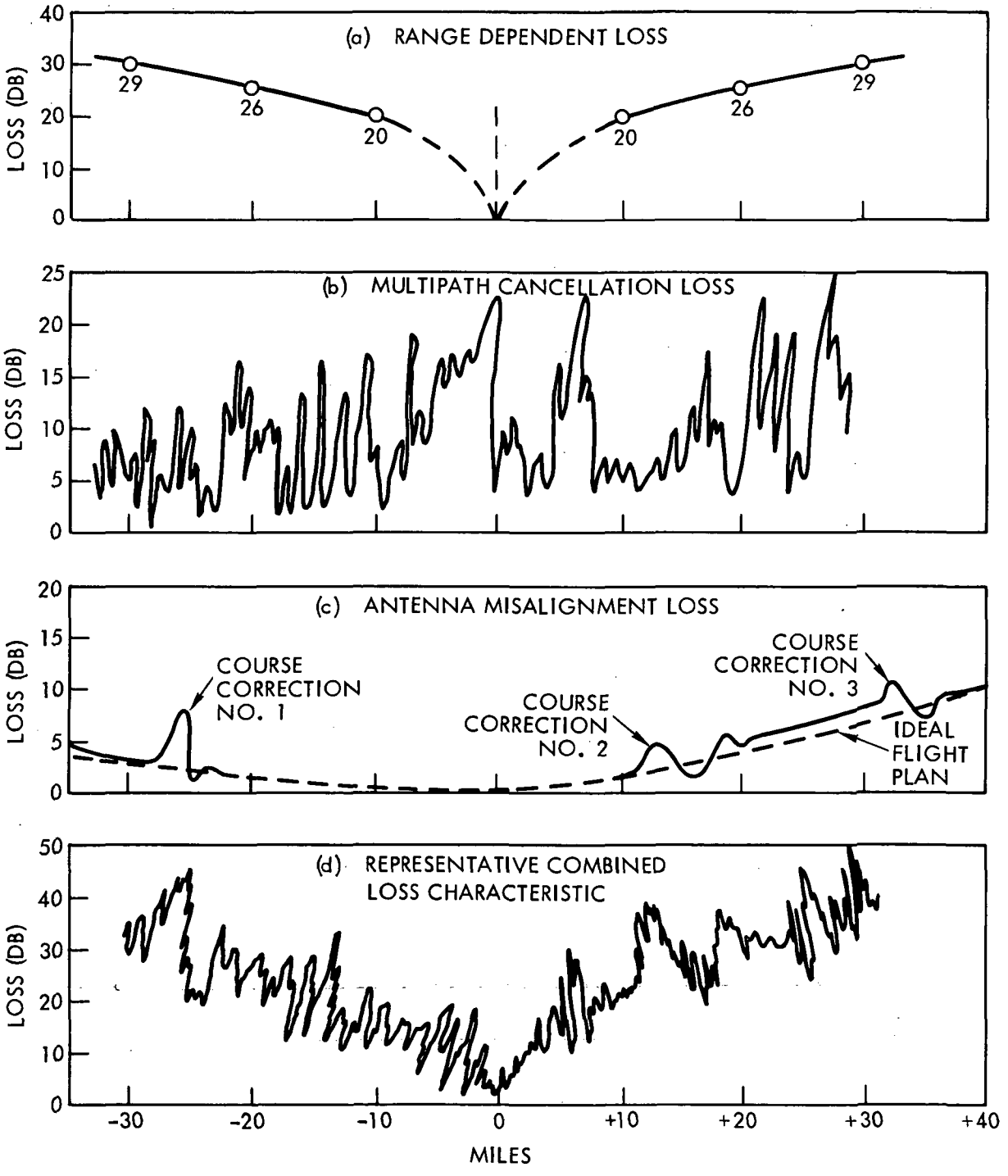



Figure 3-2. Composition of Signal Loss Factors Including Multipath

When the transmission path involves a ground to non-synchronous-satellite link, the following additional variables have to be taken into account:

a) Polarization loss due to laboratory (satellite) motion
b) Range loss as a function of laboratory motion
c) Atmospheric anomaly scintillation loss.

Polarization loss due to the imperfect alignment of the laboratory antenna parallels the two effects described for the aircraft; namely, a smooth orbit-related change and sporadic navigational maneuver-related changes. The range loss becomes a more complicated calculation for an orbiting laboratory rather than a ground station, because of the more complex three-axis geometry needed to establish the relative velocities and corresponding point values of line-of-sight range.

3.4.1.5 Scintillation

Phenomena

The earth is surrounded by an atmospheric blanket, beyond which the pressure and molecular gas density tail off into the hard vacuum of space. Solar radiation photons impinging on the outermost regions of low molecular density generate ionized layers. These layers are regions of relatively high electron density which exhibit radio wave absorbing and reflecting properties. Although the layers are dispersed, the reflection and refraction effects they exhibit are indicative of a series of concentric spherical shells, whose height and electrical characteristics vary with the solar illumination on a daily, seasonal, and long term ($\approx$11 year) basis. The commonly accepted model is shown in Figure 3-3.

During daylight hours the primary ionized region is the area embracing the D and E layers where the electron density is of the order of 10,000 electrons per cubic centimeter. The local refractive index at any point depends on the specific electron density at that point and has a fractional value. When there are variations in electron density across the beam in the plane of propagation, the normally coherent phase front can be mutilated. Under these conditions the wave front can be considered as comprising a series of individual signals which have traversed paths of different characteristic delay and attenuation. When such signals are

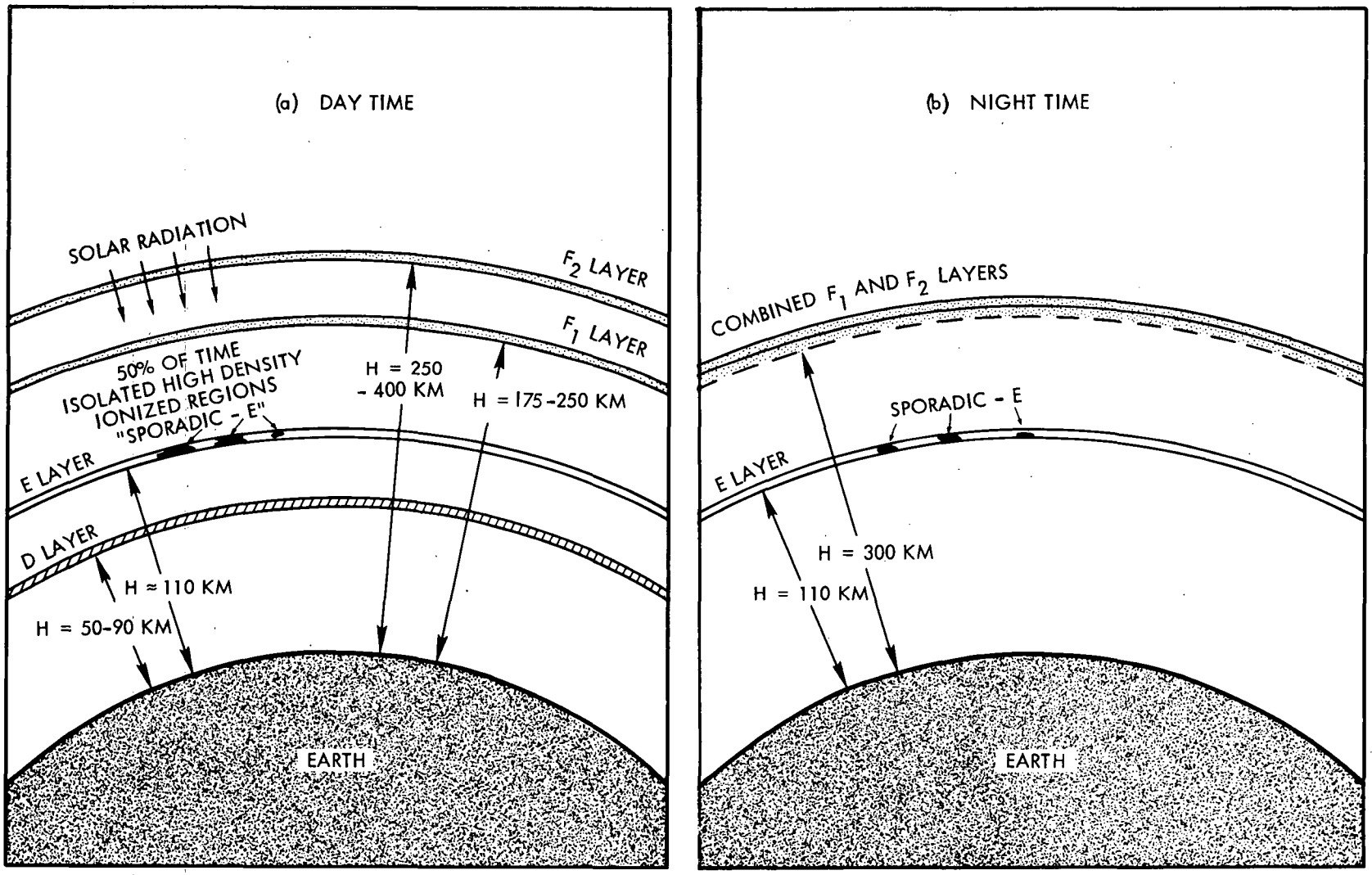



Figure 3-3. Ionosphere Model

collected and processed at the receiver, partial cancellation can occur in a manner similar to that experienced by multipath components.

For a space communication link, these effects are a function of many variables including: the path geometry, geographic region, frequency used, time of day, and level of sporadic - E.

Technique

The measurement technique involves establishing an earth-to-orbiting laboratory communication link and measuring the effect of the increasing length of ionospheric path as the line-of-sight path changes from horizon glancing tangent, through zenith to opposite horizon tangent as shown in Figure 3-4.

3.4.1.6 Polarization Rotation

The polarization of electromagnetic waves is modified by the interaction of the wave with charged particles in the ionosphere. The effect is frequency dependent and can cause additional signal loss. It is also a factor in limiting wide bandwidth modulation.

Phenomena

The ionosphere is a stratified spherical blanket encircling the earth. It consists of modest to low density gas molecules and free electrons. Solar radiation incident on the gas molecules causes ionization, liberating electrons and leaving behind ionized positively charged molecules. In the lower "D" layer of the ionosphere the particle density is relatively high so that individual electrons have a small value of mean free path, and lifetime. In the outer layers, electrons have relatively large mean free paths and can travel significant distances without being involved in a collision.

When an electromagnetic wave traverses a path having an axial magnetic field component, the plane of polarization of the wave is rotated. The effect is due to the interaction of the field with the free electrons and is termed the Faraday effect after its discoverer.

The mechanism by which the polarization is rotated is as follows: The electrical disturbance associated with the wave front exerts a small but finite pressure on the free electrons which lie in its path. As a

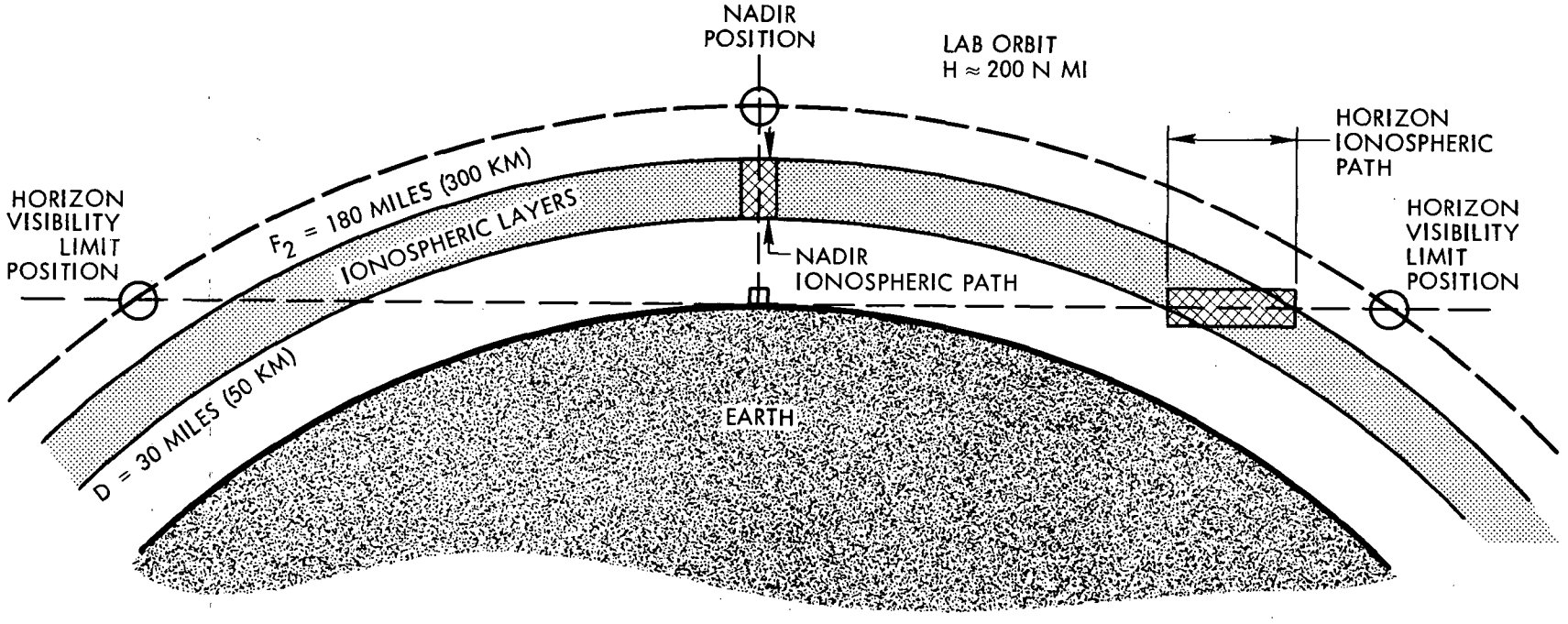



Figure 3-4. Ionospheric Paths in Scintillation Experiment

result, the electrons are given a small velocity component in the direction of the wave. The resulting initial motion of the electron in the earth's magnetic field occasions a magnetic field reaction, orthogonal to the direction of the wave motion. The interaction of the longitudinal and lateral field components results in a twisting or rotation of the polarization of the wave vectors.

The magnitude of the effect depends on the following factors:

a) Electron density along the propagation path
b) Component of magnetic field intensity along the path
c) Transmission frequency
d) Length of propagation path through the ionosphere.

Unfortunately the first two factors are dependent upon other variables. The electron density is highly dependent on the incident solar radiation, which varies with the time of day, geographic region, season, and year within the nominal 11 year cycle. The magnetic field intensity is a function of the geographic location and altitude above the earth's surface. Any transmission path will generally involve a significant distance and necessitate allowing for the spatial variation of these factors along the path, since the overall rotation is the integral of the local effects along the path.

As an indication of the order of magnitude of effect to be expected, an angular rotation of approximately 6.5 radians ($\approx$360 degrees) occurs when a 100 MHz signal is transmitted vertically from the earth to a satellite beyond the ionosphere. The angular rotation in polarization ($\Delta\theta$) as a function of transmitted frequency (F) obeys an inverse square law, i.e.,

$$\Delta\theta \propto 1/(F)^2$$

Because of this frequency dependence, under certain conditions, components of a wideband modulated signal can suffer differential attenuation and delay degradation.

Techniques

Measurement of the Faraday rotation of a radio wave entails two related measurements. First, it is necessary to determine the incremental variation and, second, to resolve the ambiguity.

The incremental measurement involves local determination at the receiving terminal of the antenna polarization angle that yields a maximum signal. Resolution of the ambiguity means establishing the integral number of $\pi$ radian rotations that have taken place. In the example previously cited involving a frequency of 100 MHz, the total twist was 6.5 radians. One cycle is $2\pi$ or approximately 6.3 radians. A measurement based on the required receiving antenna polarization angle for maximum signal would yield an answer of 0.2 radians, i.e., just the incremental portion.

There are two methods by which the ambiguities can be resolved:

a) Spatial plotting, and

b) Use of multiple frequencies.

In the spatial plotting method, a succession of incremental angular rotation measurements are made as one of the terminals moves with respect to the other. The relative motion alters the path length and consequently the total Faraday rotation. Neglecting other factors, the small change (assumed to be much less than one radian) provides a measure of the rotation rate as a function of path length. As an example, if the maximum signal corresponded to 20 degrees at a station spacing of 200 n. mi., and to 30 degrees at 205 n. mi., the indicated rotation is 10 degrees per 5 n. mi., so the corresponding zenith total radiation would be $\frac{200}{5} \times 10 = 400$ degrees. The ambiguity is $n\pi$ radians, where n equals 2 in this case and the expected increment is 40 degrees (400 - 360). The incremental term is, of course, obtained by measurement and not by extrapolation from the spatial plots.

A limitation in the use of this method lies in the time taken to secure the multiple readings. The implicit assumption made is that the only experimental parameter that varied was the path length. In a real life situation the ionospheric characteristics are highly non-linear along the communication path so that the concept of an average rotational rate is not technically defensible, and it is necessary to measure the Faraday rotation as a function of path length on a semi-continuous basis and plot the results.

The multiple frequency method is very similar in concept, but makes use of the approximately inverse frequency squared relationship for rotation. In this method, measurements are taken at three or more different

known frequencies. By combining the incremental data and solving the resulting equations, the ambiguity factor in radians can be established.

The method of taking measurements is very similar to that employed in the scintillation tests. The laboratory will orbit the earth at some 200 miles altitude. Transmitters located on cooperating aircraft and ground stztions will transmit the radio signals to the orbiting laboratory where their arrival polarization will be measured. As the laboratory circles the earth, the signal path will encompass varying lengths of the ionosphere. Measurements will be required over paths at a number of geographic locations to accommodate the range of terrestrial magnetic field conditions. Temporal variations in the incident solar radiation require measurement at various hours throughout the day-night and for all seasons.

The primary experiment variables are summarized in the following Table:

| Control Variable | Dependent Variables | Dimensions | |
|---|---|---|---|
| | | Major | Minor |
| Location | Earth Magnetic Field | Latitude | Longitude |
| Location | Solar Radiation | Latitude | Season |
| Time | Solar Radiation | Hour of Day | Season & Yr. |
| Frequency | Ionization Density | Megahertz | - |

Two hardware implementations can be used for the laboratory polarization measurement equipment: a simple rotating antenna or an orthogonal component resolver "goniometer". The first mentioned involves the use of a rotary joint allowing the antenna to be physically rotated to orient its polarization axis. The second method makes use of an assembly of hybrid transformers connected for a pair of orthogonal linear antennas (Merimac Corp.). The hybrids allow formation of various phased sum and difference terms and thereby establish the unknown angle without any physical rotation.

Data Acquisition Rate

The value of polarization rotation can be obtained either by an astronaut manually operating some form of resolving control, or semi-automatically. In either event constraints that affect the rate at which data points can, or need to be obtained, must be established.

Any of the following factors could impose limitations:

a) Rate of polarization change

b) Time needed for manual measurement

c) Response time of semi-automatic equipment

d) Desired data accuracy

e) Motion of lab or cooperating transmitter (if mobile).

If the polarization angle is changing rapidly, the astronaut may find it quite difficult to take readings. To form some preliminary ideas on the importance of this aspect of measurement, the suggested orbit of 200 n. mi. was used to derive slant range time history and tentative polarization rates as follows:

As the laboratory passes over the cooperating ground station, the slant range decreases from 700-800 n. mi., depending on the assumed horizon cut-off angle, to 200 miles at the nadir position, and increases again to the extreme value. A significant portion of this slant range path lies through the ionosphere and is subject to the Faraday rotation effect. The length of this portion increases from a minimum, at zenith, to a maximum at either range limit.

This preliminary analysis assumes that the region subject to Faraday rotation increases in proportion to the total slant range value. The rate is also a function of the frequency being used and is highest at the lowest frequency. For this evaluation a value of 100 MHz has been assumed. At this frequency the Faraday rotation at nadir is approximately 370 degrees.

Appendix A presents the geometric model and calculations used to derive slant range, range rates, total Faraday rotation, and rotation rates for a series of laboratory orbital positions, assuming a cooperating

transmitter located on the laboratory subtrack. The position range covers from 15 degrees off nadir through nadir in 1-degree steps; the 10-degree horizon cutoff angle corresponds to a 12 degree off-nadir Lab position. The results of the analyses are summarized in Table 1 of Appendix A The highest rate of change of polarization angle occurs at the range limits, where the rate is about 7.4 degrees per second.

When a human operator measures a static polarization value, he adjusts an orientation control while observing a signal display. The final setting is usually attained by sweeping through the correct value once or twice ("Rocking-Into-A-Null"). When the quantity being measured is varying, the operator must effectively track the value over the control scale. For rates of the order of 7 degrees per second, simple manual measurement does not appear feasible.

The time taken for an operator to take a reading involves several variables, including:

a) Desired accuracy

b) Design of control and indicating system

c) Operator dexterity

d) Nature of effect to be negated

For polarization angle measurements, a 2 degree accuracy in measurement relative to the laboratory structure appears a reasonable objective. Many factors are involved in the overall measurement and additional study is needed to investigate and balance their contributions in a cost effective manner.

The design of the measuring system can significantly affect the reading time; examples include controls having backlash, or incorrect gearing ratios. The indicator sensitivity and response law are also very important.

Some degree of manual dexterity is needed for all manual adjustments. The system should make full use of the man's limbs and brain but not make unreasonable demands.

When the measured parameter is varying, the way in which it varies plays an important role in establishing the operator's ability to obtain an accurate reading.

One mode of operation for manual measurement is to provide the operator with a quantizing or data entry key so that he can attempt to track the signal polarization continuously, pressing the data entry key each time he believes he has optimized the position. The key would ensure that the polarization readings are only recorded when the operator has made a fix. This approach would minimize the amount of data storage needed, but precludes taking advantage of the ground processing computers.

Semi-Automatic Measurement

There are two simple ways in which the phase measuring system can be made semi-automatic, namely:

a) Scan interpolate

b) Servo tracking.

In the scan interpolation method the antenna associated with a laboratory receiver is rotated relatively fast compared with the estimated maximum rate of phase change. As the antenna rotates, the received signal magnitude is quantized and recorded, together with the orientation of the antenna. The orientation data is derived from a binary coded angle transducer. The combined record of antenna polarization angle and signal amplitude allow the arrival polarization to be determined by magnetic tape record analysis on the ground.

The servo tracking scheme follows conventional control theory concepts. The output from the lab receiver is used to control the antenna polarization such that it seeks out and locks onto the correct inclination angle and tracks subsequent changes. This approach can be implemented using a combination of electrically controlled RF phase shifters and attenuators connected to a stationary pair of orthogonal linear (E & H) antennas.

Fundamental Sensitivity

When a linearly polarized antenna is rotated so that its axis of polarization is misaligned with respect to an arriving linearly polarized wave, the available voltage decreases in accordance with the cosine of

the angular misalignment error. A 5-degree error can be expected to cause an amplitude degradation of about 0.5 percent or a power change of about 1 percent (≈0.05 dB).

By contrast, at the orthogonal (totally misaligned) position, the signal rises from zero to 17.5 percent of maximum for a 1 degree change. This relationship is well known to those engaged in direction finding. The disadvantage of determining the null is that the receiving equipment has to operate with a much smaller signal than under aligned conditions. This results in a lower SNR requiring more integration time or higher transmitter power.

#### 3.4.1.7 Experiment Configuration

Figure 3-5 depicts a functional block diagram of the antenna and receiver-related equipment required to implement the VHF-UHF portion of this experiment. Figure 3-6 shows the information processing subsystem which formats the signal tape recorders and generates the essential preamble and postamble entries.

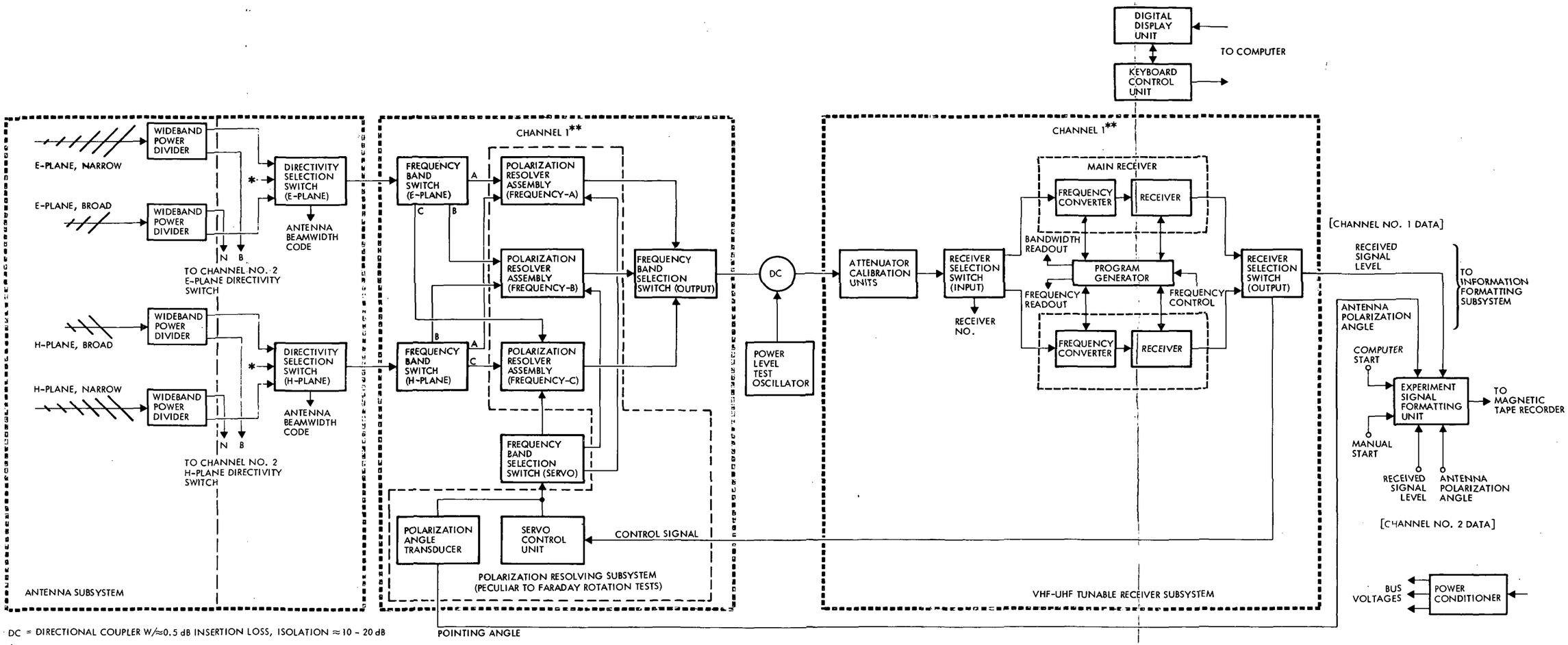
### 3.4.2 Microwave and Millimeter Wave Tests

The tests described in the following subsections are performed with microwave and millimeter wave signals. They require completely different antenna and receiving hardware so it is convenient to discuss them separately.

It is proposed that the Early Laboratory experiments be restricted to the VHF and UHF regions of the spectrum and that the microwave and millimeter wave work be initiated for the Growth Laboratory.

#### 3.4.2.1 Absolute Path Loss

The objective of these tests is to take a statistically significant amount of data concerning the total transmission path loss encountered at selected frequencies in the microwave and millimeter wave regions. The initial test frequencies will be 11, 14, 20 and 30 GHz between the laboratory and ground stations, supplemented by 60 GHz tests with cooperating satellites.




DC = DIRECTIONAL COUPLER W/≈0.5 dB INSERTION LOSS, ISOLATION ≈ 10 - 20 dB

*3RD POSITION PROVIDES SELF NOISE CALIBRATION.

**CHANNEL 2 IDENTICAL TO CHANNEL 1.

Figure 3-5. Equipment Configuration – R. F. Propagation Experiment – Antenna and Receiver Related Subsystem

(Items to right hand side of dotted vertical line show a single channel for clarity. Two channels are proposed.)

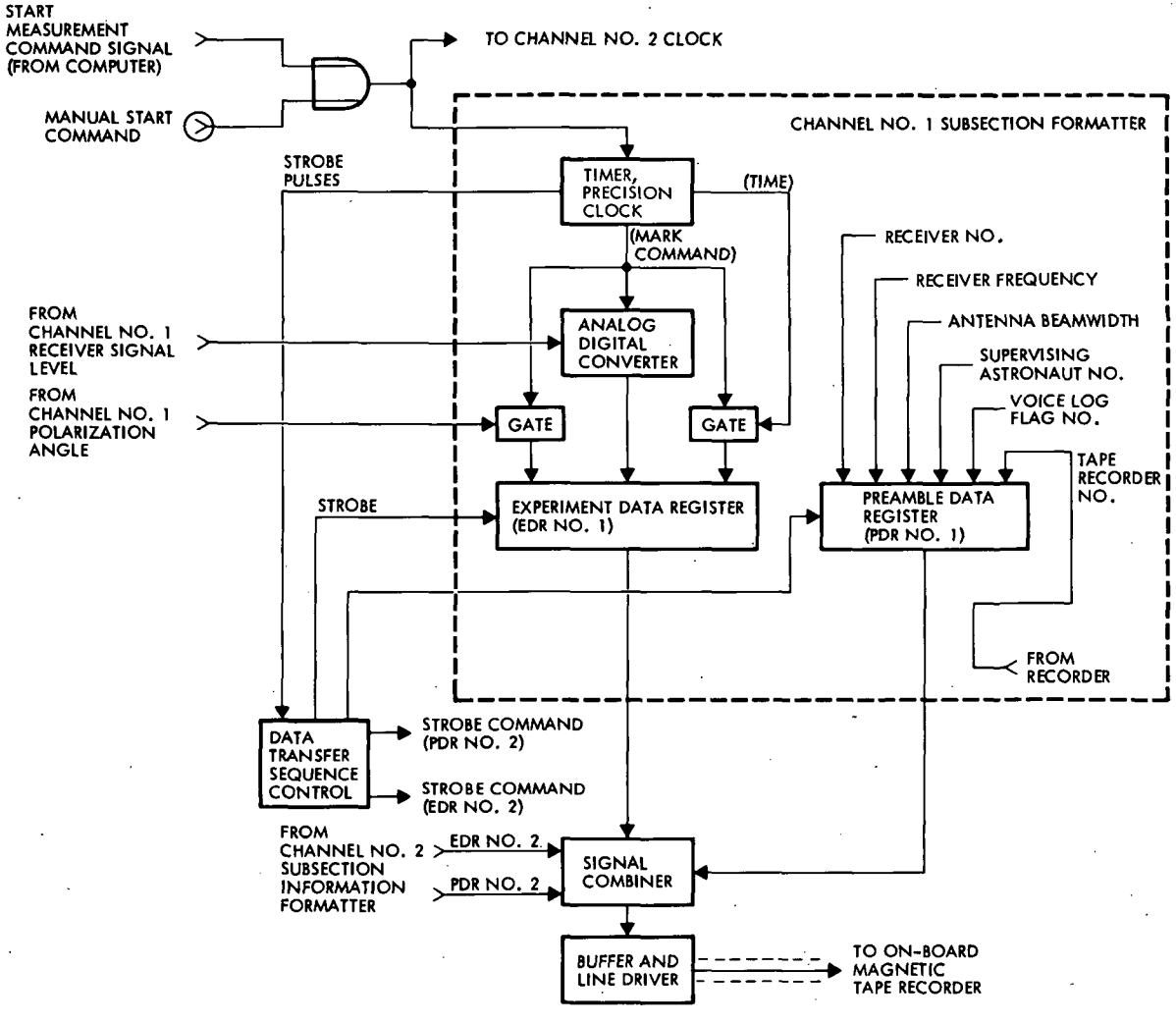



Figure 3-6. Equipment Configuration – R. F. Propagation Experiment – Information Formatting Subsystem

Phenomena

The transmission of microwave and millimeter radio waves often involves substantial attenuation. In order to design space communication and navigation systems having an adequate margin of performance, it is necessary to have statistically valid data on the transmission losses for microwave and millimeter radio waves under various conditions.

The purpose of the tests described in this subsection is to collect this data, initially for the five frequencies defined, subsequently for others as the future space communication needs become established.

Technique

In principle, the proposed measuring technique is very simple; in practice, from a space platform it presents some significant engineering challenges.

The method involves transmitting a fixed frequency radio signal of precisely known power level, and measuring the resulting distant signal power received, as a function of the line-of-sight distance between the transmitter and receiver.

In addition to the transmitter and receiver, several other system components are needed. The introduction of these items results in additional sources of error which must be analyzed and factored into the results. Examples of these potential sources of error are presented in Tables 3-2 and 3-3.

Table 3-2. System Error Factors

| Equipment Item | Parameter Source of Error | Comments | Suggested Specification |
|---|---|---|---|
| - | Distance | Propose Measurement $\pm$ 2% | $\pm$ 1/4 dB |

Table 3-3. Sources of Error in Absolute Path Loss Due to Equipment

| Equipment Item | Parameter Source of Error | Comments | Suggested Specification |
|---|---|---|---|
| Transmitter | Power Output | Linear Error Relationship | ± 1/2 dB |
| | Frequency | Not Critical, Doppler available. | TBD |
| Antennas | Boresight Gain | Linear Error Relationship *Δ | ± 1/4 dB |
| | Polar Pattern | Need Accurate & Comprehensive Data*Δ | ± 1/4 dB |
| | VSWR | SWR Pattern Results in Amplitude Error*Δ | 1.1:1 |
| Cables & Coax Switches | Insertion Loss | Linear ErrorΔ | ±0.1 dB |
| | VSWR | SWR Pattern Results in Amplitude ErrorΔ | 1.05:1 |
| Receiver | Sensitivity | Linear Effect Δ | ± 1 dB |
| | Frequency | Not Critical if Tracking and Adequate if Bandwidth Used | TBD |

* Measured on lab structure in anechoic chamber.

Δ Measured at each actual frequency to be used.

This measurement involves monitoring the transmitter power output and the received signal level as a function of the spatial separation between these two equipments. Gain variations due to non-boresight alignment of the two antennas is minimized by adopting a dual tracking mode. A beacon transmitter located at the laboratory receiver terminal feeds the common Lab antenna, but operates at a slightly offset frequency. This arrangement allows a receiver at the cooperating ground station to track the laboratory orbital motion and maintain the ground station transmitter antenna in a boresight condition.

The laboratory receiver, in turn, tracks the ground station to hold the lab antenna on boresight. These measures minimize any correction needed for antenna misalignment in the subsequent data reduction.

At low elevation angles, when the radio waves graze the earth surface, multipath effects are encountered which can cause a signal tracking system to acquire a spurious reflected wave rather than the main beam. The proposed signal design, incorporating an integral ranging capability, will clearly indicate when this occurs because the range versus time curve will depart from that associated with the laboratory orbit.

Since both the laboratory and ground station are required to have transmission and reception equipment, it is possible to perform the ranging operation from the laboratory or from the ground. Since present NASA ground tracking stations are equipped with pseudo-random code ranging systems and the design of the transponders has been proven, it appears well worth selecting this mode of operation.

## 3.5 EXPERIMENT OBSERVATION/MEASUREMENT PROGRAM

The initial RF propagation tests performed by the Early Laboratory involve collecting a sequence of amplitude and arrival-polarization test signals as a laboratory flies over the location of various cooperating and non-cooperating sources. The first phase involves obtaining preliminary data at several frequencies in the VHF band using a static orthogonal log periodic antenna aided by cooperating ground stations and aircraft. This antenna may be shared with the Terrestrial Sources of Noise and Interference experiment.

These initial measurements are based on a non-pointing, fixed antenna array for simplicity, modest cost, size and weight and maximum probability of timely availability. No analytical processing for end users will be performed in the laboratory, all data will be digitized and recorded on magnetic tape. A quick-look facility will allow the astronauts to evaluate the results as an aid in ensuring that the experimental details are optimized. Additionally, provision may be made for relaying the data to the ground via telemetry link to MSFN or TDRS for near real-time analysis by the principal investigators.

For the Faraday rotation tests, as an example, the quick-look facility will comprise the ability to replay a set of test data and have the test points processed by a local, on-board software routine to yield a characteristic for astronaut's display.

A flow chart for the sequence of operations needed for the display algorithm is shown in Figure 3-7.

The first activity in orbit will be the calibration of the equipment. This involves injecting a stairstep form of signal comprising known incremental increases in power level over a 60 dB range, and recording the corresponding digitized receiver AGC levels.

This is followed by a measurement of the noise factor of the laboratory receivers, using the on-board noise factor test set. This is a conventional device that injects a known level of white noise power, such that when the receiver output power doubles, the injected level is equal to the receiver self-induced noise.

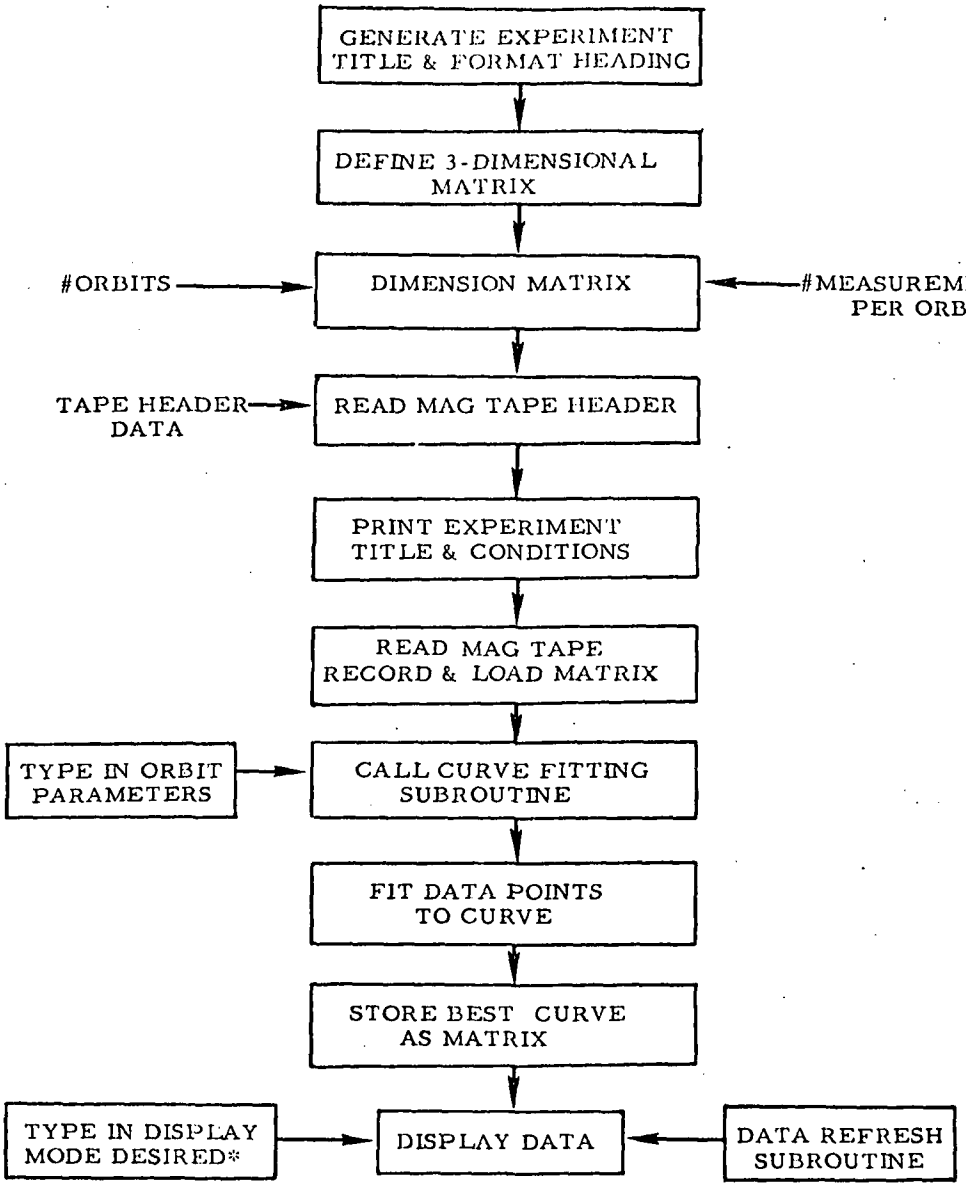



Figure 3-7. Flow Sequence for Quick-Look Software Applied to Faraday Rotation Experiment

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* Astronaut can choose to display any of the following:

1. Best fit curve (BFC) of angle vs time.
2. BFC with actual plots superimposed.
3. Expanded BFC (a few cycles).
4. Printed list of actual values (listing).
5. Printed list of BFC values (listing).
6. Statistical analysis parameters of Faraday rotation for orbit: Mean, Std. Dev., Confidence Factor, etc.

Following the calibration the astronaut initiates the propagation tests, which involve tests between the laboratory and both fixed ground stations and moving vehicles (aircraft, balloons, ships, etc.).

Although the proposed receiving equipment will operate over the entire VHF-UHF band from 100 - 1000 MHz, polarization measurements are restricted to within about 10 percent of the design center frequency of the associated resolver assemblies. For this reason the recommended equipment configuration incorporates three separate resolver assemblies which will be tuned to significantly different frequencies within the available 10:1 frequency range. The choice of three resolvers allows the two channel data collection system to be operated on any two of these three channels simultaneously. Although there is an advantage in using integer-related frequencies when the results must be manually analyzed, this is of minor interest for the proposed computer data reduction. The exact test frequencies are likely to be determined on a non-interfering assignment basis.

### 3.5.1 Preliminary Observation Plan

A preliminary observation plan covering the initial tests to be performed by the crew of the Early Laboratory is presented in Table 3-4. The group of tests represents a reasonable combination as a basis for preliminary planning, but it will have to be adapted to specific Comm/Nav program needs as these are more clearly defined.

The proposed tests commence with a power level calibration performed by the astronaut using built-in precision signal attenuators and the five-frequency local power level reference oscillator unit and then the noise factor test using the built-in white noise test set. The first test involves operating a VHF link between the laboratory and a cooperating NASA ground tracking station. This test will checkout the signal acquisition and subsequent polarization tracking. The ground station sites are optimally located and have excellent antenna patterns with well attenuated back lobes, both of which minimize multipath effects, thereby reducing the number of variables influencing the signal. An initial suggestion is to perform this test using the STADAN uplink frequency (147-151 MHz).

| Ref. No. | Measurement | Co-op Target Required | Associated Terminal | Test Freq. (Channel #1) | Test Freq. (Channel #2) | Comments/Rationale |
|---|---|---|---|---|---|---|
| 1 | Sensitivity Calibration | No | None | 100<br>300<br>900 | 100<br>300<br>900 | Ensures Selected Channels Sufficiently Clear of RFI for Useful RF Propagation Tests |
| 2 | Signal Acquisition and Polarization Tracking | Yes | NASA Ground Sta. | 147 - 151 | 147 - 151 | Initial Checkout of Polarization Tracking Loops with Low Sidelobe, Well Sited (Min Multipath) Source |
| 3 | Signal Acquisition and Polarization Tracking | No | Commercial TV Stations | 174 - 180<br>(Ch. #7) | 210 - 214<br>(Ch. #13) | Evaluates Use of Non-Cooperative Targets -- Using Existing CONUS TV Station Signals |
| 4 | Signal Acquisition and Polarization Tracking | No | Commercial FM Stations | 100 - 107.9<br>(Ch. #60 - 201) | 100 - 107.9<br>(Ch. #60 - 201) | Evaluates Use of Non-Cooperative Targets-- Using Existing FM Radio Signals |
| 5 | Signal Acquisition and Polarization Tracking | No | Commercial TV Stations | 174 - 180<br>(Ch. #7) | 210 - 214<br>(Ch. #13) | Evaluate Use of Non-Cooperative Targets-- Using Foreign TV Stations |
| 6 | Signal Acquisition and Polarization Tracking | No | Commercial FM Stations | 100 - 107.9<br>(Ch. #60 - 201) | 100 - 107.9<br>(Ch. #60 - 201) | Evaluates Use of Non-Cooperative Targets-- Using Existing Foreign FM Stations |
| 7 | Laboratory-Aircraft Comm. Check | Yes | NASA or Military Aircraft | TBD | TBD | Initial Voice or Data Exchange a Preface to RF Propagation Tests |
| 8 | Signal Acquisition & Initial Data | Yes | Same | Assigned Channel 225 - 399 | Different Assigned Channel 225 - 399 | Preliminary Multipath and Polarization at Low Altitudes |
| 9 | Data Collection (Aircraft Link) | Yes | Same | Same | Same | Collect Useful Data, Statistically Significant Iterate Parameters for Optimizing Future Tests |
| 10 | Signal Acquisition and Polarization Tracking | No | Civil Airlines (or TBD) | TBD | TBD | Evaluates Feasibility of Using Signals from Non- or Semi-Cooperating Aircraft |
| 11 | Scintillation | Yes | NASA or Military Plane | 147 - 151 | TBD | Collects Data Using Very High Altitude Aircraft to Minimize Multipath and Weather Effects |
| 12 | Scintillation and Polarization | Yes | Sub-Satellite | TBD | TBD | Collects Data Using Sub-Satellite Released from Shuttle or Laboratory in Orbit |

Table 3-4. Model Observation and Measurement Program

The next four tests evaluate the potential suitability of using various existing commercial ground transmitters as signal sources. If successful, this mode of operation would be considerably cheaper than would be the case if tracking stations or dedicated aircraft must be used for the tests. The first such test is with some U.S. television stations. These radiate signals with an effective radiated power (ERP) of up to one megawatt and even allowing for their horizontal emphasis beam pattern, radiate large signal powers into space. The Terrestrial RF Sources of Noise and Interference experiment will quantify this fact for use in the propagation experiment.

The second test is similar in concept but will attempt to use CONUS commercial FM radio stations. These are of appreciably lower power, typically 1 - 20 KW ERP. They are less attractive primarily because they are bunched in a tight 201 channel block from 88 - 108 MHz so they only provide a small range of differential test frequency, making the extraction of frequency dependent factors more difficult.

The remaining two tests of this subset are performed with foreign TV and FM radio stations and serve as a preface to extending the propagation tests from CONUS alone to a worldwide basis.

Having investigated non-cooperating fixed terrestrial sources, a series of aircraft and laboratory tests is proposed. The first of these should be performed with a cooperating NASA or military aircraft. It will fly at low and modest altitudes 1,000 - 20,000 feet and is employed to obtain initial data on multipath effects. These tests will be prefaced by a short checkout to ensure that the voice (or data) link between the laboratory and aircraft is functioning. These preliminary tests will be followed by some volume data collection to allow the ground computer software to be exercised and refined.

Next, a series of tests will be run to determine the feasibility and evaluate the merits of performing propagation tests with non-cooperating or semi-cooperating civil aircraft. By non-cooperating is meant making use of their voluntary transmissions, whereas by semi-cooperating is implied aircraft carrying a simple beacon that requires no attention from the pilots or crew of the civil aircraft. This form of

target would be a considerable cost saving by comparison with a dedicated aircraft. There is precedent for such tests.*

A scintillation measurement is proposed as the next task. For this test minimization of any multipath and terrestrial weather effects is desired so a high altitude aircraft is indicated as the cooperating source.

The last experiment of this group involves scintillation and polarization rotation measurements between the laboratory and a small subsatellite beacon deployed from the shuttle.

The foregoing suggestions are a preface to a major effort devoted to collecting statistics on the identified key propagation phenomena over a representative range of independent variables, including latitude, longitude, time of day, season, year, frequency, transmission path, etc. The final selection of techniques to be used is dependent on the outcome of the proposed preliminary test group performed by flights of the Early Laboratory, which are the key to all the future laboratory communication activities.

## 3.6 INTERFACE, SUPPORT, AND PERFORMANCE REQUIREMENTS

The proposed series of experiments is substantially self-supporting; however, they will require some liaison with the operators of the existing terrestrial sources (aircraft, TV, FM stations) and do impose the following requirements on the support vehicle systems:

| Support Item | Classification | Description |
|---|---|---|
| Electrical Power | Essential | 28 V DC or 400 Hz |
| Temperature | Trade Off | $71^{\circ}F + 3^{\circ}$ F/$76^{\circ}$ F $\pm 116^{\circ}F$ |
| Pressure | Trade Off | 28 - 31" Hg/0 - 31" Hg |
| Vehicle Ephemeris | Essential | 3-Axis Continuous History |
| Orbit | Trade Off | 200 N. Mi. /600/Elliptic |
| Time Std. | Trade Off | Day, Hour, Minute & Second |
| Communication | Essential | Voice or Data Lab←→Aircraft |
| Communication | Essential | Voice or Data Lab←→NASA/Gnd/Stn |
| ERP Data | Desirable | Civil TV & FM Stations |

* Collins Radio-Pan Am Multipath Tests with ATS-1, 1965-66.

## 3.7 POTENTIAL ROLE OF MAN

### 3.7.1 Calibration

The first task for the astronaut is system power level calibration. This will be performed during the orbit immediately preceding the first useful (CONUS coverage) orbit. It entails a systematic check to ensure that all equipment is powered and functional, followed by the power level calibration and a vehicle EMI/RFI baseline signature recording procedure, and finally the noise factor measurements. The first of these involves injecting known levels of RF signal power into the sweep receiver using the multifrequency calibration oscillator, and checking that all five signals appear on the panoramic display. The astronaut then calibrates the receiver power response at the three test frequencies. An attenuator increments the test output level applied to the receiver, while the receiver output is recorded on magnetic tape. All receivers are calibrated in the same way.

The second test involves taking an output measurement and spectrum sweep record of each receiver, at each of the three test frequencies, so as to obtain data on the residual background power density in the selected test channel.

The noise factor of each receiver is measured at each of the three test frequencies using the white noise test set. At the end of the calibration phase the astronaut returns the system to the program clock control.

### 3.7.2 Initial Data Acquisition

Following the non-CONUS calibration orbit, the astronaut collects data on polarization rotation during the CONUS overpass segments of each orbit using a cooperating NASA ground station. The data is recorded with the on-board magnetic tape recorders.

A stored voice message alerts the astronaut at selected intervals prior to each CONUS overpass to allow him to come to the control position and use the panoramic display in realtime, and/or the operator's monitor receiver, waveform display units, and make any necessary control adjustments.

### 3.7.3 Astronaut Evaluation and Equipment Adjustment

At a convenient time during the 18 hours immediately following the initial data acquisition, the astronaut replays the magnetic tape records, monitoring their outputs on the data display unit. The program clock control limits the recording period to a little in excess of the coverage time, so that the adjacent orbit records can be compacted, and are conveniently adjacent for astronaut evaluation. The total replay time for a six orbit record is only about 30 minutes in this mode, at regular speed.

On the basis of this record evaluation, the astronaut is able to optimize the equipment control parameters for the actual Faraday angle rates and signal levels recorded. The astronaut can, therefore, optimize the data collection by selecting optimum test frequencies, sweep rates, servo response, bandwidth, etc. Finally, he returns the system to the standby mode, under control of the program clock control unit, ready for the next test.

During subsequent orbits the astronaut performs a variety of propagation tests involving ground and aircraft sources. These are summarized in Table 3-5.

## 3.8 EXPERIMENT EVOLUTION

The tests comprising the RF propagation experiment have been divided into three phases to suit the available astronaut time, reasonable equipment payloads, and to incorporate an increasing understanding of the problems as this work proceeds.

### 3.8.1 Phase I

The first phase is concerned with calibrating and exercising the VHF-UHF equipment to secure preliminary test results and in particular to determine whether meaningful results can be obtained by using available non-cooperative commercial ground transmitting stations. The proposed test sequence involves progressively more difficult tasks which will provide valuable information concerning the performance which can be expected from man for extended experiments, and the degree of automation that may be desirable. These early tests will be performed by the Early Laboratory. It appears that the first Sortie Mission should be adequate

Table 3-5. Propagation Test Sequence

| Ref. No. | Test | Cooperating Vehicle | Proposed Orbital Assignment |
|---|---|---|---|
| 1 | Sensitivity Calibration | None | Non-CONUS |
| 2 | Signal Acq. & Pol. Tr. | NASA Ground Station | Orbits 1 - 6 (CONUS "A" Set) |
| 3 | Signal Acq. & Pol. Tr. | TV Stations | Orbits 1 - 3 (CONUS "B" Set) |
| 4 | Signal Acq. & Pol. Tr. | FM Stations | Orbits 4 - 6 (CONUS "B" Set) |
| 5 | Signal Acq. & Pol. Tr. | Foreign TV Stations | Non-CONUS Orbits |
| 6 | Signal Acq. & Pol. Tr. | Foreign FM Stations | Non-CONUS Orbits |
| 7 | CAB -A/C Comm. Link and Signal Acq. | Aircraft | Orbit 1 (CONUS "C" Set) |
| 8 | Signal Acq. & Data Collection | Aircraft | Orbits 2 - 6 (CONUS "C" Set) |
| 9 | Signal Acq. & Data Collection | Non-Cooperating Aircraft | Orbits 1 - 6 (CONUS "D" Set) |
| 10 | Scintillation Tests | High Altitude Aircraft | Orbits 1 - 6 (CONUS "E" Set) |

for obtaining preliminary data, and that subsequent flights can be used to obtain the quantities of data needed for the results to be statistically valid.

### 3.8.2 Phase II

For Phase II additional equipment will be incorporated so as to extend the frequency coverage from the VHF-UHF region used in Phase I, to the microwave region so as to provide at least two decades for spectrum evaluation (0.1 - 10 GHz). In addition, subject to satisfactory progress on SRT, a narrow beam VHF-UHF antenna, as discussed in the Terrestrial RF Sources of Noise and Interference experiment, will be installed. As a result of these additions, the Growth Laboratory will be able to carry out experiments and collect data on propagation effects over the microwave region as well as the VHF-UHF region. These microwave tests will include:

a) Multipath

b) Atmospheric scintillation

c) Faraday rotation

d) Absolute path loss

e) Wideband phase coherence

Whereas the initial tests were restricted to terrestrial sources, aircraft and low-orbit satellites or subsatellites, the Growth Laboratory will carry out extended communication tests with synchronous satellites.

### 3.8.3 Phase III

Phase III will incorporate propagation analysis and data collection capability covering the VHF, UHF, microwave and millimeter wave regions for full frequency capability.

Narrow beam, steerable, auto-tracking arrays for VHF/UHF and the higher bands will be installed with multiple receiving equipment and recording channels.

Substantial automation is again assumed, with the crew performing supervisory functions over routine data collection, and key roles in unique analyses where real time intelligent interaction is essential to success and efficiency.

### 3.8.4 Evolution Overview

The evolutionary development of this experiment from the first Early Lab flight through to the sophistication of the Total Laboratory is summarized in Table 3-6.

| MEASUREMENT DETAILS | | EARLY LABORATORY | | | | GROWTH LABORATORY | | | | TOTAL LABORATORY | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| PARAMETER | CONDITION | | | | | | | | | | |
| | Frequency | VHF/UHF | VHF/UHF | VHF/UHF | VHF/UHF | 0.1-10 GHz | 0.1-10 GHz | 0.1-10 GHz | | | |
| MULTIPATH | Antenna | Fixed | Fixed | Fixed | Fixed | Pencil | Pencil | Pencil | | | |
| | Target | NASA | TV & FM | Aircraft | Hi. Alt. Aircraft | NASA | NASA & Aircraft | Sub-Sat. & Sat. | | | |
| | Time of Day | N & D | N & D | N & D | N & D | N & D | N & D | N & D | | | |
| | Geographic | CONUS | CONUS Foreign | CONUS | World | CONUS | World | World | | | |
| POLARIZATION ROTATION | Frequency | VHF/UHF | VHF/UHF | VHF/UHF | VHF/UHF | 0.1-10 GHz | | | | | AUTOMATIC COLLECTION OF LARGE QUANTITIES OF DATA USING PROVEN TECHNIQUES |
| | Antenna | Fixed | Fixed | Fixed | Fixed | Various | | | | | |
| | Target | NASA | NASA | Hi-Alt. Aircraft | Sub-Sat. | Sub-Sat. | | | | | |
| | Time of Day | N & D | N & D | N & D | N & D | N & D | | | | | |
| | Geographic | CONUS | World | CONUS | World | World | | | | | |
| IONOSPHERIC SCINTILLATION | Frequency | VHF/UHF | VHF/UHF | | | 1-10 GHz | 0.1-10 GHz | | | | |
| | Antenna | Fixed | Fixed | | | Tracking | Various | | | | |
| | Target | Hi. Alt. Aircraft | Sub-Sat. | | | Sub-Sat. | Sub-Sat. | | | | |
| | Time of Day | N & D | N & D | | | N & D | N & D | | | | |
| | Geographic | CONUS | World | | | World | World | | | | |
| ABSOLUTE PATH LOSS | Frequency | | | | VHF/UHF | 1-10 GHz | 1-10 GHz | 1-10 GHz | | 10-100 GHz | |
| | Antenna | | | | Fixed | Tracking | Tracking | Tracking | | Tracking | |
| | Target | | | | NASA | NASA | NASA | Sub-Sat. | | Sync. Sats. | |
| | Time of Day | | | | N & D | N & D | N & D | N & D | | Any | |
| | Geographic | | | | CONUS | CONUS | World | World | | World | |
| WIDEBAND PHASE COHERENCE | Frequency | | | | VHF/UHF | VHF/UHF | 1-10 GHz | 1-10 GHz | 1-10 GHz | 10-100 GHz | 10-100 GHz |
| | Antenna | | | | Fixed | Fixed | Tracking | Tracking | Tracking | Tracking | Tracking |
| | Target | | | | NASA | NASA | NASA | NASA | Sync. Sat | NASA | Sync. Sats. |
| | Time of Day | | | | N & D | N & D | N & D | N & D | Any | Any | Any |
| | Geographic | | | | CONUS | World | CONUS | World | Hemis-pherical- | World | World |

Table 3-6. Evolution Summary - RF Propagation Tests

## 3.9 SRT REQUIREMENTS

Three SRT tasks have been identified in connection with the RF propagation experiment:

a) Antenna integration

b) Improvements to polarization resolver subsystem

c) Receiver frequency extension.

### 3.9.1 Antenna Integration

The antenna proposed for use with all VHF-UHF experiments is a log periodic design, because this type provides the widest possible bandwidth in a single structure.

The log period antenna also provides the dual feed E&H linear polarizations required to form the electrical polarization resolver and tracker. This need is met by using two separate orthogonally aligned, linearly polarized, log periodic assemblies, structurally integrated, to form a single coaxial structure with cruciform elements and a common boresight.

In addition to the dual polarization, it is also highly desirable to provide a choice of beamwidth. The widest beamwidth needed is about 140 degrees. This allows full coverage over slant ranges involving a minimum 10 degree horizon angle of view. The minimum beamwidth is limited by a combination of the desired 10:1 bandwidth, and the practical problems of element spacing, tolerance, and length. The latter two factors increase rapidly for beamwidth angles of less than about 45 degrees.

It appears potentially feasible to combine two different beamwidth cruciform arrays into a single structure providing both a choice of beamwidths and of two polarization planes. The first SRT task is to investigate in detail the feasibility of this concept and recommend the most appropriate solution.

### 3.9.2 Improvements to Polarization Resolver Subsystem

There are two commonly used schemes for measuring the arrival polarization angles of radio signals:

a) Mechanically rotatable antenna

b) Electrical polarization resolver assembly.

The mechanical scheme makes use of a linearly polarized antenna mounted on a bearing assembly that allows it to be rotated on its axis. By measuring the signal output level available from an associated receiver while rotating the antenna, an operator can determine the arrival polarization within the 180 degrees ambiguity pattern.

The electrical method involves shifting the phases of the signals available from a pair of fixed orthogonal linear antennas to synthesize a variable orientation linear antenna. This allows the arrival angle to be established without physically rotating the antenna. Since physical rotation implies space hard vacuum joints which present serious reliability problems, the stationary electrical method is preferable. Unfortunately present electrical resolvers will only operate reliably over about a 10 percent bandwidth.

The 10 percent bandwidth restriction implies that serious errors in calibration and degradation are introduced to the VSWR factor which occurs at more remote frequencies. It appears that secondary correction, involving servo-driven matching stubs and computer invoked modifications to the calibration, might well extend the operating range.

The second SRT task is, therefore, to substantially extend the frequency range of present VHF/UHF designs.

### 3.9.3 Receiver Frequency Extensions

The overall measurement plans call for collection of propagation effects data from 100 MHz through about 100 GHz. It is, therefore, necessary to ensure, by appropriate SRT action, that the required equipment will be available to pursue measurements over this frequency range.

Although specific hardware items have been identified for the immediate measurement needs, the criticality of this aspect suggests a separate SRT task be initiated with the objective of ensuring timely hardware availability of high quality receivers.

This involves ensuring that additional receiver models or appropriate converters will be available to cover the higher frequency bands between 10 GHz and 100 GHz to suit the proposed experiment plan and, in the long term, bridge the gap between millimeter waves and optical transmission frequencies.

Previously, receivers of the type desired have been developed almost exclusively for military intelligence and electronic warfare applications, but with the reduced emphasis of military R&D it appears unlikely that the required equipment will be developed commercially. Any equipment developed for a specific military program will almost certainly be classified and not available for incorporation in this laboratory.

For the above cited reasons it is proposed that an SRT task be instituted to investigate the availability of sweep receivers over the complete spectrum range and assemble a hardware availability calendar. This will allow identification of gaps in the desired frequency coverage. The same SRT task will then allow evaluation of the technical requirements for each of these gaps to determine the most cost effective solution. The options at this point would probably comprise the following:

a) Fund a new receiver development

b) Develop a frequency conversion adapter

c) Combine a number of available elements to produce a temporary (brass board) receiver

d) Negotiate with DOD on a joint funding

e) Defer the laboratory measurements in this region.

It is proposed that the SRT contractor evaluate the relative merits of these approaches and present a final report fully documenting the pertinent facts and recommending the most appropriate action.

## 3.10 ACKNOWLEDGEMENTS

### 3.10.1 Related Experiments

The following candidate experiments were submitted in response to a solicitation made during the Communication/Navigation Research Laboratory Study:

| Experiment | Principal Investigator and Association |
|---|---|
| 1. Millimeter Wave Propagation/ Communication | L. Ippolito, Goddard Space Flight Center |
| 2. High Frequency Channeling Between Ionization Layers Around Earth | J. Fowler, Manned Spacecraft Center<br>M. Grossi, Raytheon |
| 3. Mapping Tropospheric Radio Ducts | P. Rice, Inst. for Telecommunication Sciences |
| 4. Scintillation Observations at VHF/UHF and Microwave Frequencies | J. Tary, Inst. for Telecommunication Sciences |
| 5. Low Elevation Angle Propagation Tests | G. Gierhart, Inst. for Telecommunication Sciences |
| 6. Propagation Characteristics of the Atmosphere Near the 22 GHz Water Vapor Line | Thomson, Inst. for Telecommunication Sciences |
| 7. Atmospheric Propagation Measurements at 50 - 75 GHz | Liebe, Inst. for Telecommunication Sciences |
| 8. Spatial and Frequency Coherence of Microwave Signals | D. Crombie, Inst. for Telecommunication Sciences |
| 9. Phase Synchronization of Remote Oscillators | Thomson/Wood, Inst. for Telecommunication Sciences |
| 10. Synchronization of Oscillators via Microwave Link | L. Wood, Inst. for Telecommunication Sciences |
| 11. Measuring Tropospheric Characteristics Important to Propagation | P. Rice, Inst. for Telecommunication Sciences |
| 12. Multipath Measurements | Reference Earth Orbital Research and Applications Investigations (Blue Book), Vol. V, January 1971. |

continued

| Experiment | Principal Investigator and Association |
|---|---|
| 13. Tropospheric Propagation Measurements | Same as 12 |
| 14. Millimeter Wave Communication System and Propagation Demonstration | Same as 12 |
| 15. Experimental Determination of Maximum Bit Rates at VHF and Greater | W. Sisco, TRW Systems |
| 16. Propagation Measurements at HF, MF, LF, VLF, and ELF | W. Sisco, TRW Systems |
| 17. Pulse Multipath Study | P. Karr, TRW Systems |
| 18. Ground Multipath Statistics | J. Mallinckrodt, TRW Systems |
| 19. Multipath Statistical Path Losses | W. Sisco, TRW Systems |
| 20. A Possible Method of Alleviating the Interfering Effect of Multipath | P. Karr, TRW Systems |
| 21. Depolarization of EM Waves from 0.1 - 10 GHz | W. Sisco, TRW Systems |
| 22. Extended Propagation Measurements | D. Lipke, ComSat Corporation |
| 23. Polarization Performance of RF Transmission Systems: 2 - 30 GHz | Pollack/Hyde, ComSat Corporation |
| 24. Channel Coherent Bandwidth Determination | J. Campanella, ComSat Corporation |
| 25. HF/VHF Guided Propagation in the Lower Atmosphere | J. Barker/M. Grossi, Raytheon/Wright Patterson AFB |
| 26. Microwave Occultation Experiment | Lusigman, Stanford University |
| 27. Atmospheric Attenuation Measurements | Hawker-Siddeley Dynamics |

3.10.2 References

The following documents have been studied and their content used to varying degrees in the preparation of this report:


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5. "Candidate Experiment Program for Manned Space Stations," NHB 7150.xx, September 15, 1969.

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19. Special Issue on Topside Souding and the Ionosphere, Proc. IEEE, June 1969.

20. Stromer, P. R., "Adaptive or Self-Optimizing Control Systems - A Bibliography," Trans. IRE, PGAC-4, No. 1, May 1959.

# APPENDIX A

Referring to Figure A-1:

CD || to KQ (Both Perp to OY)

given $\theta$ then

$$\frac{VO}{CO} = \cos\theta \quad \therefore \quad VO = CO \bullet \cos\theta$$

$$VB = VO - R = (CO \bullet \cos\theta) - R$$

$$\frac{VC}{CO} = \sin\theta \quad \therefore \quad VC = CO \bullet \sin\theta$$

$$CB = \sqrt{VC^2 + VB^2}$$

$$CB = \sqrt{(CO \bullet \sin\theta)^2 + \left[(CO \bullet \cos\theta) - R\right]^2}$$

Inserting Constants: $CO = 3,644$

$R = 3,444$

$$CB = \sqrt{(3,644 \sin\theta)^2 + \left[(3,644 \cos\theta) - 3,444\right]^2}$$

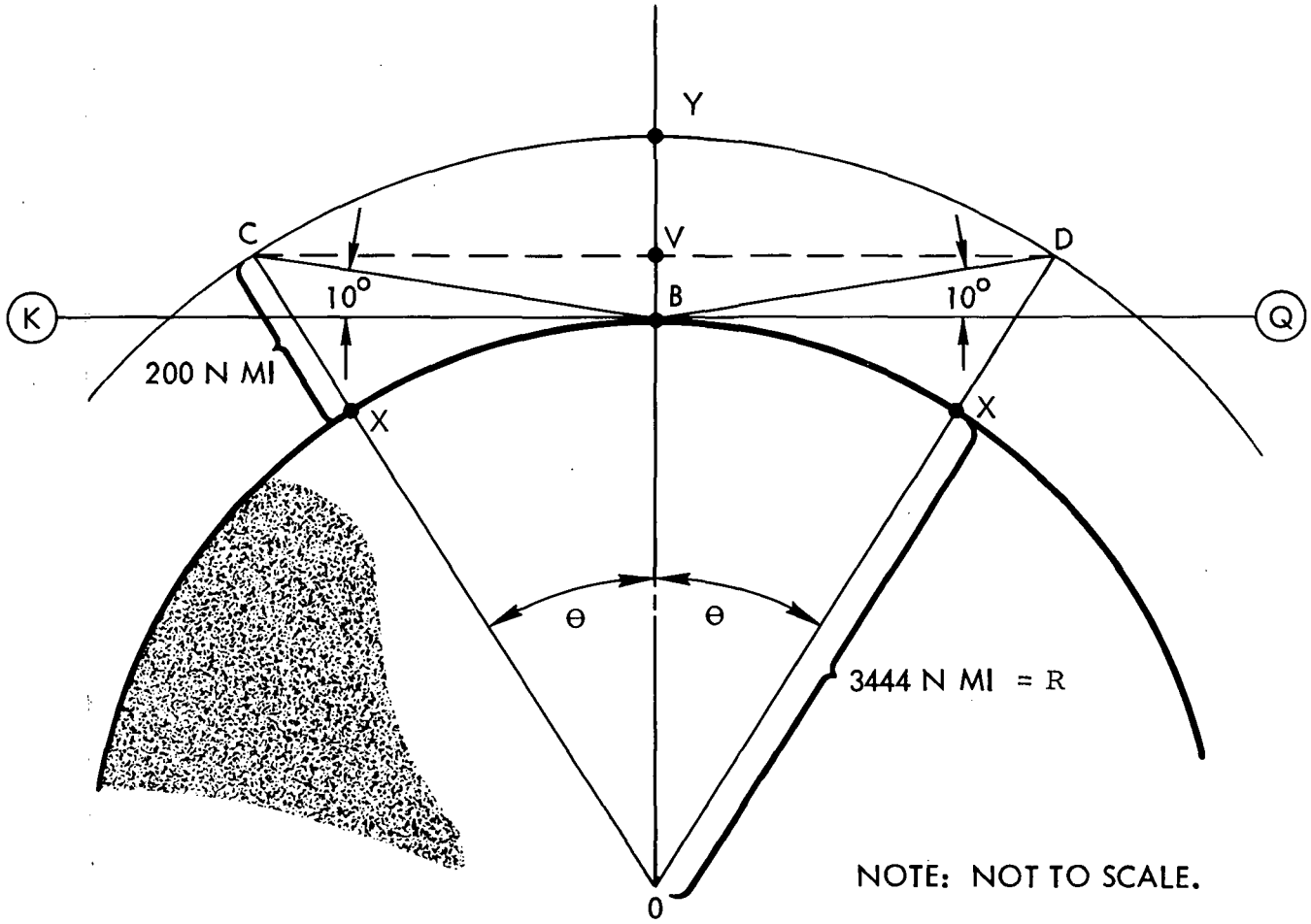


Figure A-1 - Geometric Model for Slant Range and Faraday Rotation Change versus Satellite-to-Nadir Angle.

Table A-1. Slant Range and Incremental Slant Range for 1-Degree Steps in Satellite Position Relative to Nadir, for Cooperative Station on Subtrack

| ① θ | ② Sin θ | ③ $(R+H \sin \theta)^2$ | ④ Cos θ | ⑤ $[(R+H) \cos \theta) - R]^2$ | Slant Range $= \sqrt{③ + ⑤}$ (N. Miles) | Change in Slant Range (N. Miles) | Est. Total Polarization Rotation at 100 MHz (Degrees) | Incremental Change in Polarization (Degrees) | Approximate Rate of Change of Polarization (Degrees/Sec) |
|---|---|---|---|---|---|---|---|---|---|
| 15 | .2588 | 889375 | .9659 | 5736 | 946.1 | - | 1750.3 | - | - |
| 14 | .2419 | 777013 | .9703 | 8422 | 886.3 | 59.8 | 1639.7 | 110.6 | 7.37 |
| 13 | .2250 | 672236 | .9744 | 11387 | 826.8 | 59.5 | 1529.6 | 110.1 | 7.34 |
| 12 | .2079 | 573939 | .9781 | 14447 | 767.1 | 59.7 | 1419.1 | 110.5 | 7.37 |
| 11 | .1908 | 483407 | .9816 | 17676 | 707.9 | 59.2 | 1309.6 | 109.5 | 7.30 |
| 10 | .1736 | 400180 | .9848 | 20912 | 648.9 | 59.0 | 1200.5 | 109.1 | 7.27 |
| 9 | .15643 | 324935 | .9877 | 24080 | 590.8 | 58.1 | 1093.0 | 107.5 | 7.17 |
| 8 | .13917 | 257186 | .9903 | 27111 | 533.2 | 57.6 | 986.4 | 106.6 | 7.11 |
| 7 | .12187 | 197220 | .9925 | 29815 | 476.5 | 56.7 | 881.5 | 104.9 | 6.99 |
| 6 | .10453 | 145090 | .9945 | 32384 | 421.3 | 55.2 | 779.4 | 102.1 | 6.81 |
| 5 | .08716 | 100877 | .9962 | 34653 | 368.1 | 53.2 | 681.0 | 98.4 | 6.56 |
| 4 | .06976 | 64620 | .9976 | 36578 | 318.1 | 50.0 | 588.5 | 92.5 | 6.17 |
| 3 | .05234 | 36377 | .9986 | 37985 | 272.7 | 45.4 | 504.5 | 84.0 | 5.60 |
| 2 | .03490 | 16174 | .9994 | 39130 | 235.2 | 37.5 | 435.1 | 69.4 | 4.63 |
| 1 | .01745 | 4043 | .9998 | 39709 | 209.2 | 26.0 | 387.0 | 48.1 | 3.21 |
| 0 | Zero | Zero | 1.0 | 40000 | 200.0 | 9.2 | 370.0 | 17.0 | 1.13 |

# EXPERIMENT 4

# OPTICAL FREQUENCY PROPAGATION

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# 4. OPTICAL FREQUENCY PROPAGATION

## 4.1 EXPERIMENT CLASSIFICATION

Basic and Applied Research.

## 4.2 EXPERIMENT OBJECTIVES

The objectives of this experiment are to:

a) Determine propagation characteristics of optical frequency radiation in space-to-space and space-to-ground communication links

b) Extend the knowledge and range of data associated with optical wavelength propagation phenomena in the atmosphere and in free-space

c) Define and characterize the problems in, and devise parameters for, optical communication equipment operating in a space environment.

Optical communications offer the advantages of very wide data bandwidth, small aperture size, and low power consumption for point-to-point transmission of data. Data resulting from this experiment are essential in planning and developing satellite systems for space communication, optimizing the use of the total electromagnetic spectrum, and fulfilling NASA's role in communications satellite research and development.

The communication wavelengths and link geometries recommended in this experiment are selected in accordance with their application to operational systems of interest. The wavelengths which are currently prime candidates for operational space communication links are 10.6 microns, 1.06 microns, and 0.53 microns. Link geometries of interest include satellite-to-satellite (particularly low orbit spacecraft to synchronous spacecraft), satellite-to-ground, and satellite-to-airborne relay platform. The airborne relay platform, typically a high altitude balloon-borne transponder receives high data rate laser signals and provides an RF relay to ground to preclude communication interruptions due to weather. Various complements of supporting and peripheral equipment are required to support the diverse link geometries; this factor will be an important consideration in establishing the order in which experiments are performed.

## 4.3 BACKGROUND AND CURRENT STATUS

The potential of optical frequencies for wideband communications has been recognized for many years. Technical advancement of lasers, modulators, detectors, and high speed electronics has enabled laboratory demonstration of communication links with data rate capabilities approaching one gigabit per second. However, these demonstrations have been restricted to relatively short optical path lengths.

Terrestrial experiments have been performed to measure effects of laser energy propagation through the atmosphere over distances of a few miles. The results of these experiments are not sufficient to characterize propagation effects for space-to-ground or space-to-space optical communication links. To obtain quantitative propagation data, the following experimental conditions are needed:

a) Realistic range and atmospheric path

b) Use of appropriate laser wavelength

c) Realistic values of beam size, divergence, and phase coherence

d) Appropriate size and quality of receiver optics.

The problems of laser energy propagation have been investigated analytically in considerable depth, primarily due to the difficulty of experimental measurement. These studies provide a basis for understanding propagation phenomena but do not eliminate the need for experimental data to verify the hypotheses.

Much of the early work in laser propagation was focused upon helium-neon gas and $CO_2$ lasers. Currently, the three most promising wavelengths for operational systems are 10.6 microns ($CO_2$), 1.06 microns (Nd:YAG), and 0.53 microns (frequency doubled Nd:YAG). These laser types are candidates because they are significantly higher in efficiency than other wavelength lasers. Thus, these wavelengths should be emphasized in the experimental program.

The components required for laser propagation experiments are in a developmental stage; virtually no flight-qualified components have been built. Considerable component development is needed for operational communication systems, for which size, weight, efficiency, long life,

and high data rates are important. Propagation experiments, however, may be performed with much less stringent demands imposed upon components. Based on this criteria, the status of component development is relatively favorable. $CO_2$ system components are perhaps the most advanced in terms of flight readiness, largely as a result of NASA funding to develop a $CO_2$ laser experiment for the ATS program. Nd:YAG components are presently under development with both NASA and DoD sponsorship, and are currently adequate to perform propagation experiments. The use of a manned spacecraft with a pressurized compartment minimizes the effort required to develop the laser transponder components.

The equipment category requiring the longest lead-time for development is the pointing and tracking system. Perkin-Elmer, ITT, and other contractors have developed pointing and tracking systems under NASA funding. These systems, however, were developed for terrestrial or aircraft applications and are not directly suitable for the space laser propagation experiments.

## 4.4 EXPERIMENT DESCRIPTION

The basic equipment configuration for this experiment is illustrated in Figure 4-1. It consists of a pair of transponder units, each having a laser transmitter, receiver, and tracker. One or both ends of the link may include an optical beacon to facilitate pointing acquisition.

Figure 4-2 illustrates several possible link geometry options which may be investigated. The Comm/Nav Laboratory-to-data relay satellite experiment implementation could measure free-space losses while the Laboratory-to-ground station would measure effects of the atmosphere. Alternatively, a Laboratory-to-aircraft or balloon could be used to measure an atmospheric attenuation profile.

The selection of transmitter and receiver will vary with the three wavelengths which are strong candidates for investigation: 10.6 microns, 1.06 microns, and 0.53 micron. For the Neodymium wavelengths (1.06 and 0.53 microns) it is desirable to be able to mode lock the transmitter in order to transmit subnanosecond pulses. It would also be desirable to transmit polarization modulated signals at the Neodymium wavelengths. The laser transmitters should include optics for beam width control, and a beam deflector to spatially scan the beam during beam pattern experiments.

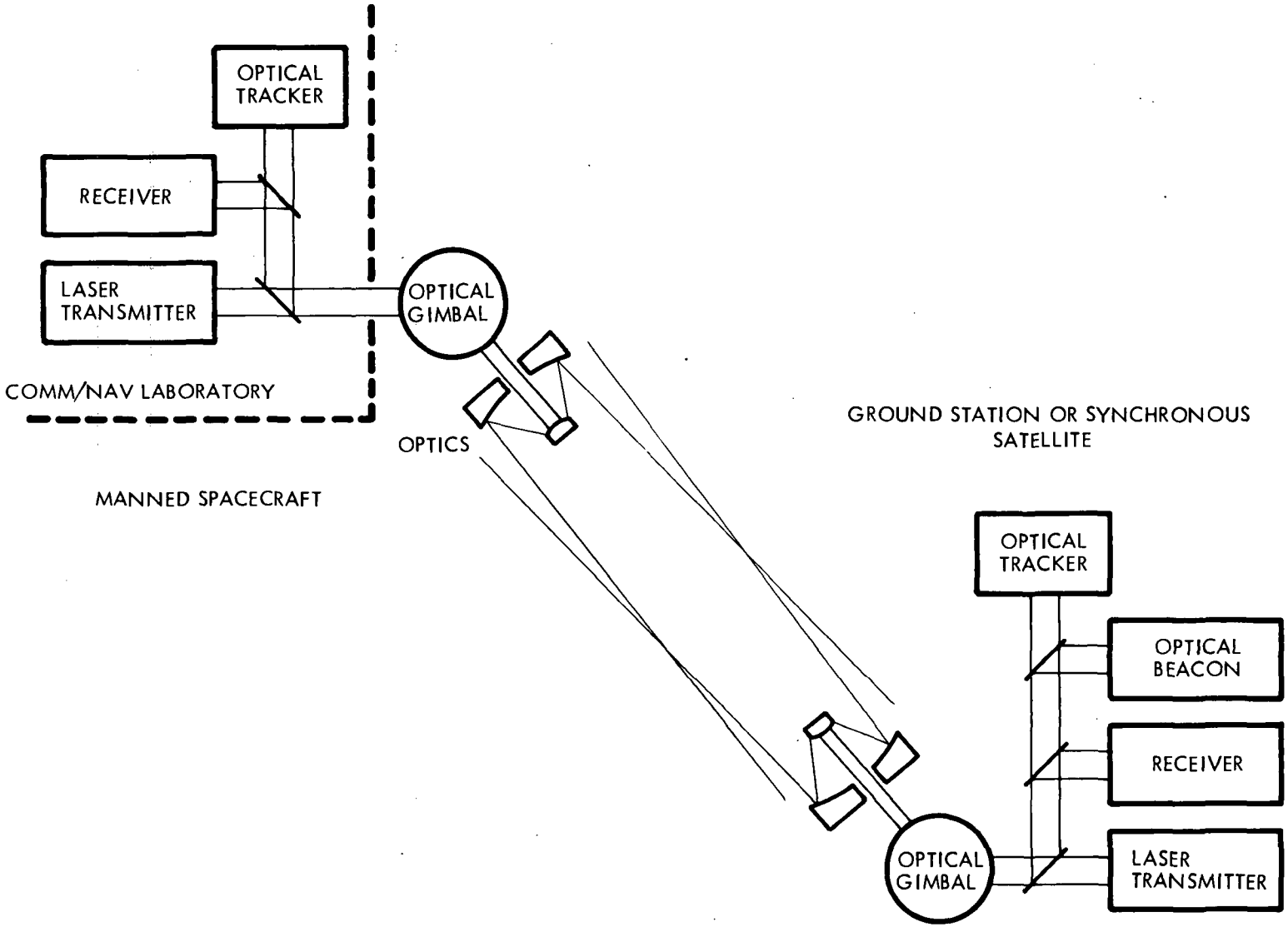


Figure 4-1. Laser Communication Experiment Functional Block Diagram

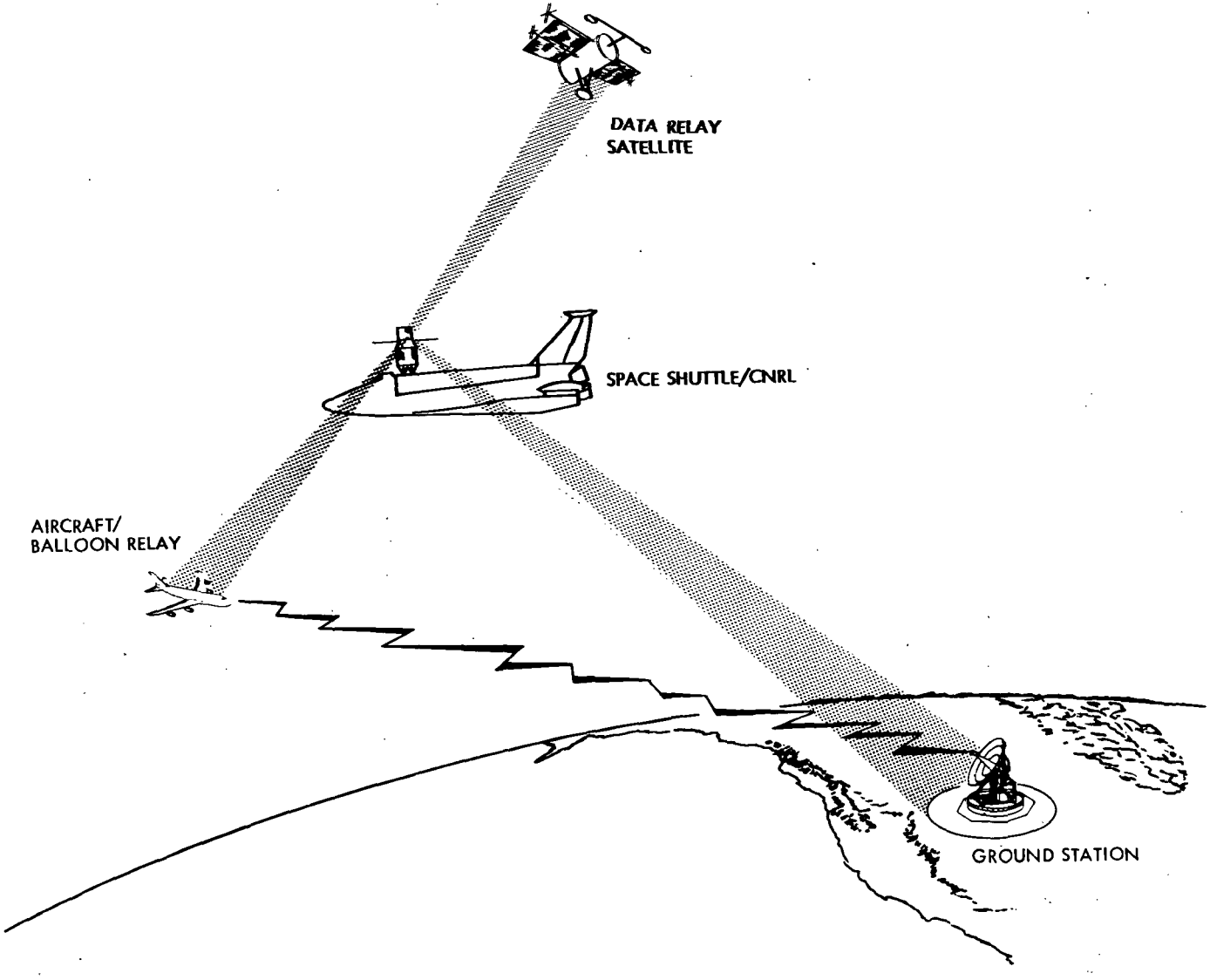


Figure 4-2. Link Geometries for Optical Frequency Propagation Experiments

The pointing and tracking system for the propagation experiment must be capable of achieving precise pointing accuracy to obtain valid measurements. Pointing accuracy in the range of 2 to 10 microradians is necessary for certain geometries and experiments. It is essential that the optical frequency propagation experiment planning be coordinated with the plans for development and test of laser pointing and tracking equipment.

## 4.5 EXPERIMENT OBSERVATION/MEASUREMENT PROGRAM

Data to be obtained from the optical frequency propagation experiment includes the following:

a) Atmospheric attenuation for each wavelength of interest, over a range of locations, weather conditions, and optical paths

b) Measurement of amplitude and frequency distribution of atmospheric scintillation effects

c) Measurement of far-field beam intensity patterns.

d) Measurement of pulse dispersion for subnanosecond mode-locked pulses

e) Determination of spatial coherence of received energy at each end of the link

f) Measurement of depolarization and possible phase or frequency shifting due to atmospheric effects

g) Determination of reciprocity of the transmission channel

h) Determination of atmospheric effects upon pointing and tracking system performance.

The largest uncertainties in optical frequency propagation are those involving atmospheric phenomena. Atmospheric effects can be conveniently measured in a low earth orbit satellite-to-ground link. Operational communication systems employing relay links from synchronous spacecraft to ground stations will be the chief beneficiaries of the investigations with this link.

In general, optical propagation measurements are performed in a fashion similar to link demonstration experiments. A search and acquisition sequence is performed to establish a two-way optical communication

link. Typically, different wavelengths are used for the two directions. After lock-on the beam widths are narrowed to simulate conditions for wideband data transmission and the received signal strength is measured at each terminal of the link. The beams are scanned to permit measurement of intensity variations in the far-field pattern. Error signals from the tracking systems are recorded to permit post-flight separation of pointing effects from propagation effects. Similarly, the transmitted power and equipment diagnostic signals are recorded for post-flight data analysis. Other measurements to be performed and recorded include:

a) Signal-to-noise ratio as a function of zenith angle

b) Signal-to-noise as a function of receiver aperture size

c) Background noise statistics

d) Modulation depth of received energy

e) Pulse width of received pulses.

Data measurement and recording requirements to support the conduct of the experiment are summarized in Table 4-1.

## 4.6 INTERFACE, SUPPORT, AND PERFORMANCE REQUIREMENTS

### 4.6.1 Environmental Requirements

The present Comm/Nav Laboratory concept provides accommodation for the majority of equipment inside the pressurized compartment of the spacecraft. However, telescope optics and gimbals will be external to the compartment and must, therefore, be designed to operate in vacuum and over a relatively wide temperature range. These components must also resist and/or be protected against degradation due to atmospheric exposure before launch. Reasonable control of the atmosphere in contact with the optical surfaces and coatings should be provided. Preliminary analysis indicates that the exterior components will not require active heating or special thermal control of the interfacing structure. All components of the system must, of course, be capable of surviving the launch acceleration and vibration. The optical components requiring maintenance of critical alignments should be mounted in a fashion which precludes mechanical resonances and high transmissability factors.

Table 4-1. Data Measurement and Recording Requirements

| Parameter \ Characteristic | Measurement Accuracy | Sampling Rate or Data Bandwidth | Dynamic Range | Number of Channels |
|---|---|---|---|---|
| 1. Receiver signal strength | 5% | 1 kHz | 200:1 | 1 |
| 2. Transmitter power | 5% | 10 Hz | 3:1 | 1 |
| 3. Tracker error signal | 1 sec | 20 Hz | $\pm$50 sec | 2 or 4 |
| 4. Beam deflector angles | 1 sec | 200 Hz | $\pm$50 sec | 2 |
| 5. Beacon output power | 5% | 5 Hz | 10:1 | 1 |
| 6. Tracker signal power | 10% | 100 Hz | 200:1 | 1 or 2 |
| 7. Transmitter beamwidth | Discrete | 1 Hz | NA | 1 |
| 8. Spacecraft attitude data | 0.5° | 1 Hz | 260°/axis | 3 |
| 9. Telescope gimbal angles | 0.1° | 10 Hz | 180°/axis | 2 |
| 10. Laser head temperature | TBD | 0.1 Hz | TBD | 1 |
| 11. Background brightness | 10% | 10 Hz | 100:1 | 1 |

### 4.6.2 Operational Requirements

For the low orbit satellite-to-ground link, experiment data collection is dependent upon satellite visibility periods from the ground station. The time and pointing angle predictions for link acquisition, on the spacecraft and on the ground, must be computed from satellite ephemeris data. Link acquisition will be automatic, and experimental procedures will be preprogrammed subject to selected operator controls. Prior to link acquisition, the spacecraft must be properly oriented to provide ground station viewing during the orbital pass, and the telescope must be slewed to the precomputed direction of initial contact.

### 4.6.3 Electrical Interface

Approximately 450 watts of prime power will be required during experiment operation, most of which is required for the on-board laser transmitter. This power budget is predicated upon laser transmitter power levels of 0.1 watt, 1.0 watt, and 5 watts for the respective wavelengths of 0.53 micron, 1.06 microns, and 10.6 microns. These transmitter power levels are suitable for any of the candidate link geometries.

### 4.6.4 Pointing Requirements

The beam coverage of the satellite laser transmitter is extremely small, in the range of one arc-second to one arc-minute depending upon the wavelength and the experiment design. However, the beam may be pointed over a wider search field. Typically, a low orbit satellite should provide a pointing capability of $\pm 45$ degrees in roll and $\pm 80$ degrees in pitch, centered about the local vertical direction.

Link acquisition in the brief available time for acquisition requires accurate initial pointing with respect to inertial references. Reasonable goals for inertial pointing accuracy are:

| | |
|---|---|
| Low Orbit Satellite Telescope | $\pm 0.5$ degree |
| Ground Station Telescope | $\pm 1$ arc-minute |
| Cooperative Synchronous Satellite | $\pm 0.1$ degree |

### 4.6.5 Ground Facility Requirements

Special ground stations are required for propagation experiments involving satellite-to-ground links. For the case of a low earth orbit satellite-to-ground link, several ground stations are preferable to provide greater daily station contact time and a greater sampling of weather conditions. Ground station locations should provide appropriate visibility conditions for propagation measurements. In general, special orbits are not required to perform propagation measurements. It is possible, however, that special orbits might be used to facilitate use of existing or desirable ground station sites and to increase station contact time.

Ground facilities must provide the following instrumentation and support functions:

a) A transponder system incorporating the elements illustrated in Figure 4-1

b) Instrumentation to measure and record the parameters identified in Table 4-1

c) Instrumentation to measure spatial coherence of received energy and the width of received mode-locked laser pulses

d) Computing capabilities to establish link acquisition and ground station handover data

e) Data processing and display equipment to permit real time monitoring and control of the experiment

f) Data processing equipment and software to process recorded data and spacecraft telemetry data between orbital passes

g) Voice communication link to the spacecraft.

### 4.6.6 Other Support Facilities

For satellite-to-satellite link experiments, or satellite-to-high altitude platform experiments, a dedicated laser transponder is required for the opposing link terminal. In general, this transponder will resemble that of the Comm/Nav research laboratory except that less flexibility is required; a single wavelength transmitter and/or receiver is adequate, with relatively little instrumentation. Computing functions and mission control would, of course, be provided by ground-based tracking stations.

## 4.7 POTENTIAL ROLE OF MAN

Representative functions that will be performed by the astronaut-scientist include:

a) Physical configuration changes to prepare for experiment variations (e.g., replacement of various experiment components to permit operation at a different wavelength

b) Electrical switching and cable connection

c) Monitoring of oscilloscopes and other displays to provide voice link information to mission control

d) Equipment functional verification prior to initiation of experimental procedures

e) Diagnostic testing and component replacement in the event of a malfunction

f) Obtaining data from other sensors for correlation with experimental results.

Skills required for personnel monitoring or controlling the experiment are principally those associated with interpreting displays and performing appropriate control functions. Some familiarity with optical alignment methods is desirable. Special training may be needed to ensure personnel safety, although definitive measures will be taken to preclude safety hazards in the design of equipment components.

## 4.8 EXPERIMENT EVOLUTION

A recommended experiment growth sequence, divided into three phases to match the projected Laboratory configurations, is described below:

Early Laboratory. Low orbit satellite-to-ground link for investigation of atmospheric propagation effects. The implementation may be restricted to direct detection systems to avoid Doppler shift problems associated with heterodyne receivers.

Growth Laboratory. The second phase of testing should include operation between a low orbit satellite and an airborne relay platform. Cooperative tests with a synchronous satellite would be desirable for this phase to investigate free-space propagation effects. Pointing and tracking capabilities for this phase will be upgraded to accommodate the narrow beamwidth requirements of a satellite-to-satellite link.

Total Laboratory. Ultimately, the Total Laboratory should provide the flexibility to operate with any of the link geometries of interest and with any of the candidate wavelength systems. Consequently, on-board instrumentation will be significantly more sophisticated than previously required. It is probable that optical frequency propagation experiments will be coordinated with the Laser Communication experiments to effect the maximum equipment commonality.

Technological progress will, of course, play a major role in determining experiment evolution. Key problems which may impact experiment emphasis are:

- Doppler shift compensation: the development of techniques to compensate large Doppler shifts would shift experiment emphasis toward heterodyne detection systems.
- Pointing and tracking: improvements in pointing and tracking technology would tend to shift emphasis toward shorter wavelength systems which are capable of achieving very narrow beams with small apertures.
- Detector technology: development of high efficiency IR detectors with high internal gain would tend to decrease interest in 0.53 micron systems.

## 4.9 SRT REQUIREMENTS

Supporting research and technology (SRT) for optical frequency propagation experiments includes development of precision acquisition and pointing equipment, and development of high-efficiency low-noise detectors for 1.06 micron receivers. SRT in high efficient laser transmitters currently underway should be continued.

## 4.10 ACKNOWLEDGEMENTS

### 4.10.1 Related Experiments

| Experiment | Principal Investigator and Association |
|---|---|
| 10.6 Micron Laser Experiment | N. McAvoy, NASA/GSFC |
| Atmospheric Effects on Laser Communications | R. Dishington, TRW Systems |
| Laser Beam Uniformity Problems in Space | R. Dishington, TRW Systems |
| Laser Communication Transponder | Pollack/Hyde/Berman, ComSat Corporation |
| Evaluation of Transmission Channel for Digital Communications | T. Kinsel Bell Laboratories |

### 4.10.2 References


1. "Deep Space Communication and Navigation Study," NAS5-10293, Communication Technology, vol. II, Bell Laboratories, May 1968.

2. R. S. Kennedy and S. Karp, "Optical Space Communication," NASA SP-217, August 1968.

3. Proceedings of the IEEE Special Issue on Optical Communications, vol. 58, October 1970.

# EXPERIMENT 5

# PLASMA PROPAGATION

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APPENDIX A

# 5. PLASMA PROPAGATION

## 5.1 EXPERIMENT CLASSIFICATION

The plasma propagation experiment involves four phases of activity: The first is concerned with performing the initial experimental investigation and collecting preliminary quantitative results. It will require significant astronaut participation. Important outputs will be a definition of the preferred equipment configuration and improved experiment procedures. This phase is classified as applied research.

The second phase involves collecting a statistically significant sample of test data under carefully controlled conditions to establish the optimum communication system under re-entry generated plasma conditions. The second phase is a combination of operational use and equipment development.

The third phase is performed at the ground laboratories and consists entirely of an equipment design and integration activity. It culminates in the installation of improved semi-automatic equipment in a Comm/Nav laboratory.

The final phase is one of operational space data collection and entails a minimum of crew participation. Their role is reduced to monitoring thepre-programmed operations, making occasional adjustments, or to re-programming.

## 5.2 EXPERIMENT OBJECTIVES

The primary objective of this experiment is to investigate the feasibility of transmitting signals from a re-entering vehicle via a relay satellite, instead of directly to the ground, thereby avoiding the problems associated with transmission through the high density portion of the plasma produced by the frontal shock wave. It appears potentially feasible to use the plasma sheath as a reflector for radio signals, depending upon the transmitted frequency, thus providing some useful antenna gain in the direction of the satellite relay. Whether this is in fact possible clearly depends on the geometry, wavelength, and the shape of the plasma sheath produced by the shock wave.

The successful conclusion of this experiment will provide the inputs necessary to establish the requirements for future data relay satellites and result in improved communications, vital to efficient and safe operation of the shuttle. A valuable secondary objective of this research is to obtain quantitative data on the phenomenum of RF breakdown associated with the plasma, caused by spacecraft outgassing. Summarizing, the objectives are to:

a) Define the preliminary measuring equipment configuration

b) Define the preferred equipment, geometry, and operational procedures

c) Demonstrate the communication improvements available

d) Prepare recommendations on re-entry support communication satellite configurations

e) Define additional space research which is required.

## 5.3 DISCIPLINE BACKGROUND AND STATUS

Plasma sheaths are produced around space and re-entry vehicles by the heating of the atmosphere (to the point of ionization) due to the shock wave propagated by a re-entry vehicle, the exhaust of propulsion engines; by outgassing of the vehicle and its components due to the elevated temperatures at re-entry, and by nuclear and solar radiation.

Attenuation of RF signals by the thermally ionized atmosphere (plasma) surrounding a re-entry vehicle is of considerable importance because of the associated loss of communication during the "blackout" period and also because of the appreciable length of time for which such losses last.

The frequency range over which the maximum attenuation occurs includes the VHF/UHF regions. Consequently, the main approach to circumventing the blackout problem has been to use frequencies either lower or higher than this band, e.g., X-band (Reference 4).

Plasma-induced communication blackouts have been experienced throughout the space program. In the early tests the loss of contact was tolerated; in recent years the brute force method of drastically increasing the transmitter power has been used. The advent of communication relay satellites has completely changed this situation making it possible to provide an indirect telemetry link from a re-entry vehicle to the ground, via the relay satellite, employing the propagation path toward the relay satellite and not through the plasma sheath in front of the vehicle. For some vehicle shapes the plasma sheath may completely surround the vehicle, but it still will be less dense in the trailing area. Consequently, experiments are required to determine the feasibility and optimum application of relay satellites to solve the communication blackout problem.

Since the shuttle program itself will involve regular atmosphere exit and re-entry for performing the proposed laboratory missions, the shuttle will serve both as an ideal test vehicle for evaluating plasma communication schemes and as a key application for the technical solutions and equipment configurations developed from the proposed tests.

The presence of plasma around a re-entry vehicle is responsible for three types of degradation to vehicle radio communication systems:

a) Backscatter mismatch

b) Excess temperature

c) Energy absorption.

### 5.3.1 Backscatter Mismatch

The presence of conductive ionized gas around an antenna drastically modifies the radiation resistance value and causes a mismatch between the antenna and its associated transmission line.

S. H. Cushner (Reference 4) has derived some preliminary estimates for the losses associated with this effect for altitudes of 230,000 and 270,000 feet for signal frequencies in the range of 100 - 1000 MHz. From these parametric relationships, reproduced in Appendix A, we see that the loss is modest for radiation angles adjacent to the normal, but becomes significant for wide angle radiation and would significantly modify

the polar diagram of any broad beam antenna. The effect is much smaller at the lower altitude.

### 5.3.2 Excess Temperature

The plasma results from local heating associated with the re-entry shock wave and vehicle skin friction. Consequently the plasma has a high effective temperature, typically of the order of 3000°K. The presence of a plasma layer at this high temperature, surrounding the antenna constitutes a thermal noise source in the field of view of any radio frequency receivers connected to the antenna. Any such receiver will experience a noise temperature of about 3000 degrees and, therefore, its effective noise figure (F) will be about 10 dB, instead of the intrinsic F of the receiver itself. Since the intrinsic F may be of the order of 6 dB, plasma excess temperature results in a significant degradation, probably in the range of 3 - 5 dB.

### 5.3.3 Energy Absorption

Over the VHF-UHF frequency range, the energy absorption effect is by far the most serious degradation factor. The loss is highly frequency dependent and, in general, increases quite rapidly as a function of radiation angle. Parametric curves illustrating this effect are included in Appendix A. Figure 5-1 shows a representative characteristic for the reduction in energy absorption as a function of transmission frequency (radiation angles of zero + 10 degrees) and explains the choice of a high microwave frequency for the plasma propagation experiment link. The absolute values of loss experienced are, of course, highly dependent of the re-entry geometry. It is too early in the shuttle definition phase to make meaningful calculations on such shape-dependent effects.

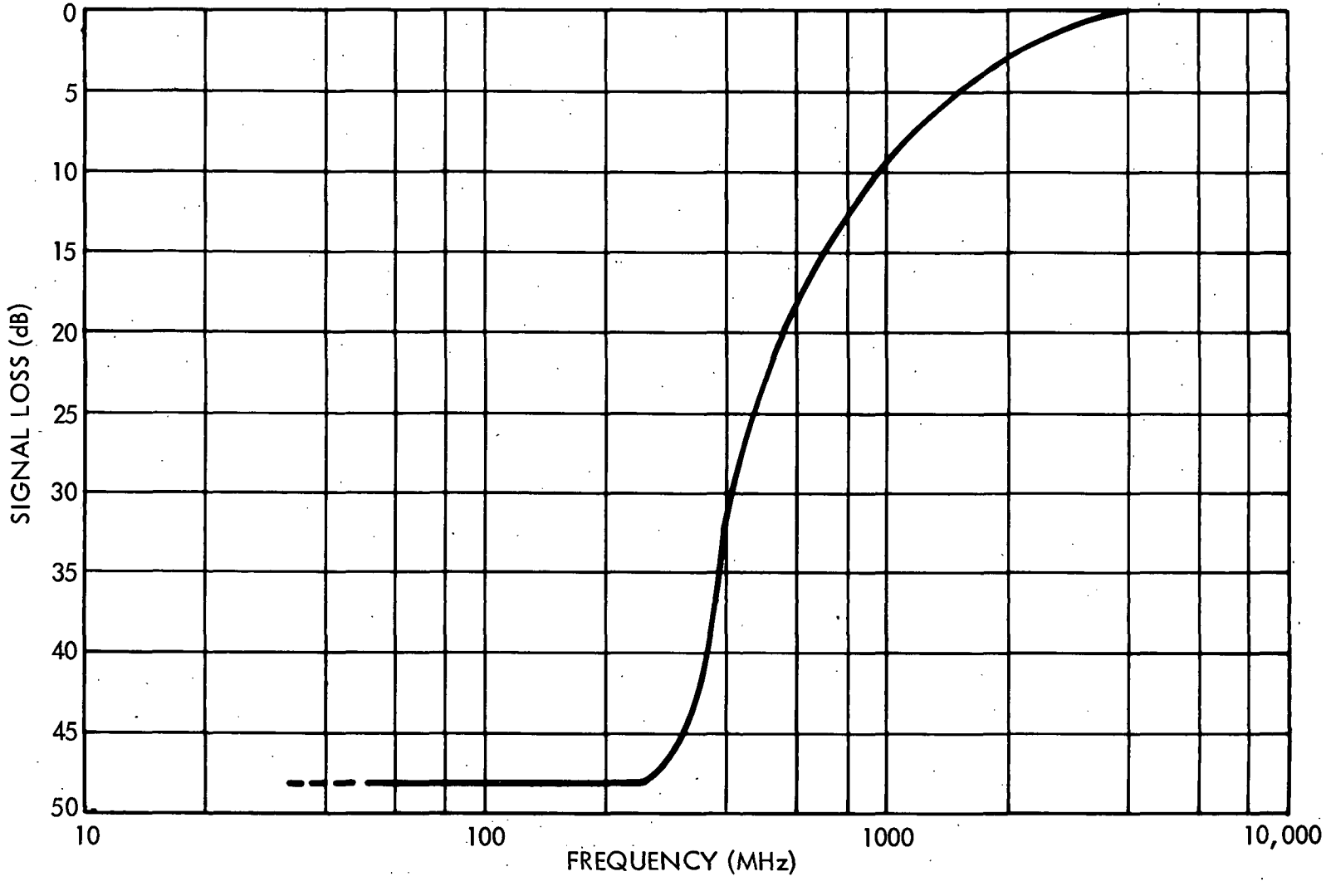


Figure 5-1. Plasma Absorption Attenuation versus Frequency for Wave Incidence Angles of 0 to ±10 Degrees (Relative to Boresight)

## 5.4 EXPERIMENT DESCRIPTION

### 5.4.1 Visibility and Test Frequency

During the re-entry phase, a blanket of ionized gas surrounds the re-entering vehicle. Since the ionization is primarily due to the extreme surface temperature caused by air friction and compression shock wave, the density is at a maximum in the "bow wave" region immediately ahead of the vehicle. It is also high along the skin surfaces, forming a dense layer thereon, with the density decreasing rapidly with distance radially from the vehicle.

The turbulence associated with the passage of the re-entry vehicle into the earth's atmosphere causes a significant dispersion of the ionized gas behind the vehicle, so that the wake has a lower ionization density than the bow wave. Although a detailed quantitative analysis is necessary, it is postulated that the wave will have a conical form, and the lowest communication attenuation will occur for a beam that is directed axially backward from the re-entry vehicle. If this mode of propagation is adopted, it imposes important constraints on the location of the communication repeater vehicle.

Basically, this experiment involves monitoring the signal transmission of a re-entry vehicle from a space station or relay satellite. Because the general attenuation versus frequency characteristic of re-entry plasmas is known, it is possible to place some bounds on the choice of frequencies that should be used for any communication link. The maximum attenuation region extends from about 10 MHz to 11 GHz, so that a frequency outside this range is indicated.

### 5.4.2 Technique

Consideration has been given to the relative advantages of using the Shuttle versus a deployed vehicle as the re-entry vehicle. The trade-offs are presented in Table 5-1. Based on these considerations, the Shuttle approach is recommended wherein the plasma experiment is performed during the essential post-mission re-entries.

The initial feasibility tests will be performed by transmitting from the Shuttle to a low orbit, repeater experiment module (satellite),

Table 5-1. Factors Influencing Selection of Re-Entry Vehicle

| Factor | Shuttle As Re-Entry Vehicle | Another Vehicle for Re-Entry |
|---|---|---|
| CREW SAFETY | • If tests are restricted to re-entries required following missions supporting other experiments, no increase in hazard.<br>• Multiple re-entries to expedite experiment progress would increase hazard. | • Allows large number of tests without crew hazard increase. |
| VALIDITY OF RESULTS | • Since a key application is Shuttle itself, Shuttle re-entry is best test. | • Effects measured for small module/satellite may not readily scale to larger vehicle because size and thermal properties very appreciably. |
| COST ASPECTS | • Shuttle has to re-enter after each mission.<br>• One small satellite can be left in desired orbit and probably re-used for many shuttle re-entry tests.<br>• Small satellite provides a re-entry communication service benefit to shuttle. | • Cheapest satellites not designed to withstand re-entry; thermal protection required.<br>• Expensive to release many re-entry modules which are probably expendable or expensive to collect and recycle. |

deployed from the shuttle prior to Shuttle re-entry. By adopting a low orbit module the range dependent loss of the shuttle-to-module link is minimized, allowing a relatively wide beam angle to be used on the Shuttle uplink. These factors simplify and reduce the cost and complexity of the repeater module. This concept is illustrated in Figure 5-2.

A frequency in the 13 - 16 GHz region is proposed for the Shuttle-to-experiment module uplink. This falls above the area of peak attenuation due to plasma, but is not so high as to involve a serious power budget problem because of the frequency-dependent loss term. It is a region for which a substantial quantity of modestly priced hardware is available. It seems probable that frequencies of 13.25 - 14.2 GHz or 14.4 - 15.35 GHz already allocated for space relay service may be appropriate.

The corresponding downlink to the earth will be to a designated NASA ground tracking station and it is, therefore, highly desirable that a network-compatible frequency be chosen. The existing NASA unified S-band (USB) allocation is suggested.

This experiment is performed during re-entry of the Shuttle following an orbital mission. The Shuttle ejects and leaves the experiment module (a small communication satellite) in the same orbit as the Shuttle. The Shuttle subsequently establishes communication with a NASA ground tracking station via the experiment module repeater. Figure 5-3 shows the essential geometrical relationships. The signal repeater module translates the Shuttle signal from the 13 - 16 GHz region to USB. In addition, the experiment module incorporates a logarithmic AGC power level measurement circuit to monitor the power level of the signal received from the Shuttle. This measurement is continuously digitized by an analog-to-digital converter within the satellite, and the resulting binary words are transmitted to the ground station on USB subcarrier. Thus, the equipment associated with this experiment fulfills a dual role of collecting data and furnishing a real time communications link from the Shuttle to the ground.

Digitizing the power level of the signal received by the satellite from the Shuttle separates the signal effects encountered on the plasma environment uplink from those of the USB downlink (such as weather). The overall performance of the Shuttle-ground station link provides a

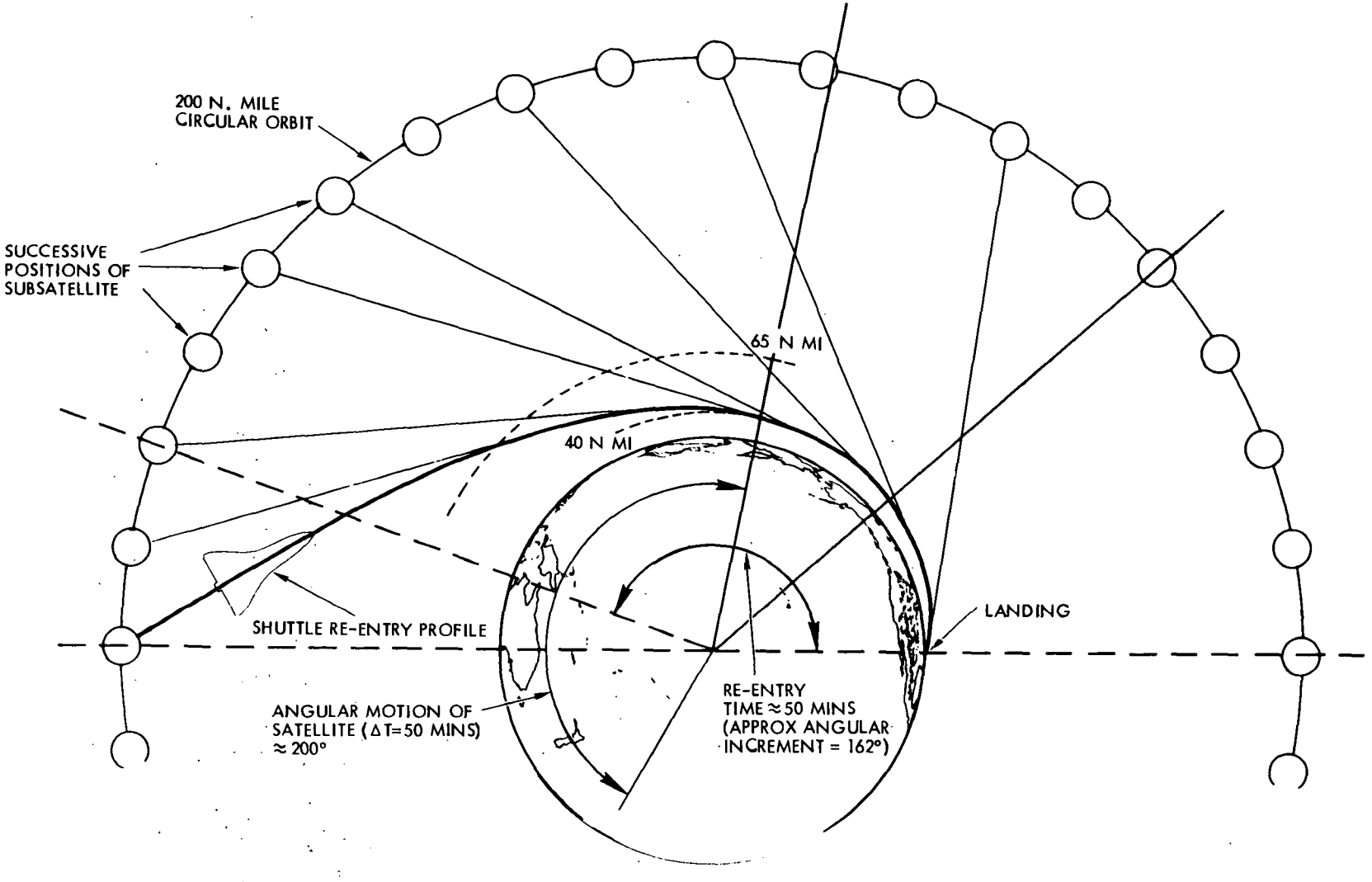


Figure 5-2. Shuttle/Subsatellite Re-entry Geometry

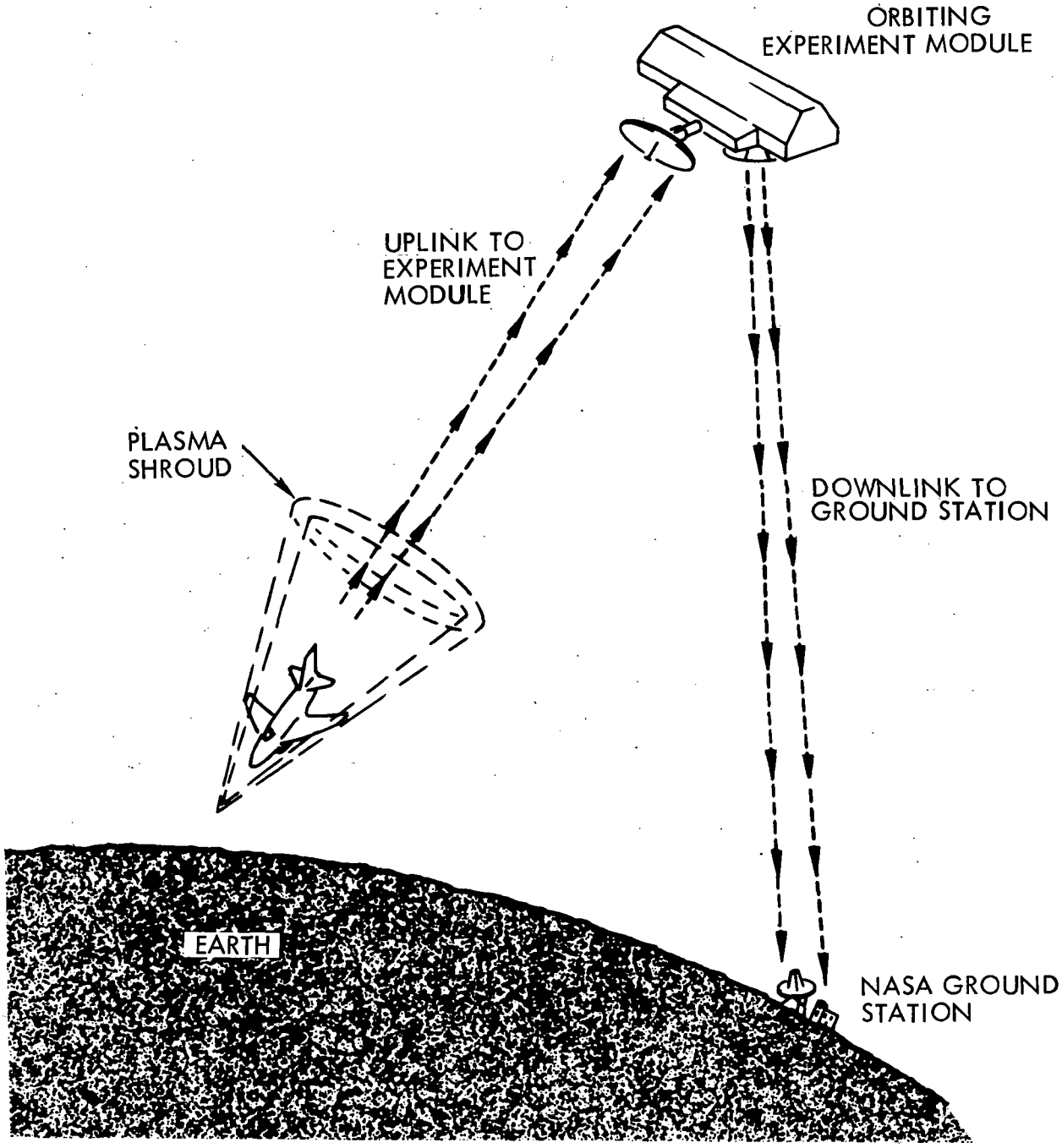


Figure 5-3. Conceptual Sketch – Communication Repeater Satellite for Re-entry Communication Support

qualitative assessment of the attainable performance for the particular combination of design parameters adopted. The subcarrier words are transmitted at a relatively slow data rate and consequently will be recovered even under adverse downlink conditions.

The experiment module will include a tape recorder which will accumulate a permanent record of the communication channel content and the digitized AGC level. This record will be available when the Shuttle intercepts the experiment module on a subsequent mission.

5.4.3 Features

For the initial test phase the Shuttle will be configured as shown in Figure 5-4.

The experiment module, left in orbit to serve as a communication relay, will incorporate the following items:

- Small 13 - 16 GHz dish antenna
- Microwave receiver (13 - 16 GHz)
- Signal processor including A-D converter and subcarrier oscillator
- USB transmitter
- USB directional antenna
- Support equipment, including solar panels, batteries, etc.

A functional block diagram is depicted in Figure 5-5.

Signal strength measurements are proposed using two mutually orthogonal linearly polarized antennas. Depending upon the success achieved in obtaining statistically reliable results, more sophisticated instrumentation may be included to obtain supplementary data on the following points:

a) Angular dependence of frequency response of re-entry plasma

b) Angle of arrival changes due to diffraction of radiation by finite re-entry plasma boundaries

c) Effect of dispersion (frequency dependence of phase velocity) on data rate. This can be due to two causes: first the dispersion indicated in b) above and second the dependence of plasma refractive index on frequency, (and possibly on the value of the magnetic field).

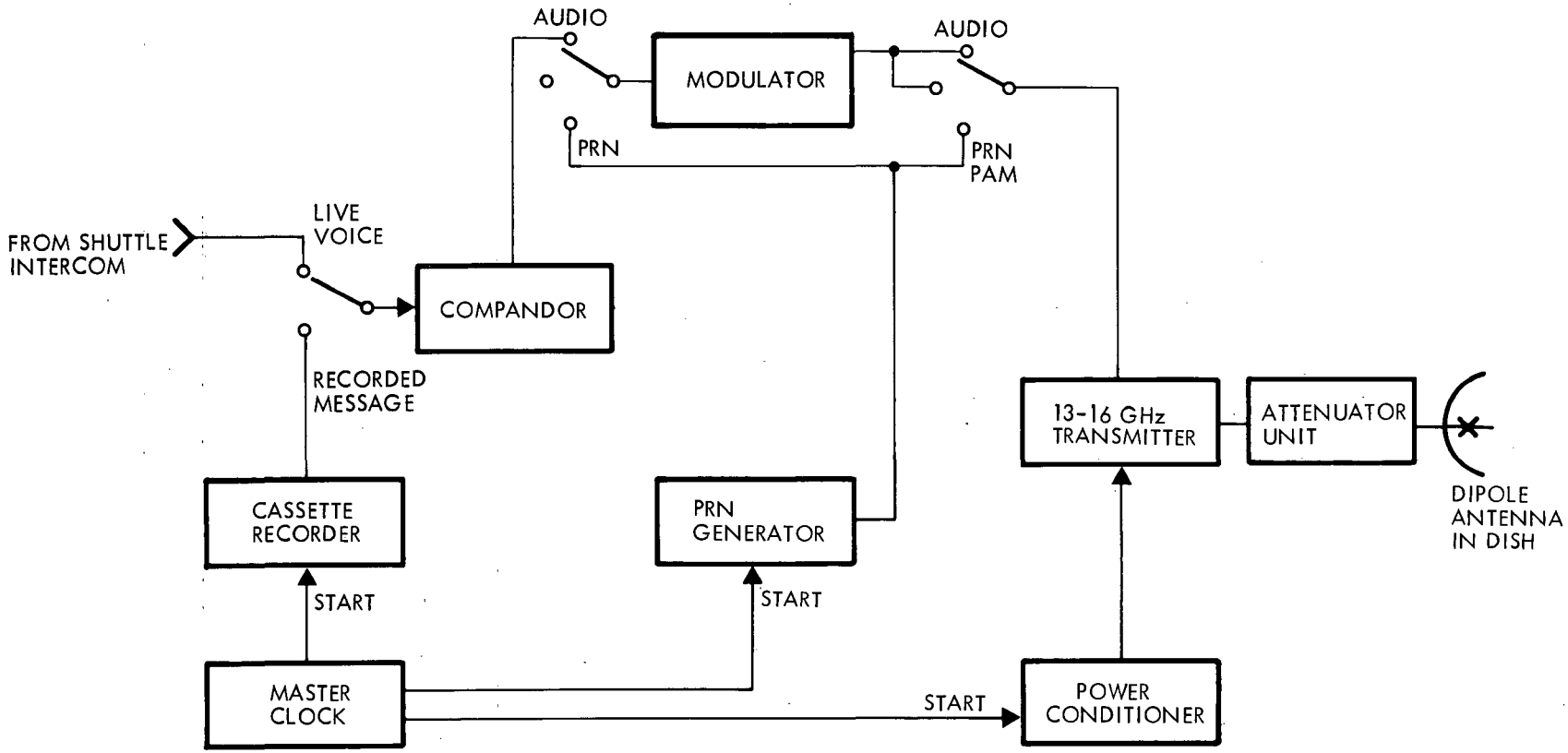


Figure 5-4. Shuttle Equipment Block Diagram — Plasma Propagation Experiment

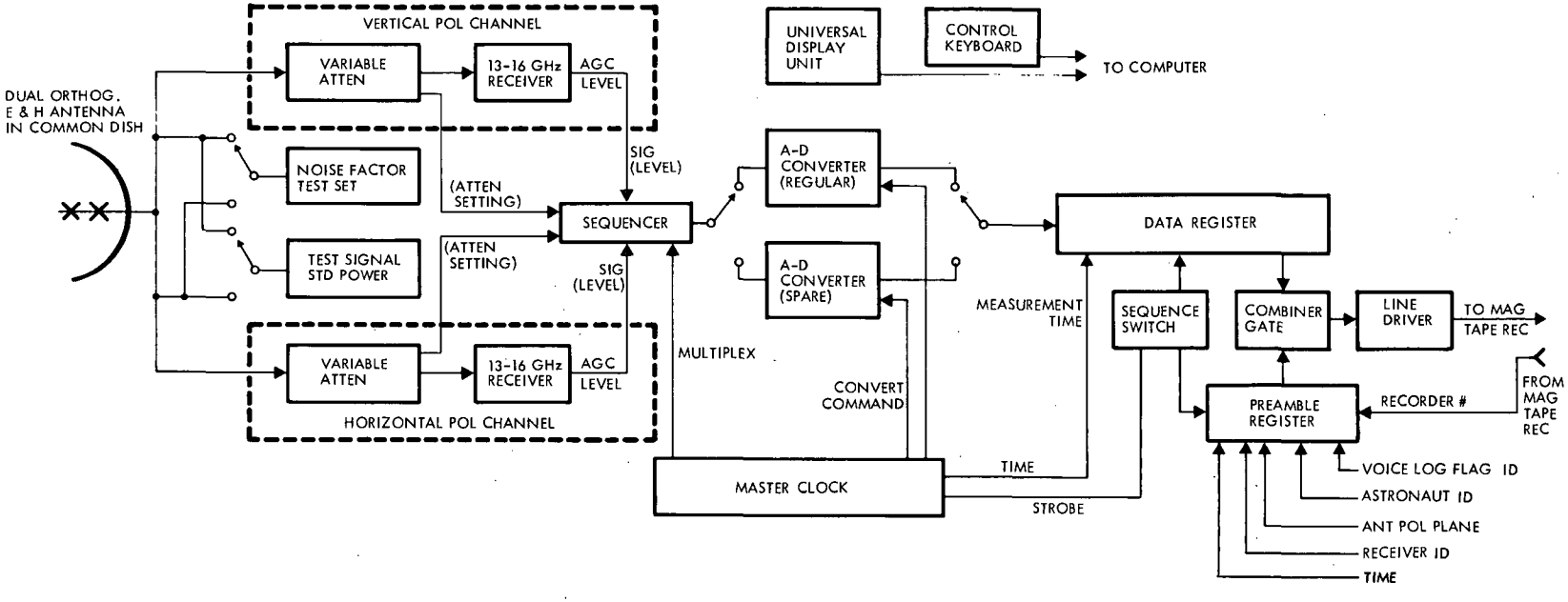


Figure 5-5. Experiment Module Equipment Block Diagram Plasma Propagation

These experiments would require more complex instrumentation in both the Shuttle re-entry vehicle and in the experiment module or space station. Such additions are compatible with the Growth Laboratory concept and the increasing degree of automation of tedious routine tasks.

## 5.5 EXPERIMENT OBSERVATION/MEASUREMENT PROGRAM

The proposed mode of operation is performing re-entry plasma experiments as a piggyback or free-loading activity at the end of three Shuttle missions. The first re-entry test will emphasize the functional checkout of the system but is expected to yield a limited amount of test data. It is anticipated that this will size the problem and indicate necessary changes in equipment configuration and operating procedures.

The second re-entry test is expected to produce useful results from both the qualitative voice/data link and the quantized signal level record. The third re-entry will be used to evaluate a bi-directional communication link between the re-entry vehicle and the experiment module.

Prior to the fourth test, installation of multi-frequency equipment is recommended which can expand the initial single channel facilities and facilitate evaluation of the potential modulation bandwidth capabilities of the test link. It is anticipated that sufficient data will be available from this experiment and the VHF-UHF, RF propagation tests to determine whether a polarization tracking subsystem should be installed. Multi-frequency tests are planned for the fourth test, with dedicated multiple re-entry sorties optional, depending on the success of the prior piggyback tests.

Subsequently, it is proposed to extend the communication concept and substitute a synchronous satellite for the experiment module, as the frequency translating repeater. This arrangement would then be used to collect data and demonstrate the feasibility of a transplasma re-entry link. This step is, of course, dependent on the results obtained in the shorter communication link via the experiment module.

Finally, the data obtained from these tests will be used to define the preferred approach for a communication link to serve re-entry vehicles.

The observation and measurement program described will rely heavily on astronaut participation to set up, calibrate and run the initial tests, develop recommendations for automated measurement and streamlined operation. In the later stages the experiment will mature to a routine data collection function and a backup communication link service requiring a minimum of support.

The proposed program is illustrated in Table 5-2.

## 5.6 INTERFACE, SUPPORT AND PERFORMANCE REQUIREMENTS

The proposed tests involve operating an experiment module, unattended, in a parking orbit at an altitude of approximately 200 n. mi. Although operation is limited to the period during which the shuttle executes a re-entry and re-orbit cycle, the module must furnish temperature control and power the plasma experiment electronics. Since the repeater and recording functions are only required for the re-entry phase, it may be possible to terminate or alternate thermal and/or power control at the end of this period rather than maintain these conditions until the shuttle returns to orbit and recovers the module.

In addition, it is required to have equipment in the Shuttle and operating during re-entry. Specifically, this requires a small rear-facing antenna dish being located in one of the shuttle instrument pods.

If the test data obtained using the experiment module indicate that a geosynchronous satellite could and would be desirable as the communication repeater platform, then an appropriate payload will be defined and a host spacecraft will be identified.

For many of the re-entry tests, a relatively broadbeam antenna can be used on both the probe and spacecraft receiving platform. Wideband transmission may necessitate adopting an autotracking narrow beam antenna. If the power budgets disclose a problem in securing acceptable SNR; autotracking may be adopted as mentioned. Attitude control of the experiment module and ephemeris data is important in this experiment since the experiment module antenna field-of-view must satisfy viewing constraints of both the Shuttle and the NASA ground station.

## Table 5-2. Proposed Observation/Measurement Program – Plasma Propagation

| TEST | SORTIE NO. | ANTENNA POLAR-IZATION | RECOMMENDED TEST CONDITIONS | | | | | | DATA OUTPUT | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Repeater Platform (RP) | | Comm. Routing | | | | |
| | | | Freq. | Re-Entry Vehicle (REV) | Type | Orbit | REV to RP | RP to REV | Signal Level | Test Record | Where Stored* |
| Primary Equipment Checkout | 1 | Dual Lin Orthog | Single | Shuttle | Exper. Module | ≈200 n. mi. | YES | NO | YES | Voice | E. M. |
| Prelim. Data Collection | 2 | Dual Lin Orthog | Single | Shuttle | Exper. Module | ≈200 n. mi. | YES | NO | YES | Voice | E. M. & G. T. S. |
| Bi-Directional Link | 3 | Dual Lin Orthog | Single | Shuttle | Exper. Module | ≈200 n. mi. | YES | YES | YES | Voice | E. M. G. T. S. R. E. V. |
| Wideband Coherence | 4 | Optional Pol Tracking | Multiple | Shuttle | Exper. Module | ≈200 n. mi. | YES | YES | YES | Data | E. M. G. T. S. R. E. V. |
| Wideband Coherence | Dedicated Optional | Optional Pol Tracking | Multiple | Shuttle | Exper. Module | ≈200 n. mi. | YES | YES | YES | Data | E. M. G. T. S. R. E. V. |
| Synch Sat. Repeater Eval. | 5 | Optional Pol Tracking | Single | Shuttle | Sync. Sat. | Synchronous Equatorial | REV Sync. Sat. | NO | YES | Voice | G. T. S. |
| Synch Sat. Repeater Eval. | 6 | Optional Pol Tracking | Single | Shuttle | Sync. Sat. | Synchronous Equatorial | NO | Sync. Sat. to REV | YES | Voice | G. T. S. |
| Wideband via Synch. Sat. | 7 | Optional Pol Tracking | Multiple | Shuttle | Sync. Sat. | Synchronous Equatorial | REV Sync. Sat. | Sync. Sat. to REV | YES | Data | G. T. S. & R. E. V. |

* E. M. = Experiment Module
G. T. S. = Ground Tracking Station
R. E. V. = Re-Entry Vehicle

The supporting services required for the experiment module are shown in Table 5-3.

Table 5-3. Experiment Module Support Requirements

| Support Item | Classification | Description |
|---|---|---|
| Electrical Power | Essential | 28 V DC or 400 Hz |
| Temperature | Trade Off | $71^{\circ}F + 3^{\circ} F/76^{\circ} F \pm 116^{\circ}F$ |
| Pressure | Trade Off | 28 - 31" Hg/0 - 31" Hg |
| Exp. Module Eph. | Essential | 3-Axis Continuous History |
| Orbit | Trade Off | 200 N. Mi. |
| Time Std. | Trade Off | Day, Hour, Minute and Second |

## 5.7 POTENTIAL ROLE OF MAN

### 5.7.1 Calibration

Power level and noise figure calibrations will be performed at a convenient time during one of the orbits immediately preceding the re-entry phase. This procedure involves a systematic check to ensure that all equipment is powered and functional prior to calibration of the receivers. The power calibration consists of injecting known levels of RF signal power into the 13 - 16 GHz receiver and checking and recording the resulting digitized AGC signal level output produced by the receiver. The test output level applied to the receiver is incremented while the receiver output is recorded on magnetic tape. Both receivers are calibrated simultaneously and in an identical manner. The astronaut plays the tape back into a display to check the recorder.

The noise figure of each receiver is measured and recorded by the astronaut using the noise test set. At the end of the calibration phase the astronaut returns the system to the control of a program clock. The shuttle transmitter for power output is verified.

### 5.7.2 Initial Data Acquisition

During re-entry the system operates unattended with the astronauts returning to earth in the Shuttle and the experiment module collecting and storing the signal amplitude record and voice sample on the tape recorder. During the later tests the experiment relays this data to a convenient NASA ground station.

### 5.7.3 Astronaut Post-Re-entry Evaluation

On the next sortie mission the crew returns to the parked experiment module to retrieve the recorded data. The astronaut can replay and analyze the data acquired during the previous Shuttle re-entry. On the basis of these results, the astronaut can make changes to the current plasma re-entry tests to be performed at the end of the current orbital mission. For later flights, data will also be available at the NASA ground station where appreciably more sophisticated record analysis can be performed.

## 5.8 EXPERIMENT EVOLUTION

The test program associated with the proposed plasma propagation experiment consists of two phases. The first is concerned with taking measurements and establishing statistical bounds for the plasma-related loss effects. The second phase emphasizes application of the data from Phase I to define a demonstration re-entry communication service, probably via a data relay using an available communication satellite. This second phase is intended as a demonstration/verification of the benefits of such a communications link.

### 5.8.1 Phase I

On the earliest sorties the data will be stored on a magnetic recorder in the experiment module, but as soon as feasible an experiment module-to-ground link will be commissioned facilitating the real-time delivery of data to a geographically convenient NASA ground tracking station for computer processing and analysis. Since the data is collected by the un-manned experiment module and the Shuttle must re-enter anyway in order to return the laboratory personnel to earth, these tests make excellent use of the shuttle time and place only modest demands on the crew.

The Phase I tests will include tests using dual antenna polarization, both single and multiple frequencies, voice and digital data.

5.8.2 Phase II

The second phase is concerned with establishing a baseline design for an unmanned satellite repeater to serve as a communication link during vehicle re-entry, installing this equipment, and demonstrating its performance using the Shuttle.

The tests will include narrowband voice and wideband data, and the accumulation of a complete record of signal characteristics versus time.

The specific beneficial results from this experiment are:

- Definition of a plasma re-entry communication service
- Identification of a plasma communication data acquisition program for the future Growth and Total Laboratory programs.

5.9 SR&T REQUIREMENTS None.

5.10 ACKNOWLEDGEMENTS

The following documents were used in preparing this experiment description:

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3. E. F. Dirsa, "The Telemetry and Communication Problem of Re-Entrant Space Vehicles," Proc. IRE, April 1960.

4. S. H. Cushner, "Re-Entry Plasma Effects on Space Shuttle Comm/Nav Frequencies," TRW IOC #7352.9-08, 2 December 1970.

5. J. E. Drummond, "Radio Propagation in Re-Entry Plasmas," Boeing D1-82-6098, October 1967.

6. P. W. Huber and T. Sims, "Research Approaches to the Problem of Re-Entry Communications Blackout," 3d Symposium on the Plasma Sheath, Boston, NASA-TM-X-56839.

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9. Reference Earth Orbital Research and Applications Investigations (Blue Book), Vol. V, 15 January 1971.

# APPENDIX A

## BACKSCATTER MISMATCH AND ABSORPTION LOSS DUE TO PLASMA

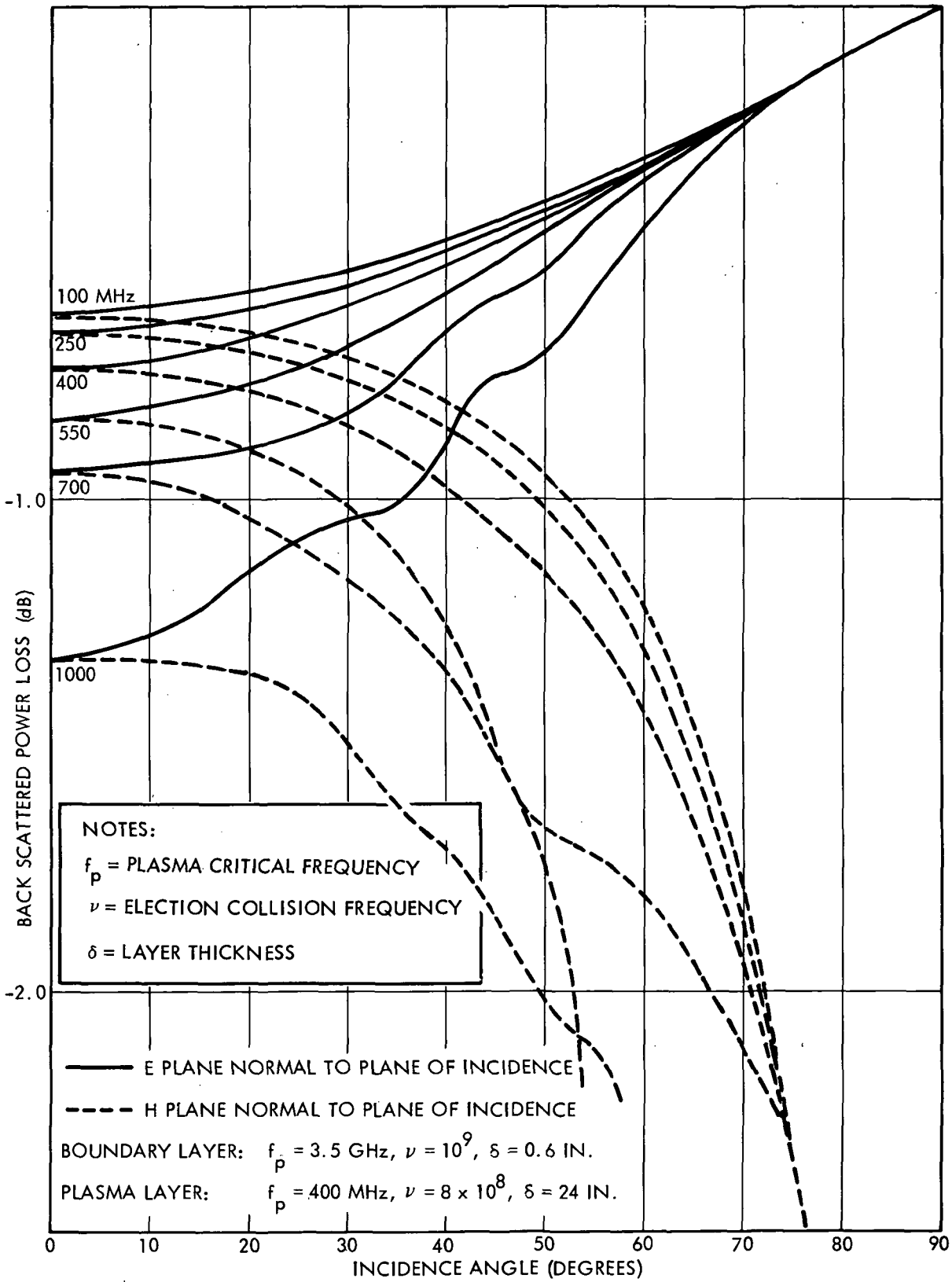


Figure A-1. Backscatter Mismatch Loss Due to Plasma versus Wave Incidence Angle and Frequency – 270 K Ft. Altitude

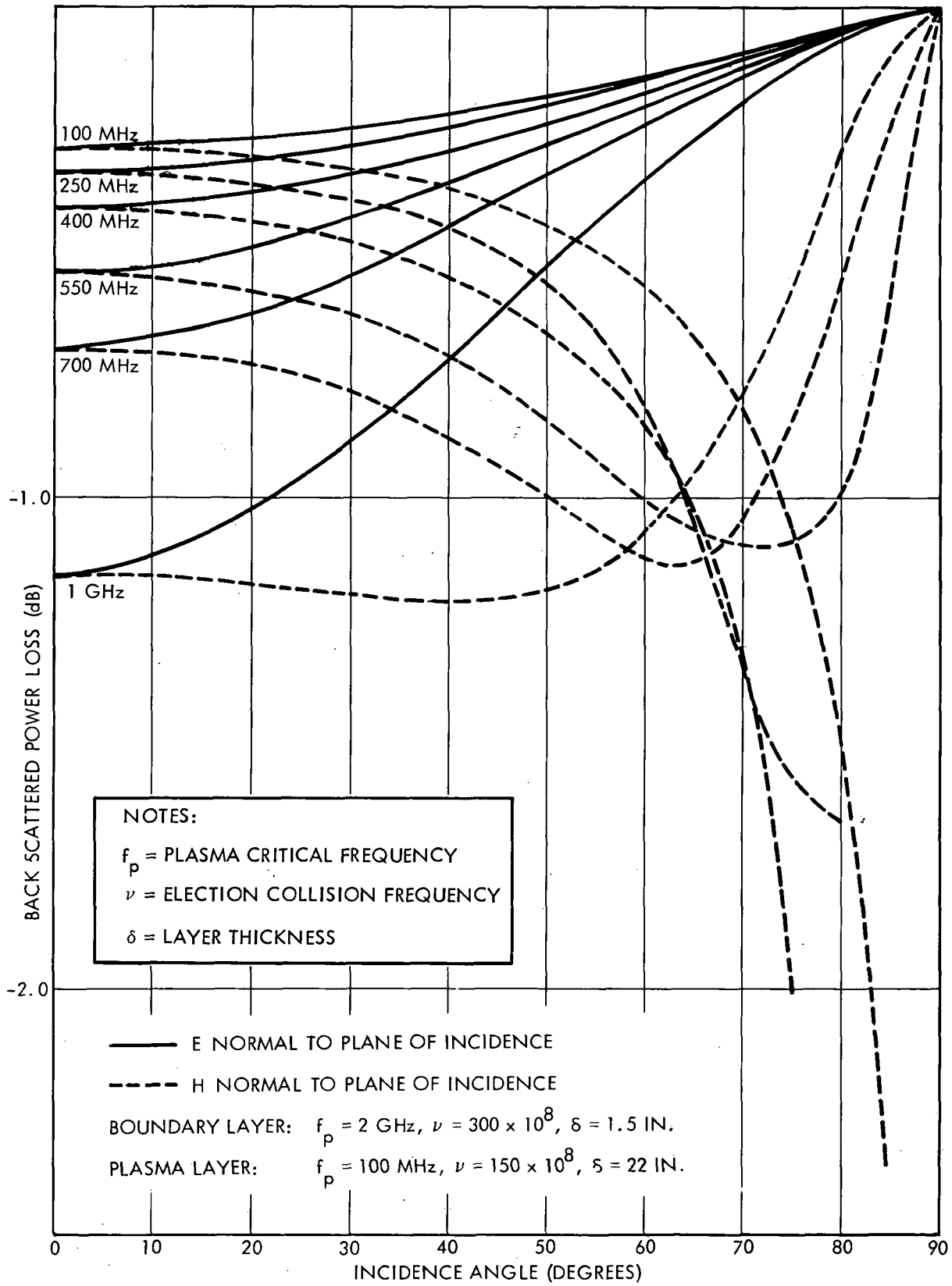


Figure A-2. Backscatter Mismatch Loss Due to Plasma versus Wave Incidence Angle and Frequency – 230 K Ft. Altitude

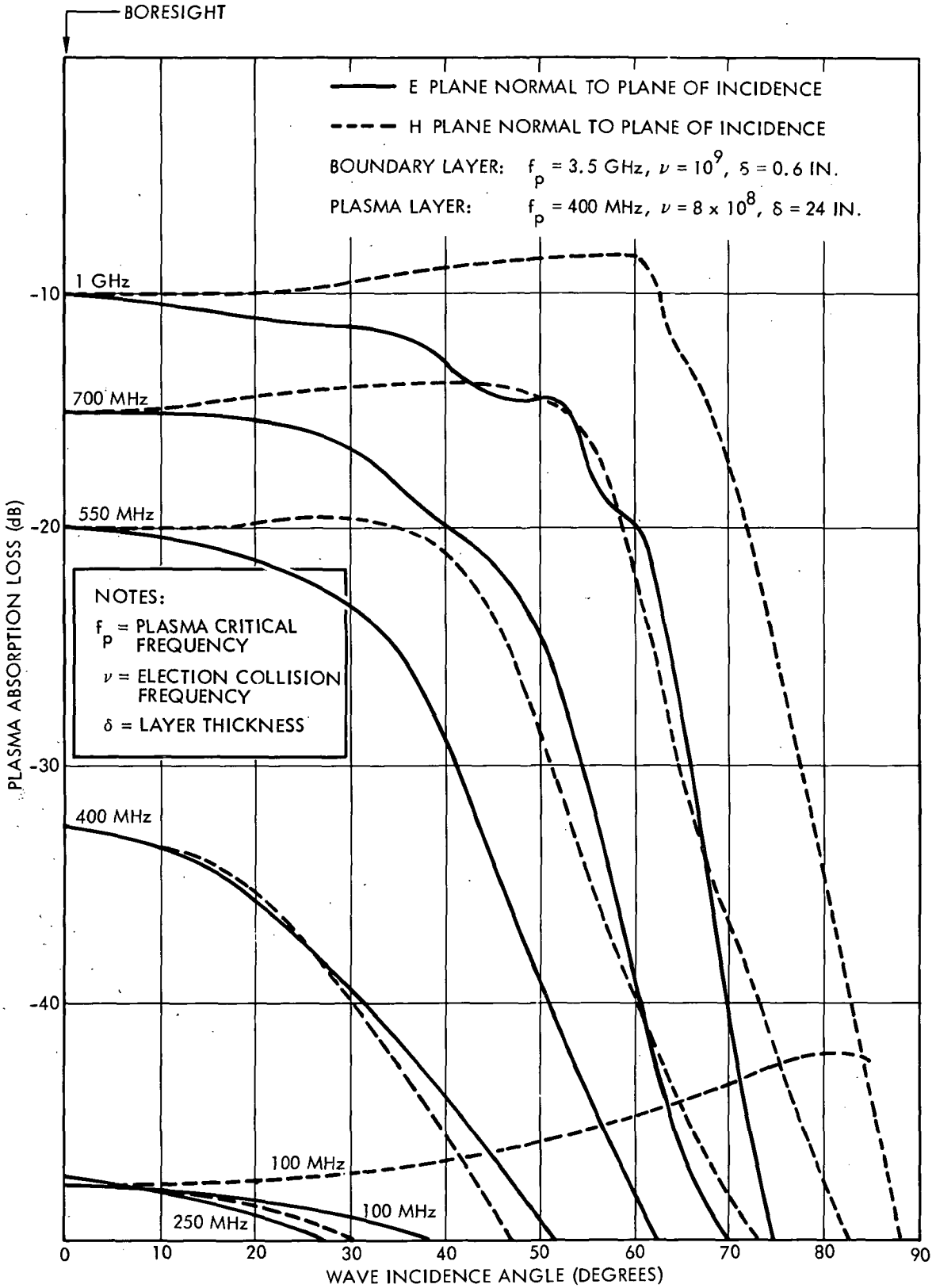


Figure A-3. Absorption Loss in dB versus Wave Incidence and Frequency for 270 K Ft. Altitude

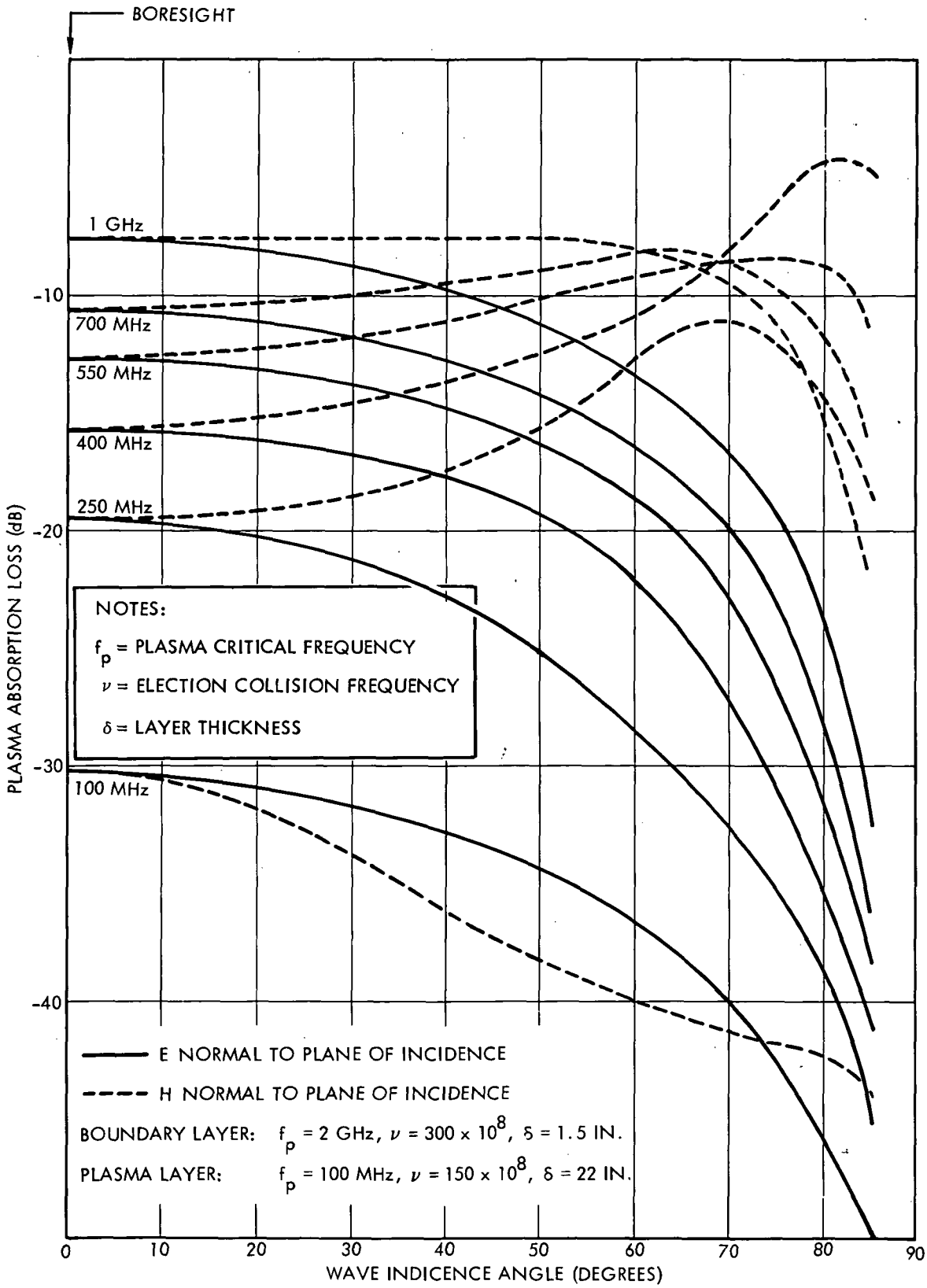


Figure A-4. Absorption Loss in dB versus Wave Incidence and Frequency for 230 K Ft. Altitude

# EXPERIMENT 6

# DIRECT BROADCAST DEMONSTRATION

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# 6. DIRECT BROADCAST DEMONSTRATION

## 6.1 EXPERIMENT CLASSIFICATION

This experiment is concerned with investigating, demonstrating, and optimizing electronic systems for direct TV transmission. Direct TV transmission refers to the mode of communication in which a satellite broadcasts direct to the home viewer rather than via a terrestrial distribution network.

The activities include experimental transmission from the orbiting vehicle, optimization of the equipment performance, establishing the sensitivity of the related variables, and interpreting the resulting data. A low cost receiving system design will be developed and tested. The experiment plan is predicated on widespread participation by amateur radio and electronic enthusiasts. There are two aspects involved, one being the space vehicle equipment configuration and the other the design for a low cost viewer adapter. On the basis of these activities, this experiment has been assigned a classification of applied research.

The proposed experiment and related testing activities are well suited to the Early Laboratory in terms of the usefulness of man, modest equipment volume, and compatibility with a 7-day sortie mission.

## 6.2 EXPERIMENT OBJECTIVES

The major objectives of this experiment are to:

a) Demonstrate the feasibility of direct TV transmission from a satellite to the individual viewer

b) Optimize the system parameters so as to attain the best compromise among the following desirable features

- Use existing regular domestic TV receiver
- Required only low cost modification or additions
- Operate without degrading existing TV services
- Require a minimum of satellite power
- Provide acceptable quality signals.

c) Define the criteria for a synchronous altitude dedicated TV satellite.

Although the experiment defined herein is devoted to a discussion of a direct TV service, it is proposed to eventually implement a service that incorporates both radio and TV transmission. The radio channels would provide weather data, standard time, and emergency information.

An important facet of the program will be identifying the design and implementation of any adapter or converter, as well as the antenna configuration required on the ground. The proposed approach is to design, fabricate and test the low cost items needed to allow direct reception by a viewer.

## 6.3 DISCIPLINE BACKGROUND AND STATUS

### 6.3.1 Regular TV

The present television services in the continental U.S. (CONUS) are provided by a combination of radio transmitters and cable networks (CATV). The majority of the population is served by direct TV transmission in the VHF and UHF frequency bands, comprising a total of 83 channels. The VHF band extends from 54 MHz (Channel 2) to 216 MHz (Channel 13), and the UHF band from 470 to 890 MHz (Channels 14 - 83).

The power levels, modulation and signal format are subject to Federal Communication Commission (FCC) regulation and enforcement. The modulation scheme used involves vestigial AM for the video portion, and FM of a separate aural carrier located 4.5 MHz above the video (picture) carrier.

In order to accommodate the large demand for TV transmission facilities, the channel allocations are repeated across CONUS on a staggered basis. This is feasible because of the isolation afforded by a combination of range differential and natural terrain obstructions.

### 6.3.2 Community Antenna Systems

CATV is a commercial venture in which a separate service company invests in real estate and installs a comprehensive antenna system at some ideal geographic vantage point. The service company then installs receiving equipment and amplifiers to acquire and transfer clean, substantially noise-free signals from the antenna site to their local office.

From the local office, the signals are sent via a network of low-loss coaxial lines and repeater amplifiers to the local communities. Individual subscribers pay an annual fee to have their homes or businesses connected to the distribution lines.

The primary application of CATV is, of course, in regions where adverse local terrain or weather conditions preclude acceptable reception or reduce reception to only one or two local stations. The principal functions of CATV are:

a) To provide the subscribers with a higher quality TV signal than would be available using his own antenna

b) To provide a larger selection of programs by importing signals too weak to be received directly by the subscriber.

The key features of a CATV network are:

a) Uses programs transmitted by regular TV stations

b) Uses a prime antenna location to assure an excellent signal

c) Incorporates multiple antennas to provide typically 8-12 separate program channels at all times

d) Avoids the homewoner investing in, or maintaining, an antenna

e) Provides a continuing service to the entire community

f) Involves an independent operating company, owning and maintaining its own reception, transmission and distribution equipment.

Signals are distributed to the user in a multiplexed form over a single coaxial cable. In rural areas, this cable, usually a 1/2 inch low-loss air dielectric type (References 1 and 2), is run above ground strung along existing telephone poles. The space is rented from the local phone company on an annual basis. Within residential communities and other locations where aesthetic considerations require it, the cable is run underground within rigid conduit. Broadband equalizing repeater amplifiers are located every 1,500 feet or so to correct for the attenuation versus frequency characteristics of the cable, and restore the signal level.

Because the cable loss is much higher at UHF frequencies than at VHF, cable TV companies translate any UHF programs (e.g., Channel 22 in the Los Angeles area) to an unused VHF channel so that all 12 channels they deliver are in the range channel 2 to channel 13 independent of their original transmission channel. The general configuration of a CATV network is shown in Figure 6-1.

The most recent development in the CATV area is a bidirectional communication link between the CATV operator and the subscriber (References 3, 4). This scheme, presently in the experimental stages,

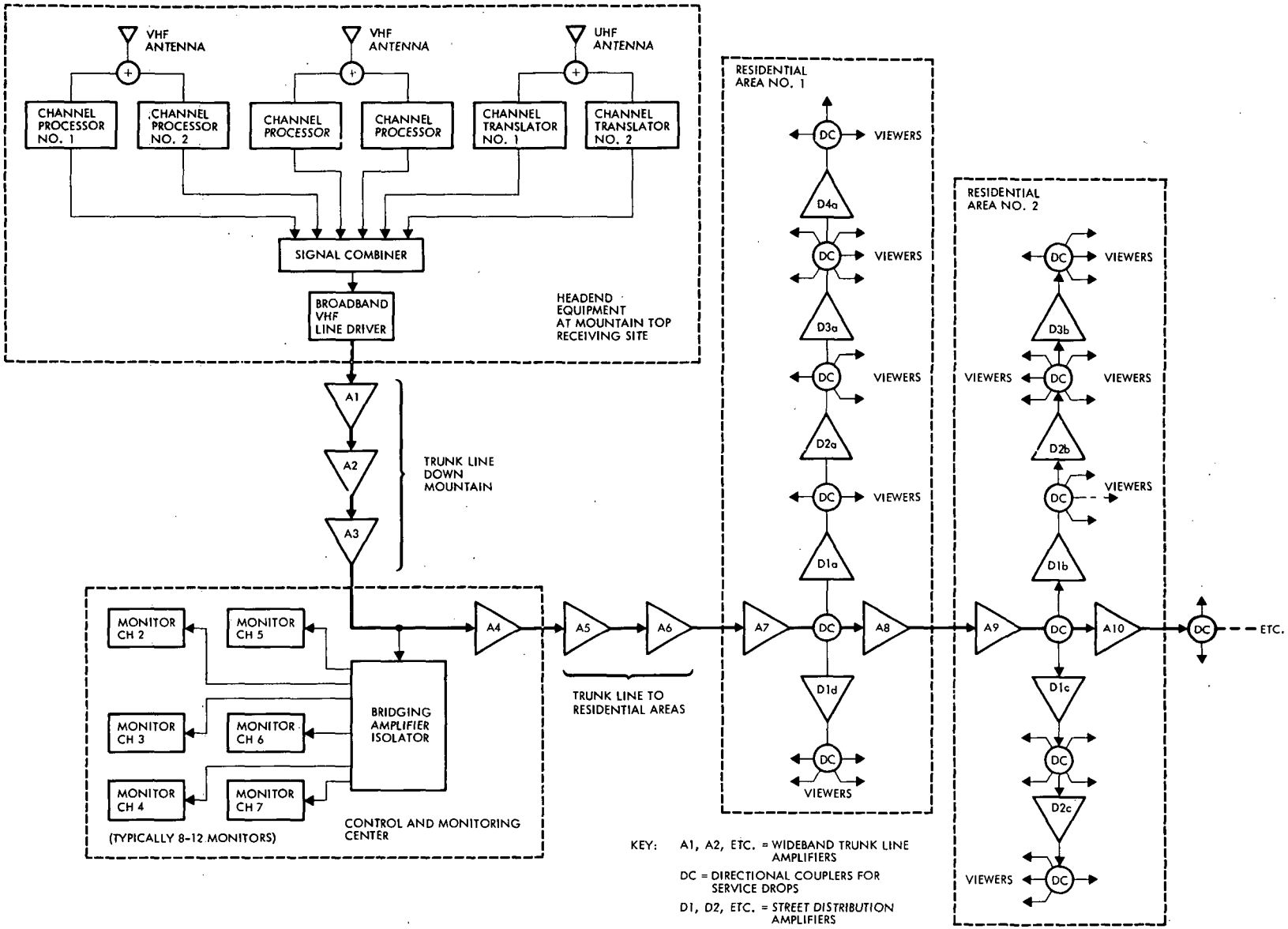



Figure 6-1. Simplified General Configuration for a CATV Distribution Service

enormously increases the scope of the whole CATV operation. It will allow the subscriber to vote on the program material and provide immediate feedback to the service operator. Applied to advertising, it offers wide ranging possible applications from rating product features to remote shopping.

At least two large CATV hardware companies (Cascade and Vikoa) are presently offering CATV repeater amplifiers for bidirectional systems. Cascade is actually installing an experimental system in California. These systems use the frequency band from 10 to 54 MHz (below TV channel 2) to transmit the return path signals.

The following statistics (from Reference 5), relating to mid-1970, indicate the growth of CATV (see also Reference 6).

| | |
|---|---|
| Number of operating CATV systems | 2, 321 |
| Number of systems under construction | 2, 000 |
| Fraction of population served by CATV | 6 percent |
| Total industry capital investment | $500 Million |
| Total CATV annual revenue | $300 Million |
| Average number of subscribers per system | 1, 500 |
| Maximum number of subscribers per system | 28, 325 (San Diego) |
| Maximum channel capacity of any system | 42 (San Jose) |

#### 6.3.2.1 CATV Interference Problems

Because a large number of users share the cost of the antenna site and equipment, the CATV operator can often afford to install an expensive receiving system which is remote from the city and free of local interference sources. The CATV company can also select a high elevation site with a clear view of the transmission source and obtain a reasonably high level of signal, a further aid in fighting noise and RFI.

The most common problem is adjacent channel interference, which is far more common with CATV than regular "live" TV because with CATV all 12 VHF channels are used, whereas with "live" TV the FCC allocation plan assures that there is at least one clear channel between each local station assignment (clear because it is beyond range).

In some urban/suburban areas there are significant problems with "ghost" signals (Reference 7). These difficulties generally arise where the CATV system is marginal from a standpoint of reception need. If the reception quality available to home owners is acceptable with a modest-cost directional antenna, a CATV company has difficulty securing enough customers to pay for a really first rate antenna site and the associated equipment. If a relatively low mast and indifferent quality antennas are used for the CATV signal source, the resulting TV signals can be degraded by multiple echo signals from local tall buildings, such as church towers, stadium lamp standards, etc. The resulting poor quality of TV signals lessens the customer acceptance of the CATV service. The net result is a form of capital investment limited negative feedback.

### 6.3.3 Satellite-Direct and Satellite-CATV

Over the past few years, cable television has expanded considerably. Increases in the number of CATV networks and the size of the customer base have provided an expanded market for CATV equipment, justifying hardware research and development. Although the present services in the United States only claim about 10 percent of the population, this is expected to rise appreciably as the quality and diversity of services are upgraded.

It appears that in the time frame of the proposed communications and navigation experiments (1980-1990) the total CATV acceptance is not likely to exceed 50 percent and that during this time individual RF reception will dominate. This conclusion is based on the results of several recent studies (References 8, 9).

It seems inevitable that, over the long term, cable TV will entirely replace conventional (radiated) transmission. In addition to the potential improvements in signal quality and increased choice of channels, there is the enormous increase in the frequency spectrum that can be diverted to other services, if the TV channels are withdrawn or drastically reduced.

The primary advantage of a satellite TV transmission system lies in its wide area coverage and is freedom from the propagation losses associated with terrain obstructions. There are a great many aspects to the suggested use of satellite TV; these are treated in the literature (References 10, 11, 12). The next step is to perform actual tests with satellite transmission of TV signals. This is an experiment which is well suited to the Early Laboratory.

Sufficient technical information exists to allow the design of a reliable and versatile direct broadcast laboratory system. The required hardware is available off-the-shelf, although there are important questions to be answered regarding its environmental performance.

6.3.4 Required Signal Level

For terrestrial TV systems, the level of signal needed to provide acceptable quality is usually established by the level of man-made noise at the receiving location. For the UHF band the FCC has established field strength levels of between 1.6 and 10 mV per meter. The larger figure corresponding to principal cities and the smaller to rural locations.

A simple dipole antenna immersed in a median field of 5 mV/meter would provide a signal of -85 dBw to its associated receiver (Reference 13).

Since man-made noise presently emanates almost exclusively from sources located on the surface of the earth, any directional antenna that points skywards will collect less noise than a similar horizontally oriented antenna used for terrestrial TV services. However, unless the beamwidth of the receiving antenna is quite narrow, and aimed toward the zenith, it will have at least some fraction of the man-made sources in its field of view. In addition, noise to the side and rear of the antenna will enter at an attenuation determined by the side lobes and front-to-back ratio.

An ideal antenna devoid of these problems would collect only thermal, galactic, and solar noise. For a frequency of 700 MHz, and fairly broad antenna beam widths, the thermal self-induced noise dominates (Reference 14). Typical TV receivers exhibit front-end noise figures (NF) of 6-10 dB. For a 6 MHz bandwidth, and an assumed cabinet temperature of 35 degrees centigrade, the effective receiving system noise power will be

about -126 dBw or lower. A typical UHF domestic TV antenna exhibits a front-to-back ratio usually in excess of 20 dB.

6.3.4.1 Urban Areas

At 700 MHz the median urban noise level is only 11 dB above the receivers self noise (NF = 8 dB). It follows that the expected front-to-back ratio will attenuate the noise due to sources behind the antenna well below (-9 dB) the receiver self noise. The only significant urban noise is, therefore, due to the sources located within the main beam (Reference 15).

The magnitude of main beam noise depends on the following factors:

- Beamwidth of antenna
- Pointing angle (relative to zenith)
- Proximity of noise sources
- Relative elevation of noise sources
- Beam shape within main beam of antenna
- Noise level.

It is probable that only a small fraction of the field of view of the proposed antenna system will be occupied by man-made noise sources. For the purposes of preliminary evaluation, it may be assumed that such urban background noise is reduced by a factor of at least 10 dB. The several levels discussed in this section are illustrated in Figure 6-2. The composite noise level, including urban and receiver thermal noise, is assumed to be +11 dB relative to the reference level of -136 dBw. Therefore, the net noise level is -125 dBw.

Since the minimum useful signal-to-noise ratio (SNR) for TV reception is about +30 dB, the required minimum signal level at the receiver site, for serving individual viewers at urban locations, is estimated to be about -95 dBw.

6.3.4.2 Surburban Areas

The median level of man-made noise in suburban areas of 700 MHz is approximately 3 dB below the self noise of the receiver. Neither the fractional amount intercepted by the main beam nor that attenuated by the

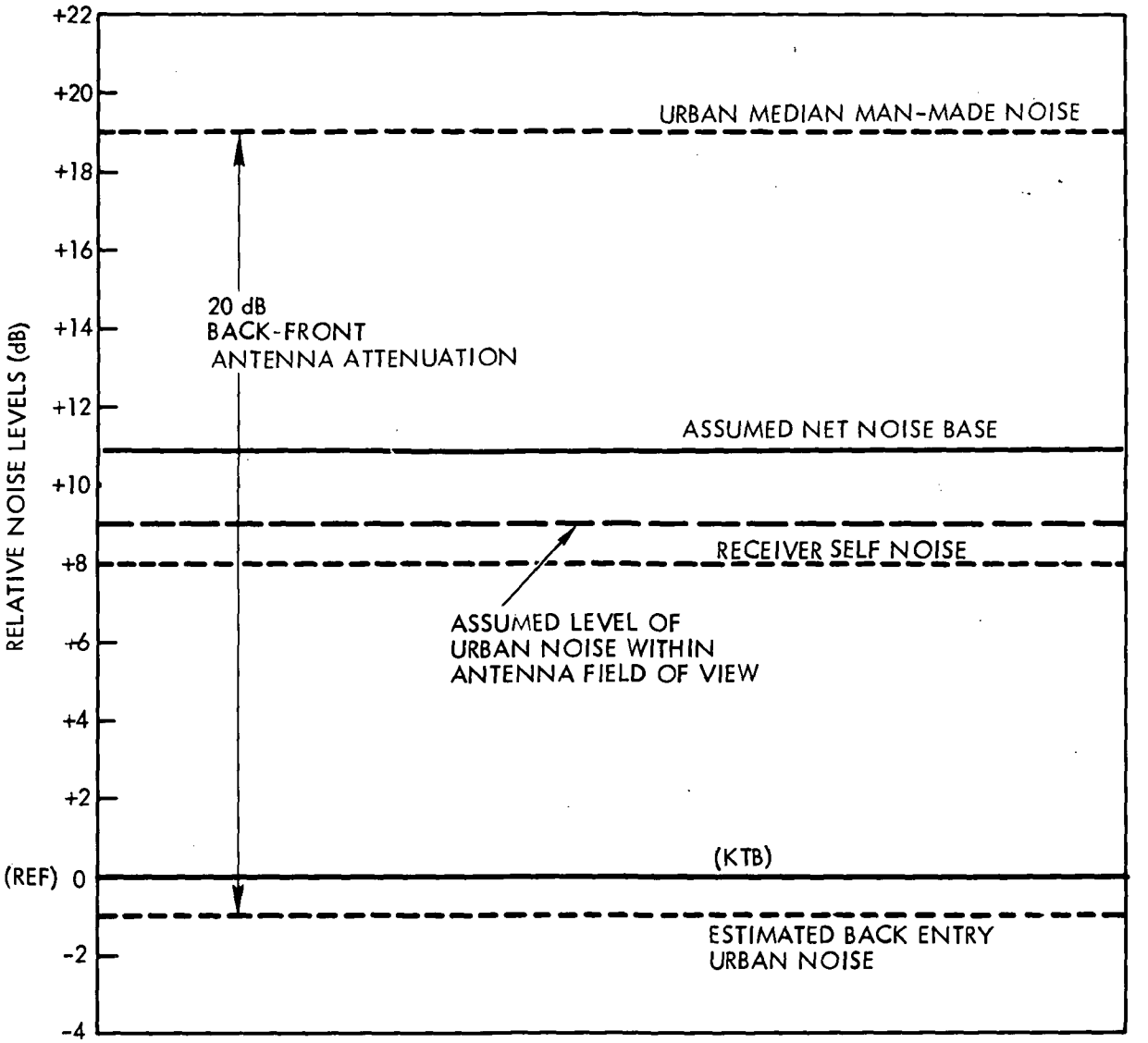



Figure 6-2. Relative Noise Levels at TV Receiver

20 dB back-to-front ratio are significant in establishing the net noise base, which is -128 dBw. To provide a 30 dB SNR, the minimum TV signal level is, therefore, -98 dBw.

### 6.3.5 Transmitter Power and Coverage Tradeoff

For a vehicle operating at an altitude of 200 nautical miles, the maximum slant range, for a 10 degree above horizon limit angle is 730 nautical miles. The corresponding free space loss (L) at 700 MHz is:

$$L(dB) = 37.8 + 20 \log R\ (nmi) + 20 \log f\ (MHz)$$

$$L = 37.8 + 20 \log 700 + 20 \left[\log (730)\right]$$

$$L = 152.4\ dB$$

Combining the results derived thus far with estimates for the remaining factors, the preliminary power budget for a down link using broad beam antennas is shown in Table 6-1.

The indicated transmitter power of over two megawatts is clearly impractical. An available compromise is to employ a relatively high gain narrow beamwidth antenna, but this reduction in beamwidth will reduce the ground footprint.

The general relationship between antenna beamwidth and gain is as follows (Reference 16):

$$G = \frac{3 \times 10^4}{(\theta)^2} \quad \text{(where } \theta = 3 \text{ dB beamwidth in degrees)}$$

The footprint radius (R) resulting from an orbit altitude (H) and a beamwidth $\theta$ can be derived by a simple trigonometric calculation as follows:

$$R = H \tan \left[\theta/2\right]$$ where R = radius in n. miles
H = altitude in n. miles
$\theta$ = 3 dB beamwidth in degrees

If the laboratory antenna is fixed, the maximum illumination time (T) for a station along the ground trace is given by the expression

$$T = 0.509R$$

Finally, when the antenna beam width is reduced the slant range (at the limit of visibility) is also reduced. Since the range loss is a logarithmic function of the range, it is not important to obtain an exact value. In the

Table 6-1. Preliminary Down-Link Power Budget

Conditions: Frequency = 700 MHz
Max. Range = 730 nautical miles

| Parameter | Source | Value | Value |
|---|---|---|---|
| Required receiver signal level | Calculated | | -95 dBw |
| Free space loss | Calculated | 152.4 dB | |
| Transmitter circuit losses | Estimated | 0.5 dB | |
| Polarization loss | Estimated | 0.5 dB | |
| Receiver antenna gain (160 deg) (at -3 dB points) | Postulated | -2.0 dB | |
| Transmitter antenna gain (142 deg) (at -3 dB points) | Postulated | -1.0 dB | |
| System margin for degradation | Nominal | 3.0 dB | |
| Loss and gain subtotal | | 159.4 | |
| Required Transmitter Power | | | 64.4 dBw (2.7 MW) |

following calculations, which cover antenna beamwidths of from 51 to 2.9 degrees, a nominal slant range of 220 nautical miles has been assumed. The reduction in free-space loss associated with reducing the slant range from 730 nautical miles to 220 nautical miles is 10.5 dB. Thus, for narrow beam antennas the minimum transmitter power is 53.9 dBw (0.25 megawatts).

Table 6-2. Summarizes the Pertinent Characteristics of the Tradeoff Between Antenna Gain and Dwell Time.

| Antenna Gain (dB) | Antenna Beamwidth (Degrees) | Footprint Radius (N. Miles) | Footprint Area (Sq. Miles) | Dwell Time (Secs.) |
|---|---|---|---|---|
| 10.0 | 51.0 | 95.4 | $34.5 \times 10^3$ | 48.6 |
| 12.5 | 38.5 | 69.8 | $20.4 \times 10^3$ | 35.5 |
| 15.0 | 29.0 | 51.7 | $11.2 \times 10^3$ | 26.3 |
| 17.5 | 22.0 | 38.8 | $6.3 \times 10^3$ | 19.8 |
| 20.0 | 16.2 | 28.4 | $3.38 \times 10^3$ | 14.5 |
| 22.5 | 12.3 | 22.0 | $2.02 \times 10^3$ | 11.2 |
| 25.0 | 9.2 | 16.1 | $1.11 \times 10^3$ | 8.2 |
| 27.5 | 7.0 | 12.2 | 625 | 6.2 |
| 30.0 | 5.2 | 9.1 | 346 | 4.6 |
| 32.5 | 3.9 | 6.8 | 194 | 3.46 |
| 35.0 | 2.9 | 5.0 | 105 | 2.55 |
| 37.5 | 2.2 | 3.8 | 61.0 | 1.93 |
| 40.0 | 1.6 | 2.8 | 33.0 | 1.43 |

For the very broad beam (142 degrees) antenna considered in the preliminary link power budget, the effective gain at the -3 dB beam edges would be -1 dB. In this case, the minimum required transmitter power is +64.4 dBw. The transmitter power necessary for various alternative antenna gains can be derived by adjusting the slant range and antenna gain accordingly.

Figure 6-3 illustrates available dwell time versus transmitter power. Assuming a conservative overall transmitter efficiency of 30 percent, the bus power required for the orbiting laboratory will be 3.3 times the radiated RF power, as shown by the broken line.

6.3.5.1 Required Dwell Time

In establishing the required dwell time for the demonstration/evaluation, it is essential to emphasize the fact that reception is only required to provide a measure of TV performance. It is not intended to provide entertainment or any conventional communication. The required dwell time is, therefore, only that needed to establish the quality of reception.

The standard U.S. television signal format uses two interlaced scans which together form a 525 line picture at a 30 Hz rate. Although the onset of the visibility period is not synchronized with the TV sweep, only one complete picture will be required to ensure that one good photographic record is obtained. Any such records will be appraised qualitatively by the human eye. The eye of a viewer integrates* successive visual images and thereby enhances the signal-to-noise ratio. It may, therefore, prove desirable to integrate a few frames to synthesize a closer approximation of the picture quality a human observer would have seen at the time of reception.

Preliminary experiments suggest that a human operator, viewing a TV receiver screen, requires about 4 to 5 seconds dwell on a single still picture to rate its quality. About 10 to 15 seconds appear to be needed to appraise a quantitative picture such as the Electronic Industries Association (EIA) resolution chart.

To compare at least four alternatives during each test, a minimum dwell time of 20 seconds for conventional still pictures, to 60 seconds for EIA chart tests is required. If photographic records are taken, or the signals are stored in a video recorder, a much shorter interval is adequate. The picture is refreshed at a 30 Hz rate so that theoretically a dwell of 1/30 second would provide one complete record. It will, however, be prudent to allow for few samples of each scene. If this replication "insurance factor" is 4, then each scene will require 4/30 seconds and the suggested four samples for comparison will occupy approximately 1/2 second.

* Aided by the associated human brain.

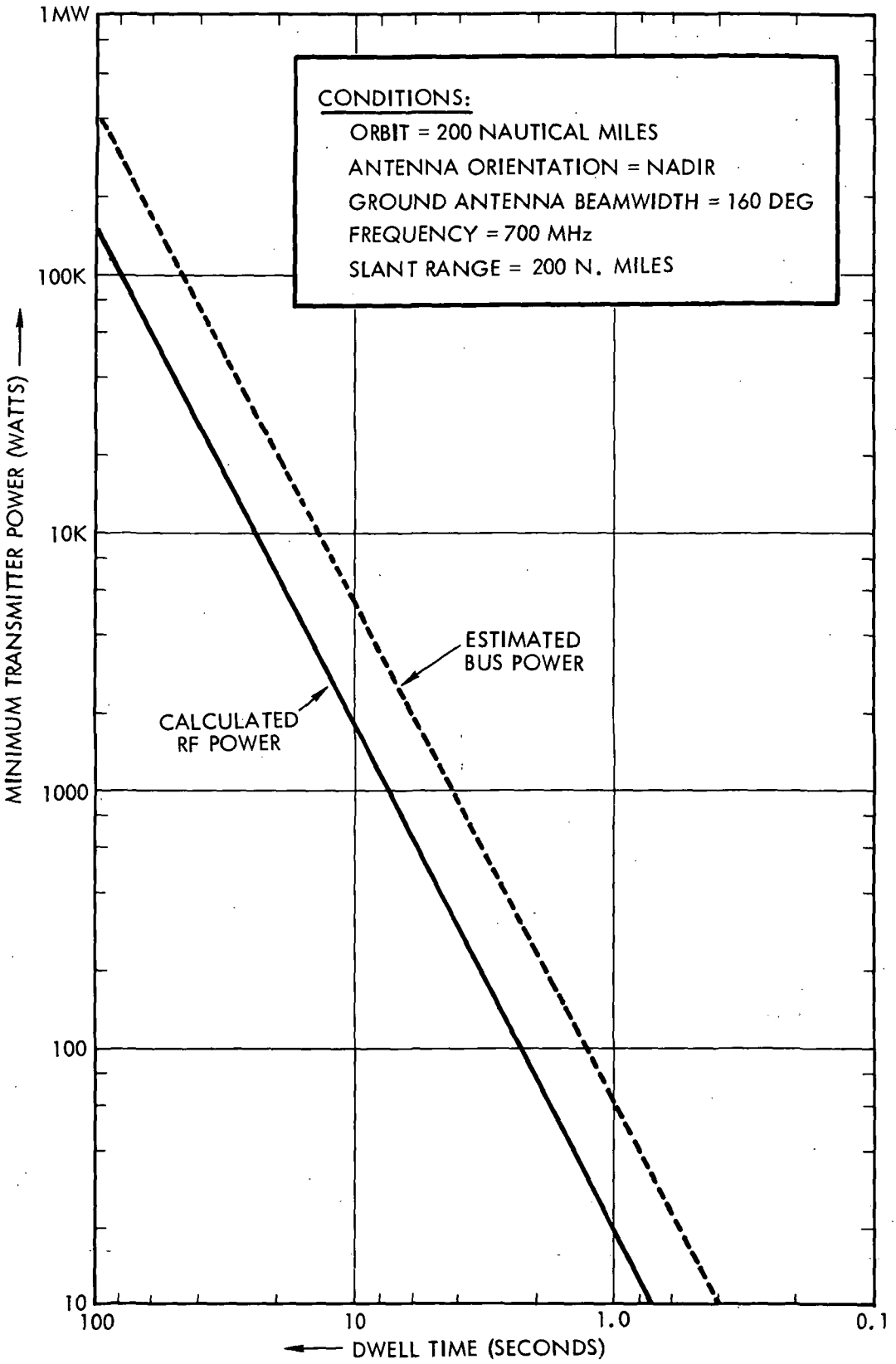



Figure 6-3. Dwell Time Versus Minimum Transmitter Power

If a video tape recorder is used the tape could be formed into an endless loop to allow for prolonged viewing. However, this is not recommended since the frequent tape passes over the head assembly rapidly wears the tape. It is preferable to digitize the signal of the "almost new" tape and then replay it via a digital-to-analog converter. This allows the digital picture information to be regenerated and reduces the degradation due to playback. A video recorder is relatively expensive and, therefore, will be of prime use in setting up the experiment at NASA ground stations. It is not an item found in the home inventory of the average amateur radio enthusiast who will (hopefully) participate in these experiments, although construction details have been published (Reference 17) and commercial machines are available for between $300 and $1000.

An important aspect of dwell time selection is the psychological disadvantage of short visibility when public participation is to be encouraged. The key question for the public participation phase is -- how long a "program" do we have to provide to capture the imagination? A highly subjective guess is 10 minutes, even were visibility not limited, it would be undesirable to have a long test that conflicted with the programs offered by commercial TV ground stations.

The preliminary dwell time requirements, developed in this subsection, are summarized in Table 6-3.

Re-examination of Figure 6-3 will disclose that a 1.0 second dwell time, for a receiving site locating on the subtrack, requires approximately 100 watts of transmitter power. It has been concluded that useful experiments can be performed from an orbit of 200 nautical miles altitude, in a period of the order of 1 second but that for later tests, involving public participation, appreciably longer periods of reception are suggested.

Table 6-3. Dwell Time Requirements for TV Direct Broadcast Experiment

| Experiment Phase | Cooperating Ground Sta. | Method of Appraisal | Suggested Equipment | Est. Recording Needs | Dwell Time (Seconds) |
|---|---|---|---|---|---|
| Initial | NASA | • Signal Strength<br>• Signal:Noise<br>• Subjective quality | Special Receiver<br>Still Camera<br>Video Recorder<br>Real Time Display | Overflight History<br>4 Shots Per Scene | -<br>0.5<br>0.5<br>20-60 |
| Main | Amateurs | • Subjective Quality | • 35 mm Camera<br>• Commercial TV Receiver | 5 Negs Per Flyover | 0.5 - 10 Mins. |

It is clear that a multiple pencil beam or steerable beam would allow us to realize the dual advantages of modest transmitter power and extended dwell time. Such antennas can be developed and installed for the later tests, with initial tests carried out using short visibility times.

Tailoring the receiving antenna to the transmitted laboratory TV footprint is an important optimization task and will usefully extend the available dwell time for a given transmitter power. This is discussed briefly in Section 6.3.6.

### 6.3.6 UHF Antennas for Satellite Reception

For the proposed tests, any of the available commercial UHF antennas can be used. Table 6-4 presents salient details of a representative range of designs. The expected costs for parabolic dish antennas were derived during a TRW study in 1968 (Reference 18). This data is illustrated in Figure 6-4.

The beam width needed at the ground station can be derived from the reception geometry. The laboratory down link beam dwells on a ground station while the footprint encloses the ground station. For a station located on the laboratory ground track, the dwell is one beam diameter. During this time the satellite moves through an arc segment of its overpass orbit. In order to avoid signal loss, the terrestrial receiving antenna must accommodate this satellite motion, i.e., have a minimum beamwidth equal to the angle subtended by the satellite motion.

For preliminary sizing of the experiment, it will be sufficient to assume equality of beam widths as the optimum condition. If the same beam widths are used for both transmitter and receiver, additional gain is realized from each antenna as the beam width is narrowed. Table 6-5 summarizes the expected parameter values for a system using this concept.

A 4 foot diameter parabolic (dish) reflector may be about the largest size that cost, convenience and windage considerations will allow. The beamwidth is about 25 degrees and the gain is 16.5 dB. Since wind motion and thermal distortion can exceed 3 degrees, this is probably a reasonable compromise, in terms of a system approach for minimizing the laboratory transmitter power. Inspection of the Table 6-5 indicates that for a realizable transmitter power of 500 watts a dwell time of 26.3 seconds is available.

Table 6-4. Representative UHF Television Antenna Performance

| Type of Antenna | Gain Over Isotropic (dB) | Gain Over Dipole (dB) | Front-to-Back Ratio (dB) | Comments |
|---|---|---|---|---|
| 1/2 wave dipole | 2.15 | Zero | Zero | Poor for location with reflections. |
| Dipole and screen | 6.25 | ~4 | <20 | Slight reflection aid. |
| Bow-tie and screen | 6.25 | ~4 | <20 | Similar to above but broader bandwidth. |
| Two bow-ties and screen | 9.0 | ~7 | <20 | Gain advantage of 3 dB. |
| Corner reflector | 11.0 | ~9 | =20 | More gain but narrow bandwidth. |
| Periodic | 10-11 | 8-9 | >25 | Good front-back ration for reflection flat gain and VSWR over entire band. |
| Stacked array Two periodics | 13-14 | 11-12 | >25 | Gain advantage of 3 dB. |
| Log periodic (1.5 elements) | 10-15 | 8-13 | >20 | Uniform gain and VSWR over band slightly poorer front-back ratio. |
| Yagi array | 7-17 | 5-15 | >20 | Higher gain possible but relatively narrowband. |
| Arrays of bow-ties | 10-17 | 8-15 | =20 | High gain but relatively narrow bandwidth. |
| Dipole parabolic dish | 16-21 | 14-19 | >20 | Very high gain, difficult to align. Narrow bandwidth. |
| Broadband Antenna and Parabolic Dish | 16-21 | 14-19 | >20 | As above, but broad frequency coverage. |

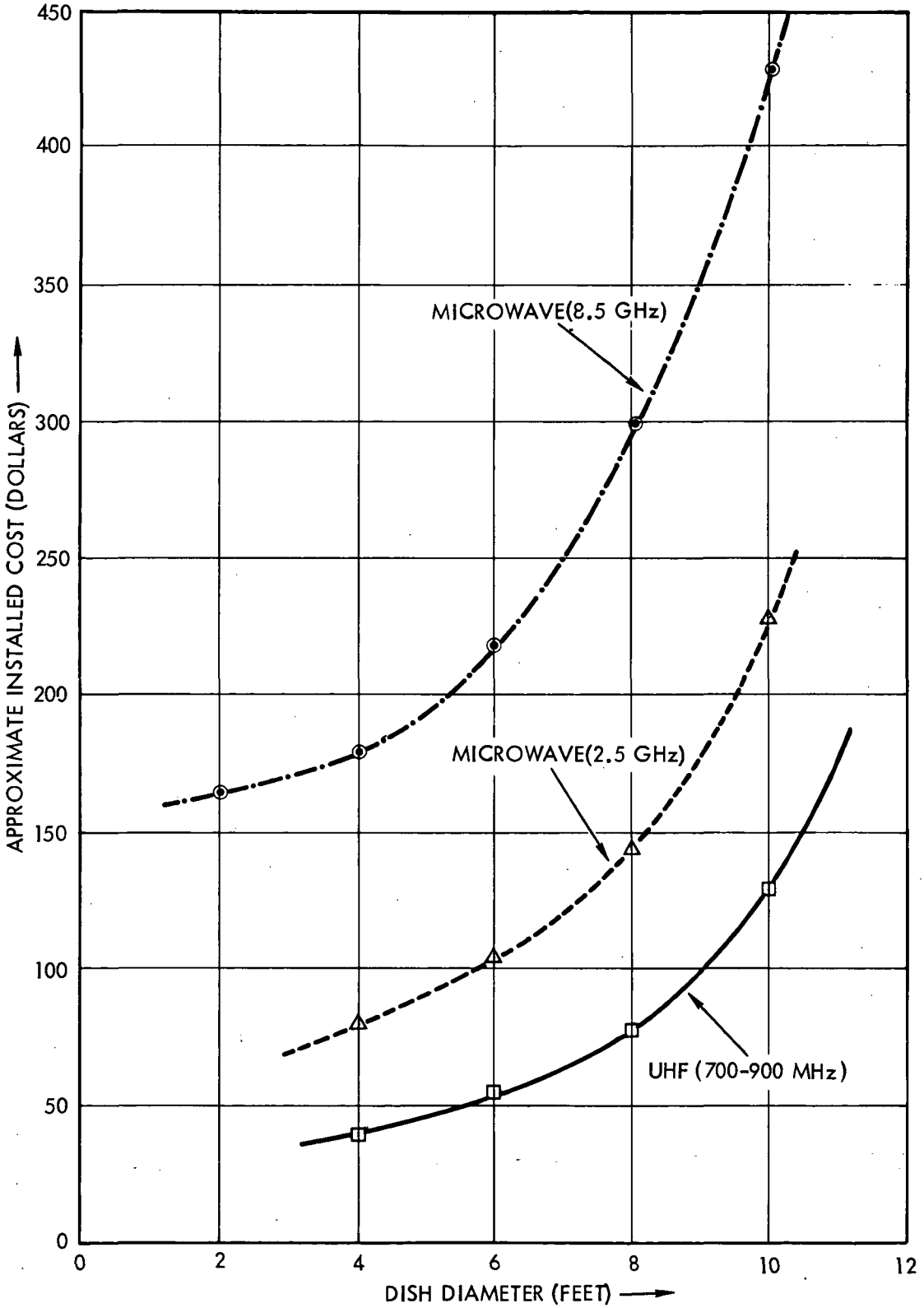



Figure 6-4. Expected Cost for Installed Parabolic Antennas

Table 6-5. Available Dwell Time Versus Minimum Transmitter Power

| Parameters | Units | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Antenna Beamwidth | Degrees | 51.0 | 38.5 | 29.0 | 22.0 | 16.2 | 12.3 | 9.2 | 7.0 |
| Antenna Gain (each) | dB | 10 | 12.5 | 15 | 17.5 | 20 | 22.5 | 25 | 27.5 |
| Min. Transmitter Power Required | dBw<br>Watts | 36.9<br>4900 | 11.9<br>1550 | 26.9<br>490 | 21.9<br>155 | 16.9<br>49 | 12.9<br>15.5 | 6.9<br>4.9 | 1.9<br>1.55 |
| Available Dwell Time | Seconds | 48.6 | 35.5 | 26.3 | 19.8 | 14.5 | 11.2 | 8.2 | 6.2 |

### 6.3.7 Ground Station Location Errors

If the receiving stations are not located on the laboratory subtrack of the particular orbit, the available dwell time will be reduced. The maximum dwell time corresponds to the diameter of the assumed circular) footprint pattern. If the receiving station is offset, the available dwell time corresponds to a chord of the footprint.

For convenience of application, the solution has been generalized with percent time expressed as a function of percentage offset. The results are given in Table 6-6.

Table 6-6. Dwell Time as a Function of Receiving Station Location

| Receiving Station Offset (Percent of Footprint Radius) | 10 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Available Dwell Time (Percent of Maximum) | 100 | 99 | 96 | 91 | 84 | 75 | 64 | 51 | 36 | 19 | Zero |

It can be seen that significant offsets result in only a modest reduction in the available dwell time, with 75 percent of the maximum dwell available for a half radius offset.

It was previously determined that for nearly matched beamwidth antennas we could expect to realize 26 seconds of dwell time along the subtrack. This corresponded to antenna beamwidths of approximately 29 degrees. For this beamwidth the footprint radius is 52 nautical miles. Thus, we see that it will only be necessary to locate a receiving station within $\pm 26$ nautical miles of the subtrack line in order to realize 75 percent of the maximum dwell time (19.5 seconds) as a worst case.

To better illustrate the actual values involved, the attached graph, Figure 6-5 shows how the expected dwell time (in seconds) is related to the actual offset (in miles).

A number of factors, bearing on location accuracy effects, have not yet been evaluated. They include:

- Transmitting antenna pointing accuracy
- Initial pointing (alignment) error of ground antenna
- Accuracy of predicting ground trace (ephemeris)
- Degradation in SNR due to weather conditions

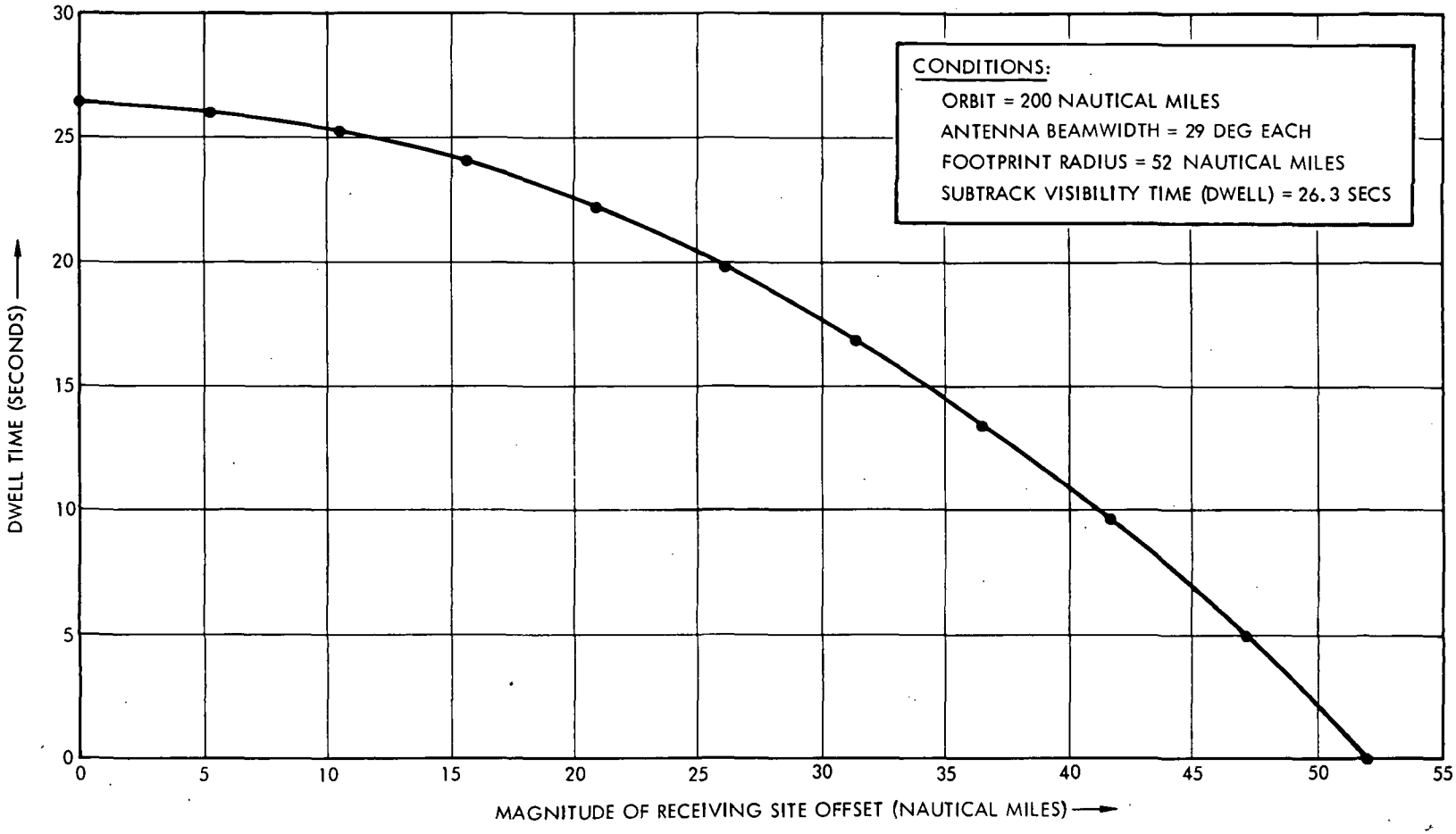



Figure 6-5. Variation of Expected Dwell Time Versus Displacement of Receiving Site From Laboratory Subtrack

## 6.4 EXPERIMENT DESCRIPTION

### 6.4.1 Orbiting Laboratory

For the initial test phase the experiment module will be equipped with a video tape recorder, a universal modulator and a wideband UHF transmitter. Supplementary test equipment will provide the means to check the power output modulation, carrier frequency and harmonic level. The video tape recorder will be used in the playback mode to provide a known source of picture data for transmission. A separate flying spot scanner will be used with EIA resolution chart replicas as a source of stationary test frame signals, as shown in Figure 6.6.

The primary sources of picture material for the first few tests will be the flying spot scanner and the video tape playback unit. The flying spot scanner, equipped with transparencies for EIA and similar test patterns, will be used for setting up the ground stations and initial adjustments. As soon as satisfactory reception has been secured, the test will be expanded to use the moving scenes available from the recorder.

At a later stage, the astronauts will use a TV camera located inside the experiment module so that they can act as announcers to add human interest for the viewers. Additional cameras, shown on the block diagram will be brought into service subsequently to extend the picture material to include the laboratory interior and views of the earth.

The several signal sources are combined in a conventional video fader/mixer under astronaut control. The signal channel video output is applied to a universal modulator which will accept the normal vestigial sideband AM, but also accommodates a variety of alternatives so that these can be explored as means for enhancing the system performance and to allow narrow bandwidth slow scan transmissions.

The proposed transmitter is of conventional design, comprising a RF exciter unit which establishes the transmission frequencies, and a series of frequency multiplier stages. The exciter drives the final power amplifier output stage, which in turn feeds the antenna.

The recommended antenna is a dual beamwidth assembly providing a choice of wide angle ($\theta \approx 140$ degrees), low gain ($G \approx 2$ dB), or narrow

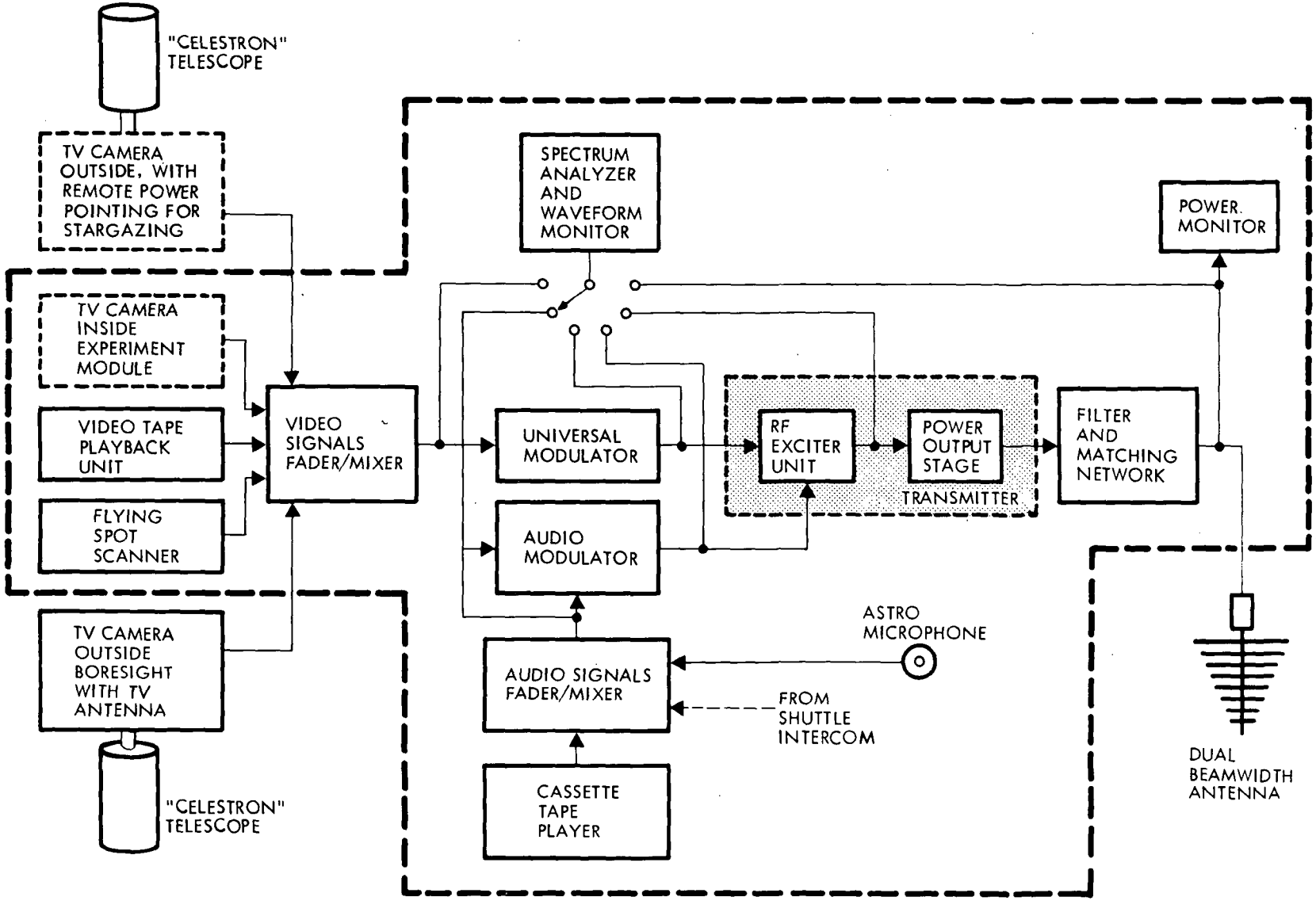



Figure 6-6. Equipment Configuration for Experiment Module

beam ($\theta \approx 25$ - 29 degrees) and a useful gain (see discussion in Section 6.3).

A separate modulator is employed to frequency modulate the sound carrier signal generated by the RF exciter unit. This modulator can be coupled to a local cassette recorder convenient to the operating astronaut, to the astronauts microphone or to the shuttle intercom network. The selection is made via a conventional audio mixer/fader unit controlled by the astronaut.

A power monitor and a combined spectrum analyzer-waveform monitor oscilloscope are provided to assist the operator in maintaining the TV system in proper operating condition and to allow him to make experiment related changes in the parameters. The power monitor is used to provide a continuous check on the transmitter output level; the spectrum analyzer is used to measure frequency deviation and modulation index, watch for overloading, etc.

### 6.4.2 Ground Monitoring Arrangements

The initial tests will be carried out between the orbiting laboratory and simple receiving equipment installed in small NASA test vans. Each van will be equipped with three antennas, a communication receiver, two TV receivers, an experiment control clock, and various items of supporting test equipment. A video recorder is considered an optional feature. The configuration of this equipment is shown in Figure 6-7.

The communications receiver provides a master timing signal to standardize the local experiment clock controller. Signals from WWV or an existing navigation service can be used. Alternatives requiring further study are: direct radio reception of timing from a NASA facility, or a land line connection via the Bell network.

The experiment clock and controller unit serves four functions:

- Provides crew with accurate time for experiment coordination
- Activates audible alarm prior to laboratory overflight
- Automatically starts 35 mm recording camera just before overflight
- Provides command signals to A-D converter and multiplexer.

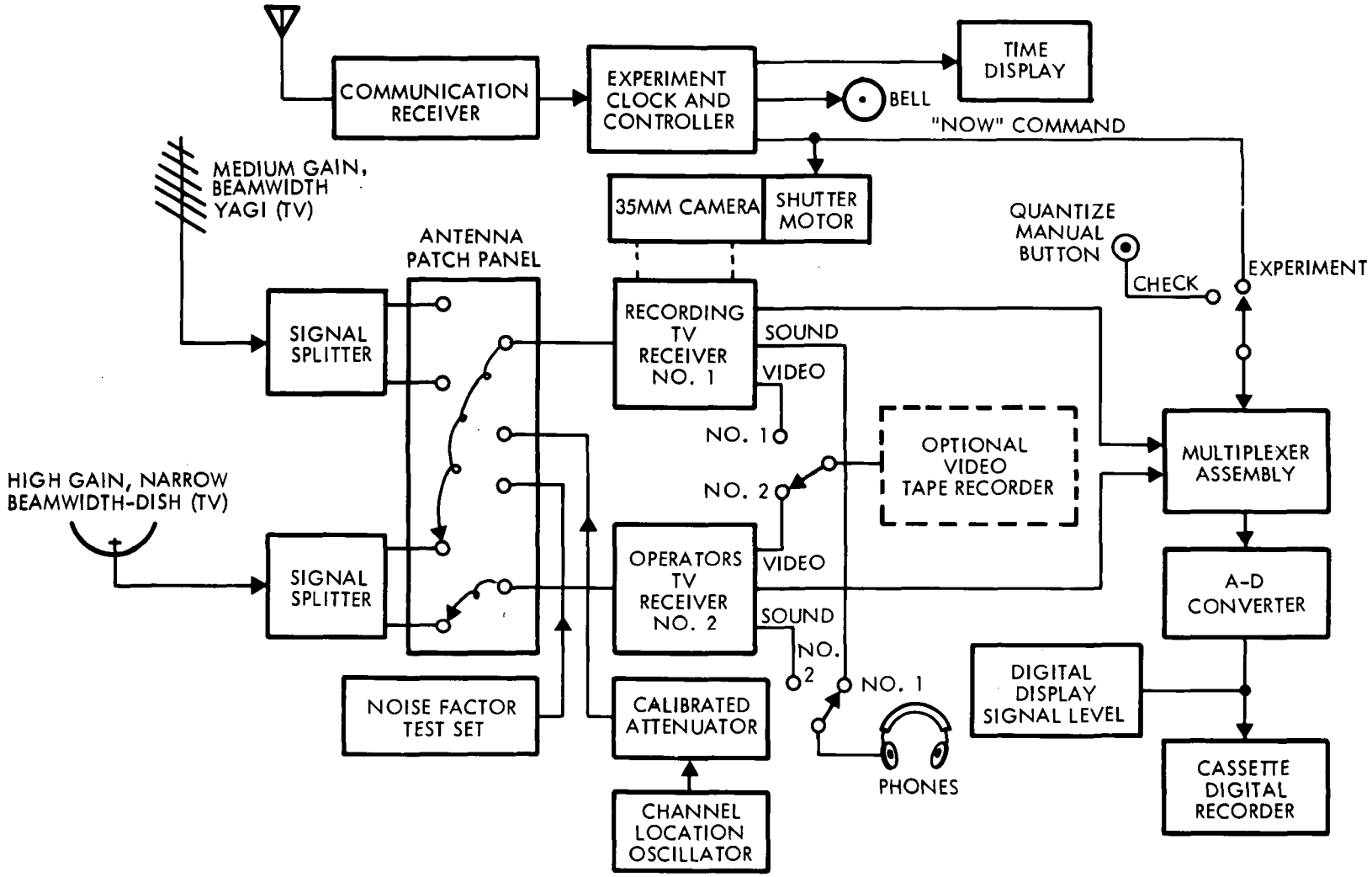



Figure 6-7. Equipment Configuration for Ground-Based Test Van

The related time display is a simple digital readout using light emitting diodes that converts the electrical time signals to visible characters. A second display using smaller characters is built into the 35mm camera hood. A mirror reflects these characters into the field of the camera lens so that the time value appears within each photo frame. This permanently correlates each film record with the time at which it was obtained.

The proposed 35 mm camera is a Robot, or similar, having integral power film advance. Activation of the camera shutter will be provided by a solenoid, energized by pulses from the experiment clock controller. Controls will be provided to permit adjustment of the frame rate to suit the other experiment details.

Two antennas are proposed for the TV equipment, one will be a medium gain, and modest beamwidth Yagi type, representative of those intended for fringe area TV reception. The second antenna is a relatively high gain dipole-in-a-dish assembly. This will evaluate parabolic units of 4 to 6 foot in diameter as discussed in Section 6.3.6. Both antennas will be mounted on sturdy tubular frame members attached to the roof of the truck. The mechanical design will allow these units to be folded flat and locked in place while travelling.

The antenna outputs will be fed into the truck via 300 ohm low loss, feeder lines, through waterproof seals. Inside the vehicle these lines will terminate in RF receptacles attached to passive signal splitters at an antenna patch panel. The input connections for two TV receivers and two test sets will terminate in identical receptacles on the same panel.

The panel provides the equipment operator with a versatile and simple means of interconnecting the RF equipment to suit the various tests. The two splitters are furnished so that both TV receivers can be operated from either one of the antennas.

Two test sets are proposed to allow the operators to check the performance of the TV receiving system "on-site". A noise test set will be used to measure the noise figure of the receiver, using the conventional ambient noise power doubling method.

A channel location oscillator is proposed so that the operator can tune the receiver to the correct laboratory frequency. The signal emanating from the orbiting laboratory is present for such a relatively short time that the usual tuning associated with domestic TV channel selection is impractical.

Two TV receivers are recommended, with one assigned to photographic recording and the other for operator real-time use. The photographic unit would be modified by adding a light exclusion hood and the 35 mm camera unit. Each receiver would have its signals routed to receptacles for external use. The signals involved are:

- Video output, with synch
- Sound output from FM demodulator
- AGC level as a measure of received signal level.

The two video signals will be applied to a coaxial switch and the single output will constitute the point for connection of an optional video tape recorder. The sound outputs will be controlled by a switch allowing either signal to be applied to either the operator headset or the ceiling mounted speaker.

The time history of the TV signal magnitude as experienced by the test receiving system is of interest. This data is obtained by applying the AGC line voltages of the two TV receivers to a multiplexer and analog-digital converter. These components divert the receiver AGC signals into the converter where they are quantized and fed to a digital cassette tape recorder. The recorder uses the small Phillips C-150 cassettes and is a more convenient storage scheme than paper tape. The resulting record is a series of digital words corresponding to the quantized receiver AGC levels. The system is calibrated by injecting known RF signal levels, via a variable attenuator, from the channel location oscillator.

### 6.4.3 Low Cost Equipment Development

Analysis of the results of these initial tests will establish the basic facts needed to define the preferred configuration and performance requirements for low cost ground receiving stations.

Parallel work on developing appropriate hardware, testing it, and documenting the results is recommended. These results and design

data will provide the means whereby the more technically competent amateur radio enthusiasts will be able to participate in the second phase. An excellent example of this approach exists in the published NASA work on a low cost receiving station design for the satellite weather transmissions (References 19 and 12).

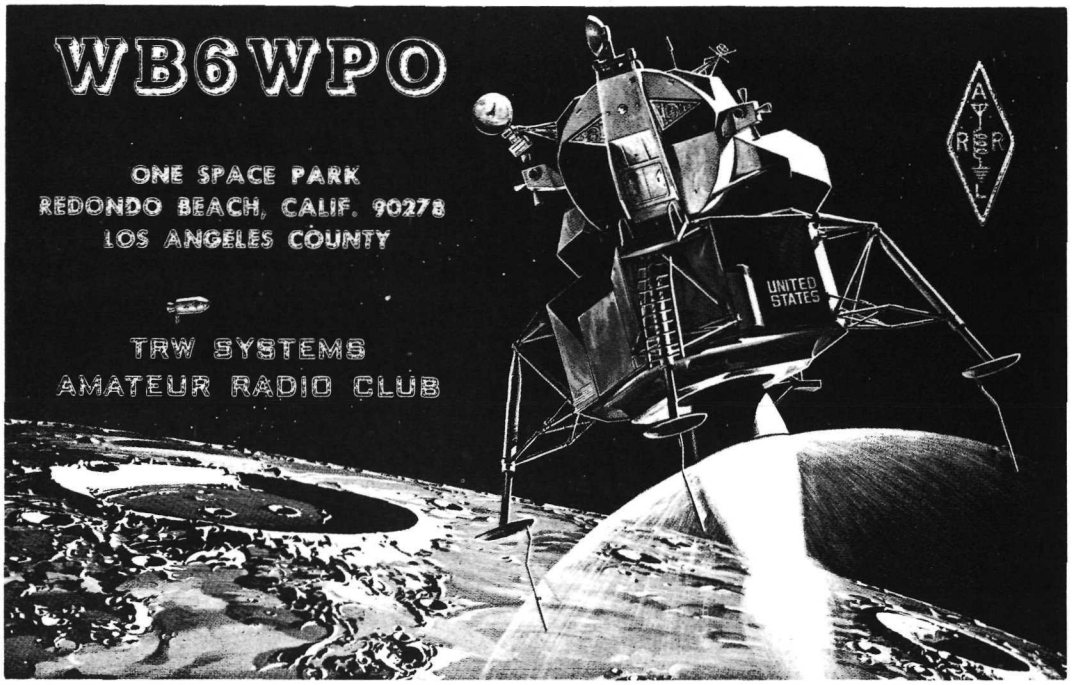
## 6.5 EXPERIMENT PROGRAM

The tests comprising this experiment have been divided into two categories. The first phase of the work involves transmission of still scenes and EIA resolution test patterns from the laboratory to two mobile NASA receiving test vans. These tests will be supplemented by limited transmission of animated scenes using the video tape recorder in the laboratory with prerecorded tapes.

Following, and overlapping, is a program of equipment development to establish the preferred configuration for a low cost receiving system suitable for the more technically minded members of the public. This work will be published and efforts devoted to bringing it to the attention of the amateur radio groups to encourage equipment fabrication and participation in the next phase of tests.

The second test phase will provide both a considerably increased volume of test data and cover a wide range of geographic locations, terrain variations, and weather conditions. To encourage participation, it is suggested that NASA introduce a space QSL card procedure whereby participants that submit signal quality reports and photos receive a confirmation card. In the early days of radio, commercial radio stations welcomed reports from listeners and sent QSL cards. With the enormous increase in both transmitting stations and listeners, this practice has almost lapsed. Amateurs, of course, still use this scheme.

In order to get the best interaction between the NASA program office and the cooperating amateurs, it will be necessary to devote a significant effort to this aspect of the experiment. As an example, it is clear that a standard reporting form should be designed, so that the amateur viewers can present their comments in a uniform format and to document aspects of their reception experiences that might not have seemed critical to them. An example of a representation QSL card appears in Figure 6-8.




The Lunar Module used in the Apollo Program to land American Astronauts on the moon, utilizes a controllable thrust Descent Engine, an Abort Guidance System and a Signal Data Demodulator, all developed and manufactured by TRW Systems Group, Redondo Beach, California. TRW Systems Group also provides major support to the Apollo Program in earth-lunar trajectory computations, world-wide communications through the Intelsat III Communications Satellite, Systems Engineering Support at the Houston Manned Space Center and Launch Support activities at the Cape Kennedy Space Flight Center.

RADIO _____ Confirming

QSO OF _____ 19 ____

AT _____ ST, GMT, ON _____ MHz

UR CW/AM/2XSSB SIGS RST _____

XMTR _____ PWR _____

RCVR _____ ANT _____

Pse QSL Tnx _____

**ARS** _____

Figure 6-8. Sample QSL Card

During the second phase a number of tests will also be performed using slow scan TV compatible with the signal format presently used by United States radio amateurs (Reference 21). The slow scan transmissions reduce the bandwidth requirements by as much as three orders of magnitude, providing up to 30 dB improvement in link signal-to-noise ratio margin. Various experiments will be performed absorbing different fractions of this margin in reduced antenna gain and in longer dwell times. If this 30 dB is wholly applied to broadening the beamwidth, the antenna gains at the laboratory and ground sites can be reduced by 15 dB each, thereby extending the dwell time to a large fraction of the theoretical maximum of about 10 minutes (at 200 n. mi. altitude). These tests will use the wide beam ($\theta \approx 140$ degrees) antenna.

For the third phase it is proposed to commission the boresighted external TV camera. This camera will be aligned such as to focus on the same nadir point as the TV antenna array. By connecting this TV camera to the transmitter, the astronaut will permit the ground TV receivers to display a map on their screens. The map will unfold across the TV viewers own location so that photos taken of the TV screen will provide both qualitative data on the picture SNR and correlation with the field of view of the laboratory antenna during the transmission of that frame. Figure 6-9 is a reproduction of an actual photograph taken from a commercial black and white TV receiver during normal programming. A regular 35 mm single lens reflex camera* was employed. Additional study will be needed to determine what compromise should be made in trading field coverage for resolution. Ideally the views should permit identification of local landmarks. A "Celestron" high quality, modest cost telescope is suggested (Reference 22). Table 6-7 summarizes the proposed experiment program.

Figure 6-10 is an artist's sketch illustrating the mode of operation proposed for collecting data on the feasibility of direct broadcast. The experiment plan calls for initial tests using two small test vans equipped with TV receiving systems. An appropriate vehicle for this purpose would be the surveyor's vehicle used by civil engineers. This is a 4-wheel drive, rough terrain design provided with dual rear wheels. It has excellent storage space for the ancillary items and a sturdy decked roof for antenna mounting and personnel access. The suggested arrangement for these tests is shown in Figure 6-11.

* Honeywell Pentax with F1.8, 55 mm lens.

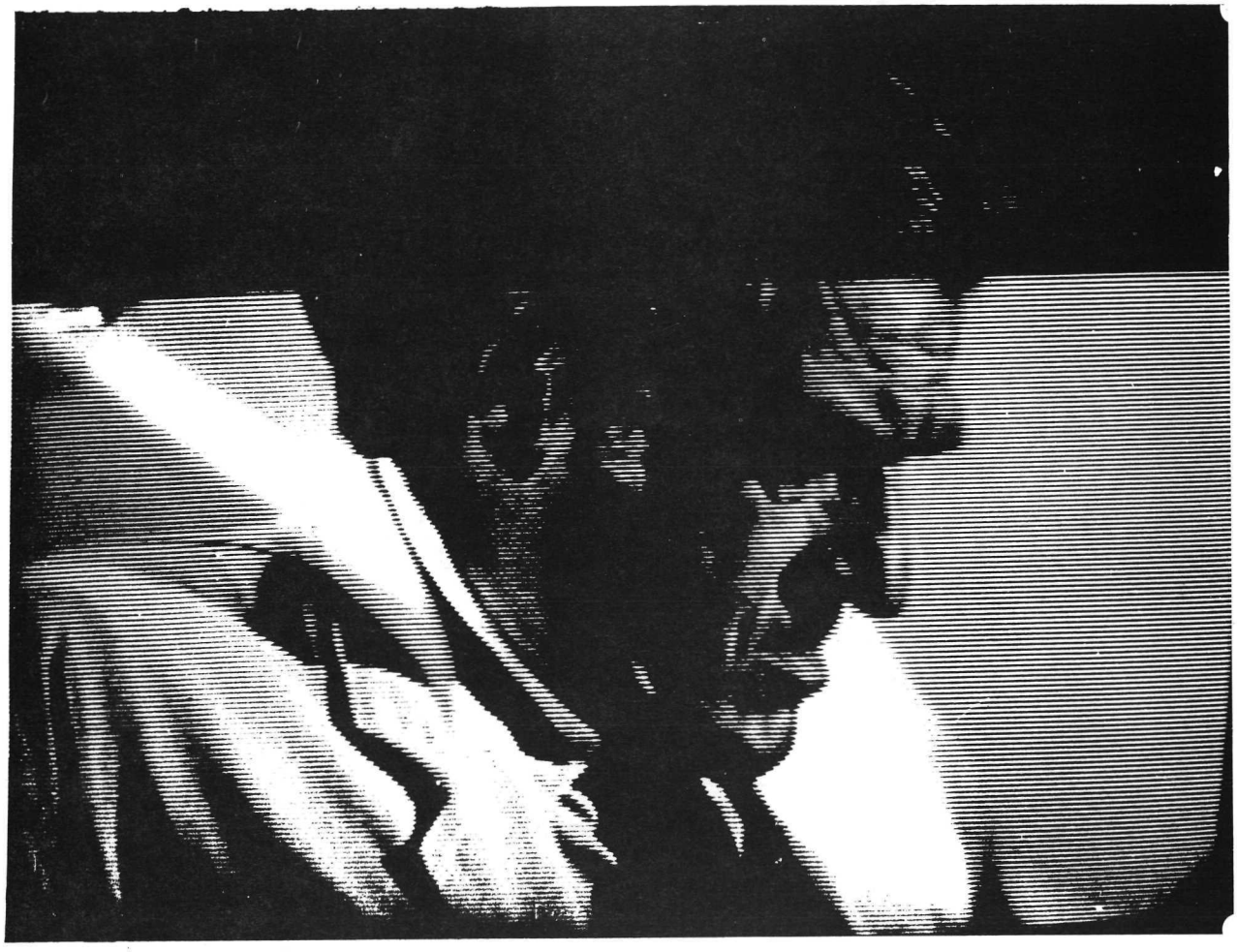


Figure 6-9. Photograph of TV Receiver Picture

Table 6-7. Model Observation and Measurement Program

| Activity Phase | Test No. | Cooperating Terminal | Transmitted Media | Comments/Rationale |
|---|---|---|---|---|
| Preliminary | 1 | NASA Operated Test Vans (2) | • EIA Test Pattern and Voice on Audio Carrier | Verify signal levels, antenna orientation, checkout experiment clock/timing. |
| Preliminary | 2 | NASA Operated Test Vans (2) | • Test Pattern, Stills<br>• Astro Announcer | Collect data used to define system for cooperating amateurs. |
| Intermediate | 3 | NASA Operated Test Vans (2) and Fixed Low Cost Receiving System (LCRS) | • Test Pattern, Stills<br>• Astro Announcer,<br>• Pre-Recorded Video Tape<br>• Location on Audio Carrier | Checkout receiving systems using design proposed for cooperating amateur viewers. Experimental transmission of position on voice channel. |
| Intermediate | 4 | NASA Operated Test Vans (2) and Fixed Low Cost Receiving System (LCRS) | • External Nadir Camera<br>• More Sophisticated Ephemeris and Voice | Evaluate geographic correlation and interest value -- Determine best compromise between FOV and resolution. Revised position transmission tests. |
| Amateur Participation | 5 | NASA Test Vans<br>NASA LCRS<br>Amateurs | • Astro Voice Astronaut<br>• Announcer Camera<br>• EIA and Similar Patterns | • Checkout of LCRS assembled by amateurs.<br>• Initial evaluation by amateurs. |
| Amateur Participation | 6 | NASA Test Vans<br>NASA LCRS<br>Amateurs | • Astro Voice<br>• Announcer Camera<br>• EIA and Similar Patterns<br>• Nadir Camera | Initial evaluation of geographic map by amateurs. |
| Amateur Participation | 7 | NASA Test Vans<br>NASA LCRS<br>Amateurs | • Slow Scan TV of EIA<br>• Astro-Voice | Evaluates possibilities of slow speed scanning TV for direct satellite ground link. |

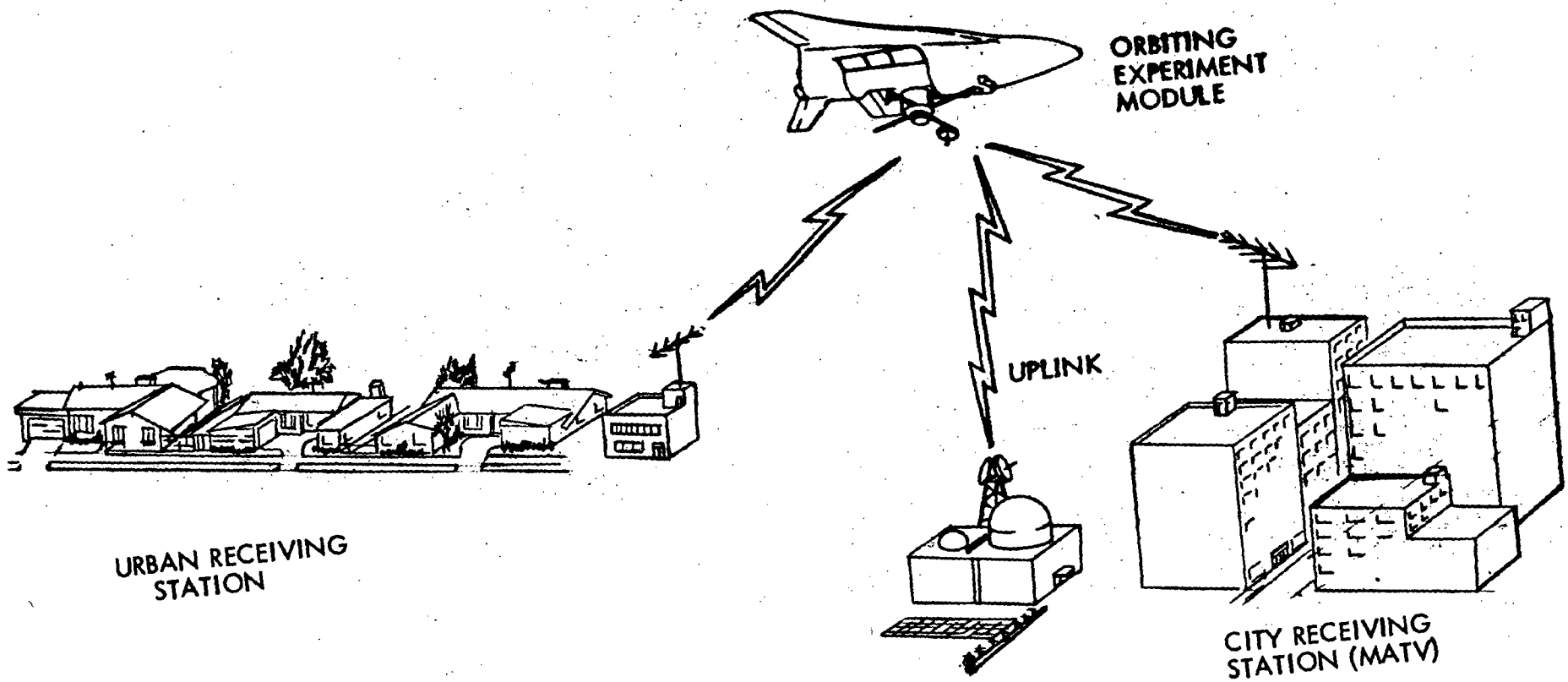



Figure 6-10. Artist's Concept – Mode of Operation Proposed for Collecting Data on the Feasibility of Direct Broadcast

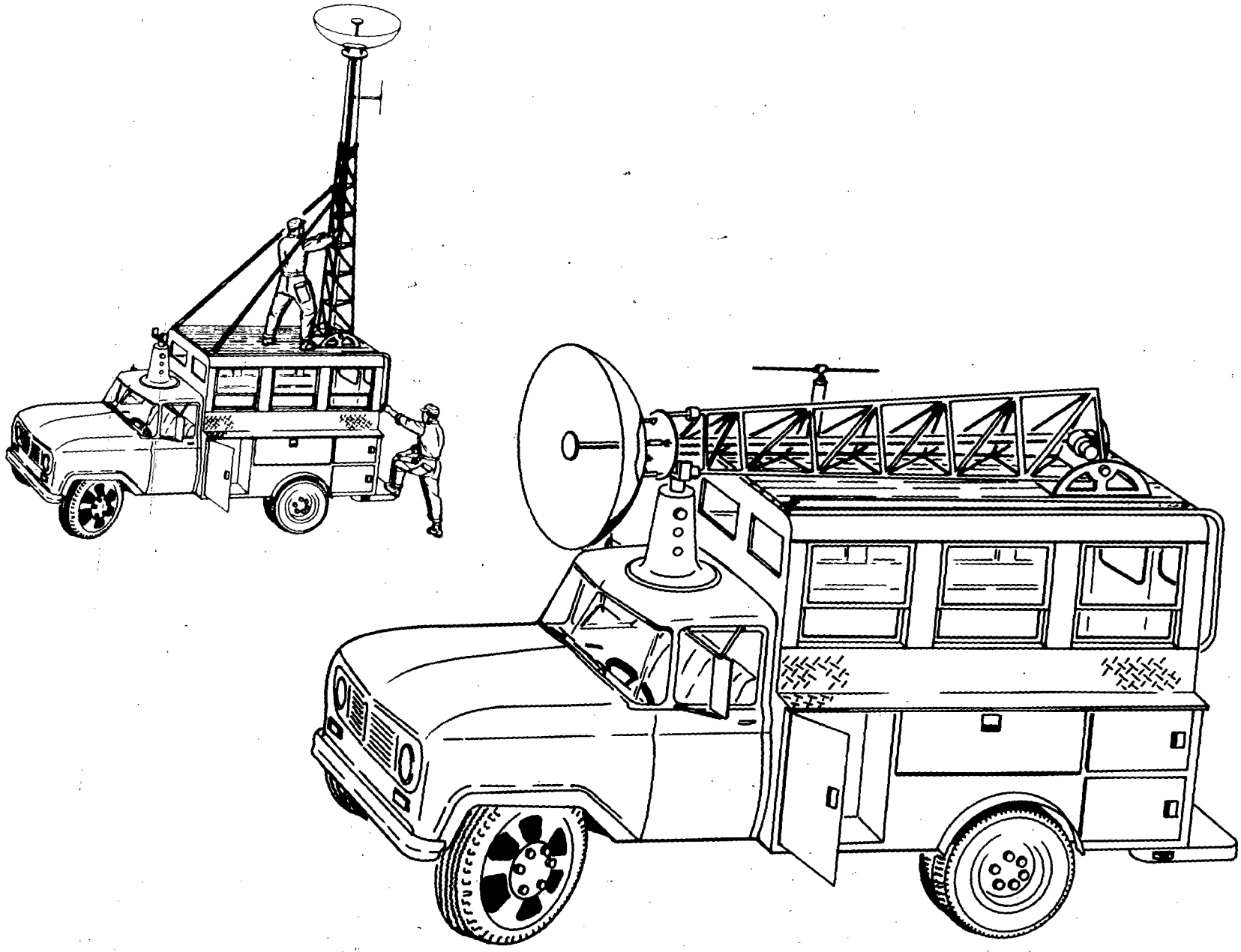


Figure 6-11. Recommended Test Van Concept

## 6.6 INTERFACE, SUPPORT, AND PERFORMANCE REQUIREMENTS

The equipment specified for the direct broadcast experiment has significant interface aspects. The basic services and desired operational constraints are listed in Table 6-8.

## 6.7 POTENTIAL ROLE OF MAN

The astronaut is an important element in performing the proposed experimental tests of direct TV reception. For tests involving the cooperation of amateur radio enthusiasts, the astronaut serves as the announcer and is "on camera" in real time. The physchological value of this approach in engendering enthusiasm and public interest should be considered a very important factor.

### 6.7.1 Calibration

The first astronaut task is equipment checkout and adjustment. This is scheduled for the orbit preceding the first useful CONUS coverage orbit to preclude wasting valuable CONUS viewing time. The calibration and adjustment will include verifying that the correct modulation and frequency have been selected and checking the transmitter power output. The transmitter will be operated for a sufficient period to allow thermal stabilization. The action of the main power control attenuator used to establish the ERP will be tested using the power monitor unit.

The waveform monitor/spectrum analyzer will be sequentially switched through the five video sources to check the output of each. The video tape recorder will be rewound ready for CONUS playback. The desired transparencies will be loaded into the flying spot scanner. For The pan, tilt, and telescope magnification controls of the two external cameras will be tested. Finally, the video fader will be tested to ensure a smooth changeover can be effected between the several video sources.

Next the audio subsystem will be checked, including the astronaut's microphone, local cassette tape player, the shuttle intercommunication interface, and the associated audio signal mixer and fader.

The oscilloscope will then be switched to the spectrum analyzer mode and used to check the sideband structure of the RF signal for the selected modulation. In general the flying spot scanner will be used as

Table 6-8. Direct Broadcast Experiment Interface Requirements

| Support Item | Classification | Description |
|---|---|---|
| Electrical Power | Essential | 28 V DC or 117 V, 400 Hz; Approx. 3 Kw max. |
| Temperature Control | Tradeoff | $71^{\circ}F \pm 3^{\circ}F$ use; $76^{\circ}F \pm 116^{\circ}F$ storage |
| Atmospheric Pressure | Tradeoff | 28 - 31 in. Hg use; 0 - 31 in. Hg storage |
| Vehicle Ephemeris | Necessary | 3-axis history and altitude |
| Orbit | Tradeoff | 200 n. mi/intermediate/synchronous |
| Time Standard | Tradeoff | Day, hour, minute and second |
| Voice Communication | Necessary | Two way to ground for contacting test vans and LCRS |
| External Camera | Suggested | Space on 3-axis platform for nadir pointing camera |
| Heat Transfer | Necessary | Need to remove heat from TV transmitter ($\approx$2 - 3 Kw) |

the video source and a special audio test tape run through the cassette recorder to check the audio and picture transmitter channels, respectively. The analyzer will be switched to check the output of the final filter to ensure that the transmission is clear of spurious components.

Transmission of ephemeris data over the audio channel is being considered. If implemented, the astronaut will check the elements of this feature also, specifically that signals are being obtained from the shuttle interface and that these are being correctly formatted for transmission.

### 6.7.2 Initial Tests

During the first few tests the astronaut will be transmitting signals to the NASA test vans. His role will include voice contact with the monitoring personnel, alerting them and working with them to transmit appropriate TV pictures during the flyovers.

### 6.7.3 Public Participation

In the subsequent stages of the experiment, the astronaut's activities significantly expand. He will be involved in setting up, running, and narrating a wide range of test material, including remote control of outside cameras.

## 6.8 EXPERIMENT EVOLUTION

The suggested sequence of tests for the direct broadcast experiment is shown in Table 6-9. The initial tests are performed between the laboratory and NASA-operated receiving equipment. These activities include developing an appropriate design for a low cost receiving system, and culminate in publishing the recommended design.

The second group of tests is based on involving a significant number of non-NASA participants, including US radio amateurs. Concurrent with this volume reporting activity, NASA will develop a pointing pencil beam antenna to extend the dwell time for selected recipient areas. An output from this period will be a definition of the equipment configuration for tests in the microwave region.

The third group of tests will evaluate the tracking pencil antenna performance and extend the investigation to cover altitudes above 200 n. mi. and non-circular laboratory orbits. During this phase there will be signi-

Table 6-9. Suggested Evolution for Direct Broadcast Experiment

| Activities | Phase I | Phase II | Phase III |
|---|---|---|---|
| • NASA Field Tests | | | |
| • Definition of LCRS | | | |
| • Testing of LCRS | | | |
| • Publish Data | | | |
| U.S. Amateur Participation | | | |
| U.S. School Participation | | | |
| Foreign Tests (Mil. Participation) | | | |
| Define UHF Pointing Antenna | | | |
| Define Microwave Tests | | | |
| Publish Results | | | |
| UHF Tracking Antenna Tests | | | |
| Microwave-NASA Truck Tests | | | |
| Define Microwave LCRS | | | |
| Publish Microwave LCRS | | | |
| Amateur Microwave Tests | | | |

ficant testing over foreign countries, hopefully on a non-cost basis, in cooperation with amateurs. Preliminary tests will be performed between the NASA test vans and the laboratory on microwave frequencies. Concurrent studies will be made of design techniques for reducing the cost of the microwave antenna converter needed to adapt the domestic TV receiver to this frequency of operation.

## 6.9 SRT REQUIREMENTS

The primary tradeoff involved in direct broadcast from low altitudes is visibility time versus SNR. If, however, a steerable array is used in the orbiting laboratory, the beam can be aimed at the intended recipient and contact maintained by locking onto the target or programming the beam motion to compensate for the orbital motion. This antenna can have high gain and thus allow the use of broadbeam receiving antennas on the ground. Such an arrangement allows one to realize a total visibility time very close to the maximum value determined by the geometry of line-of-sight.

In the technical discussion it was shown that the system would operate with a modest transmitter power (500 - 1000 watts) only if a total antenna gain of at least 30 dB were available at the transmission and reception ends of the link. To maximize visibility time and simultaneously minimize the cost of the ground receiving antenna systems, it is proposed to use wide beam fixed antennas on the ground and a high gain pointing antenna at the laboratory. Assuming a 160 degree beamwidth antenna for the viewers, its gain will be of the order of +1 dB; the remaining 29 dB must be furnished by the laboratory pencil beam unit. The characteristics of such an antenna for 700 MHz operation are:

- Gain = 29 dB
- 3 dB Beamwidth = 5.2 degrees
- Diameter = 19 feet.

The development of a deployable antenna of this minimum performance to suit the laboratory dimensions appears highly desirable.

In addition, the antenna will require a steering facility. During a period of approximately six minutes, it will be necessary to vary the pointing angle over a range of 140 degrees, i.e., an average angular correction rate of about 0.4 degrees/second.

## 6.10 ACKNOWLEDGEMENTS

### 6.10.1 Related Experiments

| Experiment | Prinipal Investigator and Association |
|---|---|
| Television Relay Using Small Terminals | T. Miller, Goodard Space Flight Center |
| Direct Broadcast Demonstration | D. Lipke, ComSat Corporation |
| Radio Direct Broadcast | R. Briskman, ComSat Corporation |
| High Power 12 GHz Transmitter | R. Walp, Hughes Aircraft |

### 6.10.2 References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# EXPERIMENT 7

# COMMUNICATIONS RELAY EXPERIMENT

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# 7. COMMUNICATIONS RELAY EXPERIMENT

## 7.1 EXPERIMENT CLASSIFICATION

The communications relay tests are divided into two broad classes of experiments: applied research and development, and operational testing. The iterative nature of the experiments and their dual role for improving communications relay technology and also providing communications services for other experiments precludes assigning particular subsets of the communications relay tests to a single specific category.

## 7.2 EXPERIMENT OBJECTIVES

The objectives of the experiments in order of the required and/or preferred sequence of attainment are as follows:

a) Statistical evaluation of data error rates over the VHF forward link using a number of radio frequency interference reduction techniques

b) Development and evaluation of acquisition and handover techniques and procedures to maintain maximum use of the Ku-band shuttle relay link

c) Comparison of S-band and Ku-band performance for medium rate data under operational condition

d) Comparison of modulation techniques for continuous transmission of high quality wideband signals under operational conditions

e) Demonstrate real time high quality color TV coverage of on-board and extra-vehicular activities and experiments.

The first objective is to determine the maximum data rate for a highly reliable order wire to any user spacecraft by a comparison of the performance of combinations of practicable techniques for suppression of RFI with the simplest practicable installation. This could determine allowable boundaries of operation of spacecraft of varying degrees of sophistication, culminating hopefully in the ultimate goal of high quality two-way voice communications between the Tracking and Data Relay Satellite (TDRS) ground station and the shuttle, irrespective of its altitude or the level of radio frequency interference (RFI). Interference with the shuttle to TDRS link can be more easily evaluated at the ground station and is less difficult to combat because the range differential

between the RFI and the required transmitter is negligible and considerable effective radiated power (ERP) could be used in the shuttle transmitter if necessary.

Items b) and e) represent necessary steps in the achievement of a very high data rate, high quality communications capability under operational conditions. Once achieved, continuous two-way real time transmission of data up to that required by color television, meeting International Radio Consultative Committee (CCIR) standards will permit full participation by ground based investigators in the on-board experiments by a quick look at preliminary results, modification of procedures and with the use of visual aids to facilitate a nutual understanding of problems by astronauts and ground based experts.

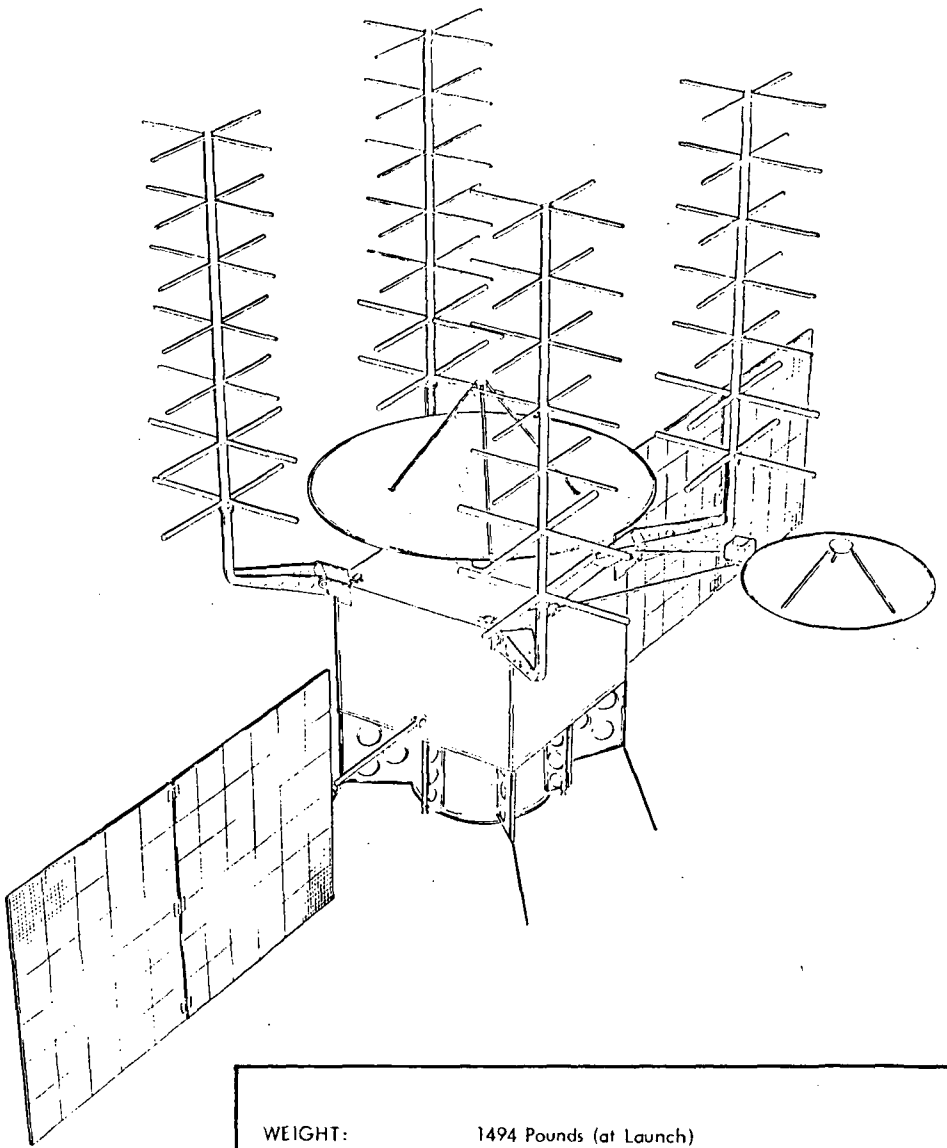
This will speed up the experimental work, help to prevent errors and enable the maximum use to be made of the limited time available on early flights. As longer flight times become available, selected examples of the spacecraft activities, the use of weightlessness and high vacuum in experiments and manufacturing processes can be demonstrated and broadcast over the TV networks. Other growth items include propagation measurements to the TDRS across the top of the ionosphere, at VHF, S-band and Ku-band.

## 7.3 DISCIPLINE BACKGROUND AND STATUS

### 7.3.1 General

The first TDRS is assumed to be operational in 1978 (with a normal development cycle of about four to five years after the award of a program definition phase).

Figure 7-1 shows an artist's conception and the main characteristics of a candidate 3-axis TDRS configuration; Figure 7-2 illustrates the deployment of two of these spacecraft with the attainable earth coverage illustrated in Figure 7-3. Table 7-1 contains a summary of the specification of the major relevant features of the TDRS communications links as determined by Reference 1.



| | |
|---|---|
| WEIGHT: | 1494 Pounds (at Launch)<br>784 Pounds (Spacecraft at Apogee Motor Burnout) |
| SIZE: | 14.6 Ft Height (Fully Deployed from top of VHF Antennas to Bottom of Apogee Motor<br>27.7 Ft Width (Across Solar Paddles)<br>4.7 Ft Height (Main Body)<br>4.2 Ft Width (Main Body Square) |
| STABILIZATION: | Spin Stabilized During Transfer Orbit<br>Three Axis Stabilized in Synchronous Orbit |
| LIFETIME: | 5 Years |

Figure 7-1. Typical TDRS Spacecraft Configuration

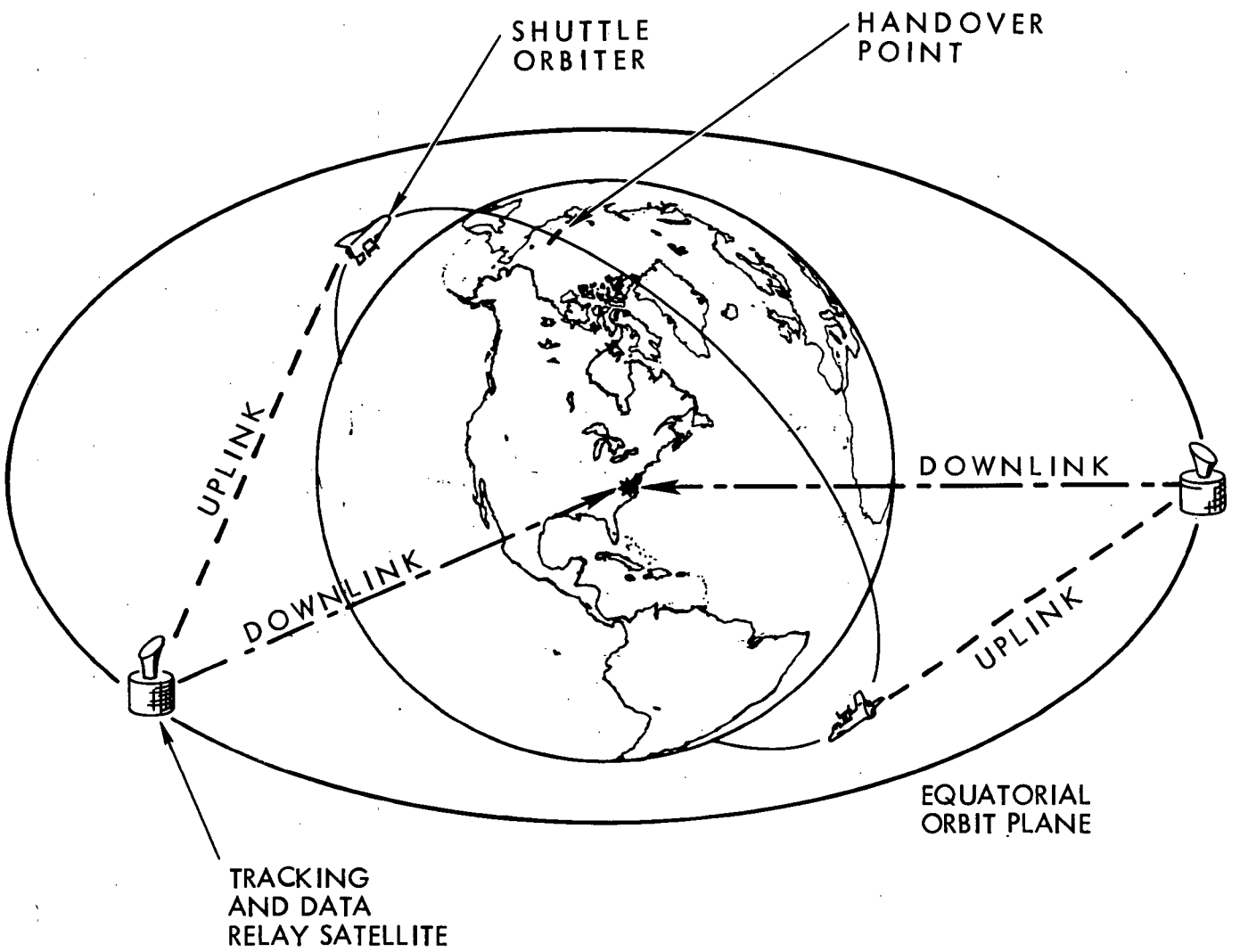



Figure 7-2. Communication Relay Experiment Geometrical Configuration

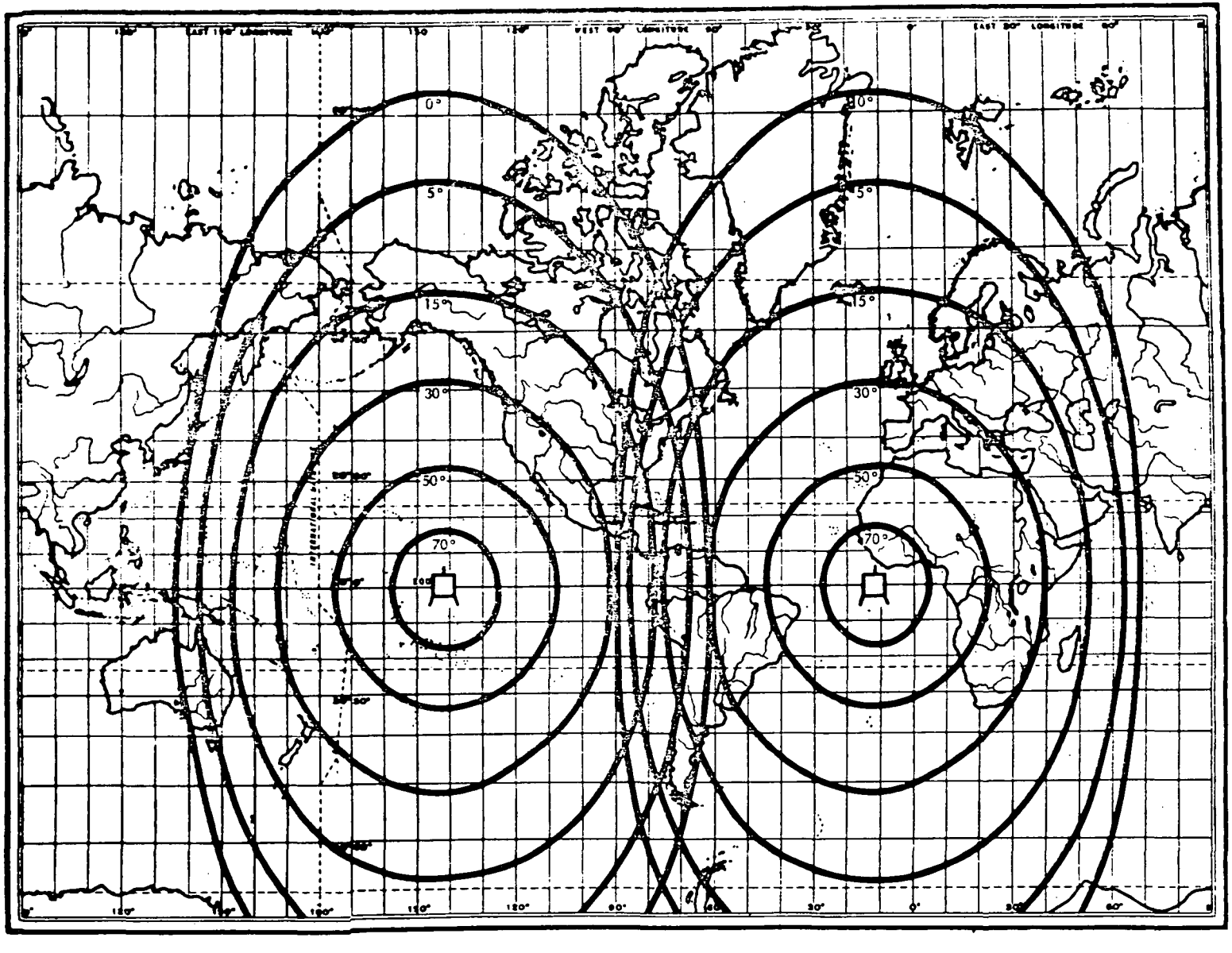



Figure 7-3. Visibility of the TDRSS

Table 7-1. TDRS User Requirements

| User Type | Forward Link | | Return Link | |
|---|---|---|---|---|
| | Data Rate | Carrier Frequency | Data Rate | Carrier Frequency |
| Low Data Rate User (VHF) | 100 - 1000 bps (Command) (Voice if possible) | 126 - 130 MHz or 148 - 149.9 MHz (2 MHz BW) * | 100 - 10,000 bps | 136 - 144 MHz (2 MHz BW) * |
| Medium Data Rate User (S-Band) | 100 - 1000 bps (Command) Voice | 2025 to 2120 MHz | 10 Kbs - 1 Mbs | 2200 - 2300 MHz |
| High Data Rate User (Ku-Band) | 100 - 1000 bps (Command) and Data up to Video | 134 to 14.2 GHz (200 MHz) * | >1.0 Mbs and/or Video | 14.4 - 15.35 GHz (200 MHz) * |

* Ref. 2 "Planning Model for Ground Network and Synchronous Satellite Communication System" NASA Hq. Memo D. R. Lord, 21 May 1971.

7.3.2 VHF Link

It is expected that a VHF initial operational capability will be established rapidly since adequate link margins are available in the absence of interference from terrestrial emitters (Table 7-2), but some RFI problems are expected by the command receiver of some of the small user spacecraft, particularly when passing over certain regions of the Continental United States (CONUS) and Europe.

An appreciation of the possible magnitude of this problem is illustrated in Tables 7-3 and 7-4 which give an estimate of the number and power levels of potential emitters in sight of the relay satellites which may cause interference to the communications link from the orbiter to the TDRS. An estimate of the Shuttle/TDRS uplink (at 136 - 138 MHz) shows that if all of the emitters were active simultaneously, a 2.4 Kbs data rate could be supported with an ERP of 27 dBw using spread spectrum techniques. This would permit the use of a vocoder voice circuit, and a higher quality voice circuit appears feasible (Table 7-5). A poor to moderate voice circuit should, therefore, be always available and a high quality voice circuit may be possible at least part of the time. Alternatively, the ground station could monitor the spectrum and command (by order wire) the shuttle to use narrow band (unspread) modulation at chosen frequencies in the "quiet" parts of the spectrum. This may be difficult in a very dynamic RFI situation, particularly for the TDRS-to-shuttle link, which therefore presents a problem of a different type and magnitude. The shuttle will be in view of a much smaller number of emitters at a given time and will remain in view of a particular emitter for a much smaller percentage of the time. It may also be able to use the body of the space vehicle as a shield. These advantages, however, are offset by the limitations of the TDRS ERP and its considerable range disadvantage with respect to a ground emitter which may amount to between 23 and 37 dB. Consequently, full two-way voice communications between the shuttle and the TDRS may not be possible at all times unless a small part of the band can be reserved for narrow band operation. A number of techniques (spread spectrum, RFI cancellation, antenna pattern control) and combinations of these techniques will be investigated analytically and experimentally in ground based laboratories but must also be tested

Table 7-2. TDRS VHF Link Budget (No RFI)

| | TDRS to CNRL | CNRL to TDRS |
|---|---|---|
| Frequency | 127 MHz | 137 MHz |
| Transmitter Power (per carrier) | 14 dBw | 20 dBw |
| Transmitter Antenna Gain | 13 dB | -2 dB |
| ERP (per carrier) | 27 dBw | +18 dBw |
| Space Loss | ~ -167 dB | ~ -167 dB |
| Receiver Antenna Gain | -2 dB | +13 dB |
| Misc. Losses (Polarization, Pointing) | -3 dB | -3 dB |
| Received Signal Level | -145 dBw | -139 dBw |
| Noise Density (1200 deg K) | -198 dB/Hz | -198 dB/Hz |
| Carrier to Noise Density Ratio (C/Nu) | +53 dBw | +59 dBw* |
| Margin 1000 bps CPSK $10^{-6}$ error (3 dB losses) | +20 dB | - |
| Margin 10,000 bps CPSK $10^{-6}$ error (3 dB losses) | - | +16 dB |
| Margins, Voice for 0.3 Articulation Index — Narrow Band FM | +13 dB | +19 dB |
| Margins, Voice for 0.3 Articulation Index — Pulse Duration Mod/PSK | +13 dB | +19 dB |
| Margins, Voice for 0.3 Articulation Index — Delta Mod/PSK | +8 dB(12 dB**) | +14 dB(18 dB**) |

* Assuming high dynamic range TDRS to Ground Link.

** QPSK with error correction coding.

Table 7-3. TDRS Potential Interference Sources (136 - 144 MHz)

| Radiated Power (Watts) | TDRS #1 (Pacific) No. of Users | | | | TDRS #2 (Atlantic) No. of Users | | | |
|---|---|---|---|---|---|---|---|---|
| | 136-138 MHz | 138-140 MHz | 140-142 MHz | 142-144 MHz | 136-138 MHz | 138-140 MHz | 140-142 MHz | 142-144 MHz |
| 0-10 | - | 10 | 10 | - | - | 10 | 10 | - |
| 10-20 | 10 | 50 | 50 | 10 | 10 | 50 | 50 | 10 |
| 20-30 | - | 10 | 10 | 10 | 10 | 10 | 10 | 20 |
| 30-40 | 40 | 70 | 10 | 10 | 40 | 70 | 10 | 10 |
| 40-50 | 10 | - | 10 | 10 | 10 | - | 10 | 10 |
| 50-60 | 40 | 60 | 50 | 100 | 40 | 410 | 270 | 320 |
| 60-70 | 10 | 10 | 10 | 20 | - | - | - | - |
| 100 | 5 | 20 | 25 | 5 | 25 | 65 | 65 | 45 |
| 200 | 5 | 10 | 6 | 5 | - | 1 | 1 | - |
| 250 | - | 1 | - | - | - | - | - | - |
| 1 kw | - | - | 1 | 1 | - | - | - | - |
| TOTAL | 120 | 241 | 182 | 171 | 135 | 616 | 426 | 415 |

Table 7-4. TDRS Potential Interference Sources (126 - 130 MHz)

| Radiated Power (Watts) | TDRS #1 (Pacific) No. of Users | | TDRS #2 (Atlantic) No. of Users | |
|---|---|---|---|---|
| | 126-128 MHz | 128-130 MHz | 126-128 MHz | 128-130 MHz |
| 10-20 | 10 | 10 | 20 | 20 |
| 30-40 | 10 | 10 | - | 10 |
| 50-60 | 700 | 450 | 780 | 500 |
| 100 | 10 | 30 | 10 | 10 |
| 200 | 10 | 40 | 15 | 20 |
| 250 | - | 15 | 2 | 1 |
| 300 | 5 | 10 | 5 | 2 |
| 350 | 5 | 60 | 5 | 60 |
| 500 | 1 | 6 | - | - |
| 1000 | 3 | 3 | - | 1 |
| TOTAL | 751 | 634 | 837 | 624 |

Table 7-5. VHF Link Budget (RFI Dominated)

| | TDRS-to-CNRL | CNRL-to-TDRS |
|---|---|---|
| Frequency | 127 MHz | 137 MHz |
| Transmitter Power (per carrier) | 14 dBw | 20 dBw |
| Transmitter Antenna Gain | 13 dB | -2 dB |
| ERP (per carrier) | 27 dBw | +18 dB |
| Max. Assumed RFI ERP (total) | -37 dBw | -37 dBw |
| Range Advantage (230/23,000) | -40 dB | N/A |
| Signal/Interference Ratio | -50 dB | -19 dB |
| Max. Process Gain (2 MHz/1 Hz) | +63 dB | +63 dB |
| Theoretical $C/I_o$ | +13 dB | +44 dB |
| Required Voice $C/I_o$ | ~+40 dB | +40 dB |
| Voice Margin (PDM/PSK) | -27 dB | +4 dB |
| Data Margin (2400 bps CPSK) | -24 dB | +7 dB |
| Data Margin (10,000 bps CPSK) | - | +1 dB |
| Receiver Antenna Front to Back Ratio | +15 dB | - |
| RFI Cancellation at Receiver | >20 dB | >20 dB |

under operational conditions to ensure acceptable performance due to the subjective nature of the voice link evaluation.

Medium Data Rate Link

Although not described in Reference 2, it is assumed that the TDRS will have an S-band medium data rate link as well as the Ku-band link as suggested in GSFC RFP 20388/24S (Reference 1). It is also assumed that the S-band antennas will be computer-pointed, but the Ku-band antennas will use monopulse tracking. This is due to the fact that the S-band beamwidths are wide (5 - 10 degrees), making computer-directed pointing very easily attainable, but an S-band monopulse horn assembly would create objectional blocking problems in the antenna reflector sizes postulated either with a cassegrain or focal point feed (an offset feed is feasible but creates a number of mechanical problems). Conversely, a Ku-band monopulse feed creates no major aperture blocking problems and can in fact be mounted in the center of an S-band feed horn or quadrapole assembly) but the TDRS beamwidth is too narrow (0.8 degree requiring 0 - 0.2 degrees $3\sigma$ tracking error) to use computer pointing unless the attitude control of the spacecraft is very accurately maintained. This may consume too much attitude control propellant and thus a logical combination uses a combined single S-band horn and a monopulse Ku-band feed with computer pointing at S-band and Ku-band auto-tracking.

It is, therefore, reasonable to assume that S-band data at rates up to at least 1 Mbs will have been demonstrated by the TDRS return link prior to the first flight of the Communication/Navigation Research Laboratory (CNRL). The S-band 1 Mbs data link can, therefore, be used as a reference for comparison. Later versions of the TDRS may have several combined S-band/Ku parabolic reflectors and it may well present an undesirable constraint to require an S-band acquisition aid. Thus, the ultimate goal is to perform the acquisition process without external aid except for a priori knowledge of the approximate relative positions of TDRS and shuttle. Moreover, autotracking by the TDRS and the shuttle appears necessary to maintain each of the beams sufficiently near the boresight position to prevent unacceptable loss of signal strength.

Having established the optimum search acquisition modes experimentally, handover problems can be investigated to maximize the fraction of each orbit for which a high quality high data link is maintained. A comparison of S-band and Ku-band transmission can be made at various data rates in each direction using error rate counters to determine the quality of each circuit over a period of time. A particularly interesting comparison will be at low grazing angles to the TDRS causing a long path through the ionosphere which may reveal dispersive effects at bandwidths of the order of 50 MHz. This measurement can be made most conveniently using a carrier and two coherent narrow bandwidth side bands to avoid a requirement for high ERP in the spacecraft, but a more complete investigation of the characteristics of the top of the ionosphere warrants a more comprehensive program using VHF, SHF and Ku-band simultaneously in a later flight.

The ultimate object of this experiment is to demonstrate the maximum capability of the system which may, for instance, use a 200 Mbs data link, or two wideband analog TV pictures. In this phase, on-board or extra-vehicular activities may be broadcast or the link may be used to broadcast real time TV views of the earth with or without image motion compensation.

## 7.4 EXPERIMENT DESCRIPTION

### 7.4.1 General

Figure 7-2 illustrates the geometrical configuration of the two Tracking and Data Relay Satellites, the TDRS ground station complex and the CNRL which is applicable to either the VHF or the Ku-band experiments. The feature common to both experiments is that CNRL communication contact with the ground stations is maintained for at least 90 percent of every orbit with a maximum of two handovers per orbit.

### 7.4.2 VHF Experiments

The VHF experiments are configured as shown in the functional block diagram of Figure 7-4. The antenna group consists of a Yagi or log periodic antenna (with a beamwidth of approximately 50 degrees, thus requiring only coarse pointing information) and two hemispherical coverage receiver antennas which can be summed after preamplification to produce a roughly omni directional pattern except for a region near the intersection of the two patterns. The latter are also used individually to provide hemispherical coverage in the general direction of the TDRS and a reasonable front-to-back ratio to reduce ground originated RFI. A changeover switch is incorporated in the switching and diplexing unit to provide this capability irrespective of the attitude of the shuttle. Reference 3 illustrates the hemispherical coverage capability obtained from an experimental airborne crossed slot antenna at about 250 MHz showing an excellent front-to-back ratio on boresight (20 dB). This ratio deteriorates if the RFI source is not directly under the space vehicle but the rejection does not worsen very rapidly until about 60 degrees where the RFI is at greater range. A hemispherical "top" coverage capability with uniformly 0 dB (or greater) gain is obtained. Better RFI rejection can be attained by lining part of the inside of the bay doors with RF absorbing material to reduce diffraction effects and this may possibly help even when the host vehicle is in an "upside down" attitude (i. e., bay looking toward earth).

It is possible that this type of antenna may be incorporated into the underside of the shuttle or attached in a form which would survive launch and orbit insertion stresses but would be allowed to be destroyed on reentry, providing it did not jeopardize the structural integrity of the

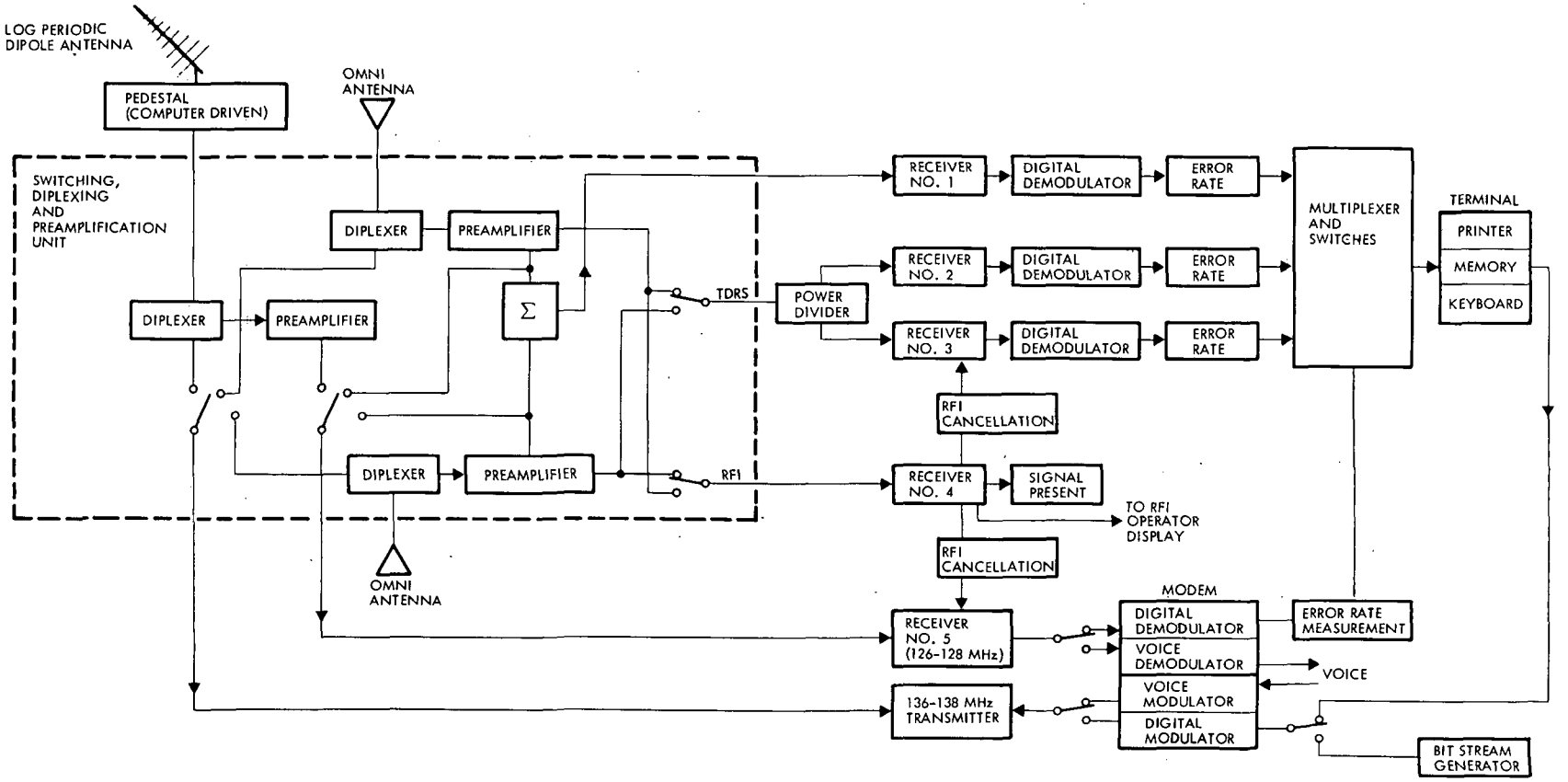



Figure 7-4. VHF Communications Relay Experiment – Functional Block Diagram

spacecraft. Alternatively it may be attached by an astronaut after insertion into orbit during extra-vehicular activity (EVA) and also removed prior to re-entry. However, if none of these alternatives are acceptable, a simpler mechanical design (such as a retractable blade antenna) may have to be used for the "bottom" antenna. In this case the body of space vehicle is not as effective a screen (Reference 3 compares the antenna patterns of the crossed slot and a vertical blade mounted on a KC135) and, moreover, the coverage immediately above the blade is very poor, thus degrading TDRS reception when the shuttle is in the inverted attitude.) Further investigation of the antenna configuration is required. In order to simplify the description of the VHF experiment, it will be assumed that two hemispherical coverage antennas can be used which can provide separate receiver coverage from the direction of the earth or from the TDRS and can also be combined after preamplification to simulate an omni directional antenna. The use of suitable (automatic or manual) changeover switches enables this to be accomplished regardless of the attitude of the spacecraft. The three outputs--"Omni", "TDRS", and "RFI"--are fed to four receivers (Figure 7-4). Receiver No. 1 receives the TDRS and RFI without discrimination, demodulates the combined signal, and measures and records the data error rate. Receiver No. 2 receives the TDRS signal and earth-originating RFI attenuated by the back-to-front ratio of the top hemispherical antenna and demodulates and records the data error rate. Receiver No. 3 is similar but in addition has an RFI cancellation circuit. The cancellation signal is derived from the "bottom" hemispherical coverage antenna through Receiver No. 4 which has an RFI signal present indicator and also supplies the unmodified RFI signal to the Terrestrial Sources of RF Noise and Interference experiment where the spectrum may be examined in detail.

Receiver No. 5 uses the Yagi antenna to obtain the best possible signal available as a reference and also for communication with the TDRS whenever possible. Otherwise the "bottom" hemispherical coverage will be used. This receiver can also operate with or without RFI cancellation. The modem used with No. 5 receiver and all of the other modems can operate with or without spread spectrum techniques. Thus, the experiment configuration serves multiple objectives. It provides a VHF communication service for the other payload experiments using the best antenna system.

It also acts as a reference link (at another TDRS frequency or code) in conjunction with a number of receive channels with different antenna and RFI cancellation capabilities which can record the data error rate on one TDRS channel continuously for the duration of the sortie, thus gathering quantitative RFI data and system performance as a function of time and position. It will also permit a test of various RFI reduction techniques under operational condition. More subjective tests on voice communication can also be tested. Summarizing, the experiment will enable a systematic and controlled investigation of the RFI problem and equipment performance under operational conditions which can be used to optimize the TDRS system.

This experiment is also coordinated with the Terrestrial Sources of Noise and Interference RFI measurement experiment on reception of a "signal present" indication in Receiver No. 4. The entire band of interest (126 - 128 MHz), after amplification, is transferred to the other operation display of the allied experiment. A panoramic receiver is used to examine the spectrum.

### 7.4.3 Ku-Band Communications Relay Experiment

RFI is not a major problem at Ku-band because of the very narrow beamwidths which are used by terrestrial services in this band to obtain adequate link margins. A similar requirement for the TDRS/CNRL links, however, increases the problems of pointing their respective antennas and acquiring the signal. Doppler shifts and local oscillation drifts may require a frequency search of 1-1/2 MHz while an antenna angle pointing ($3\sigma$) accuracy of 0.14 degree is required to reduce the total antenna pointing losses to 1 dB or less. Computer-directed pointing to this accuracy would impose severe demands on the shuttle and TDRS spacecraft and it is, therefore, assumed that automatic tracking will be required at each end of the link. Automatic tracking to this accuracy can be readily attained but acquisition, although quite practicable, is a formidable problem. Figure 7-5 illustrates a conceptual block diagram for the Ku-band implementation. There are many possible combinations of procedures which can be used for acquisition assuming that the uncertainties in the attitude control and a priori knowledge of the other spacecraft location may be equivalent to several beamwidths. For example, the $3\sigma$

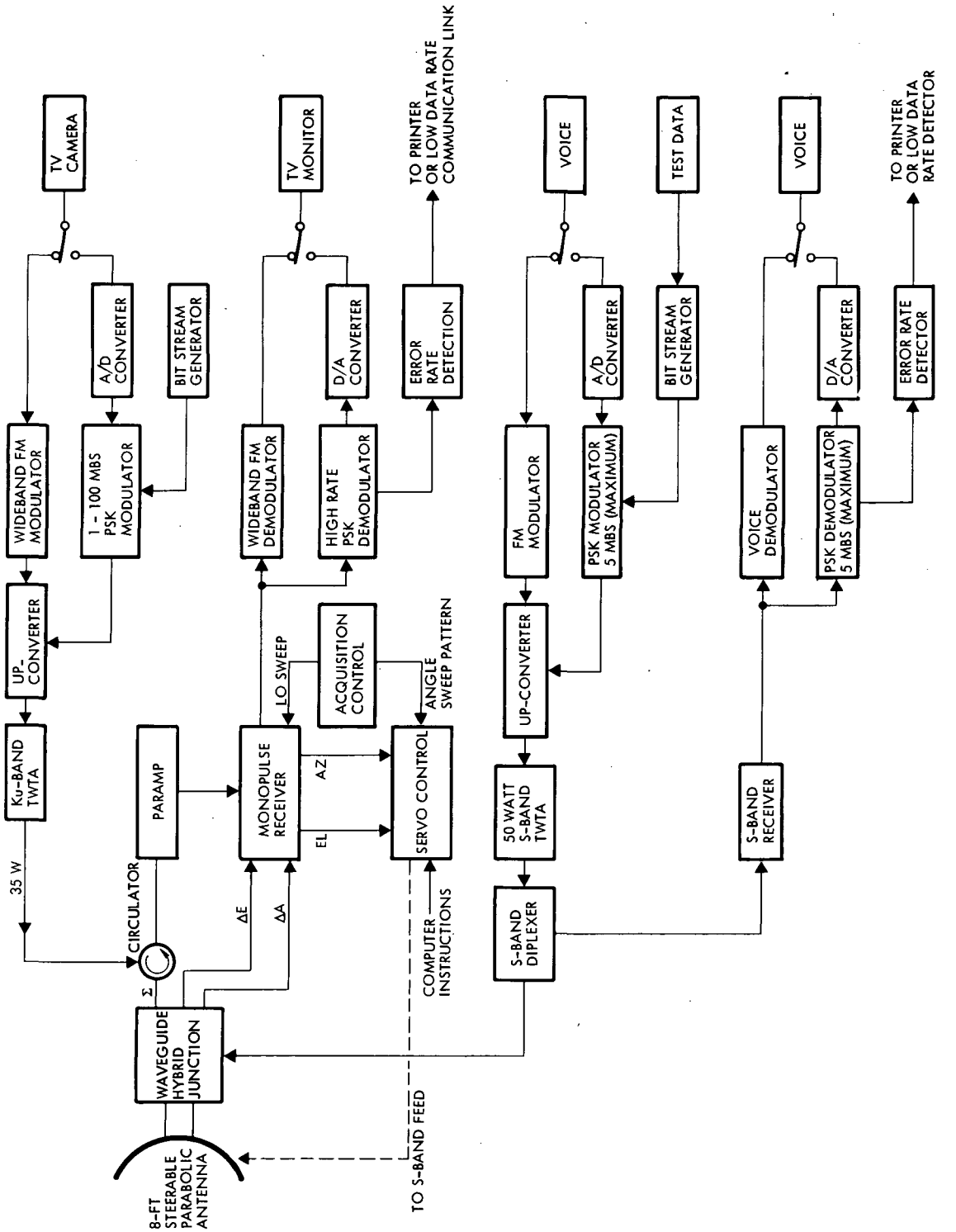



Figure 7-5. Ku-Band Experiment – Functional Block Diagram

solid angle to be searched could be as much as ±3 degrees with 3 dB beamwidths of 0.6 degree and 0.8 degree for CNRL and TDRS, respectively.

Two basic methods are proposed for the acquisition procedures, which are outlined in Tables 7-6 and 7-7. Method A may be the most efficient method but requires an additional Ku-band beacon which may not be feasible in most TDRS user spacecraft. However, it can be readily implemented in the Early Laboratory and this method provides a reference against which the effectiveness of various parameters of Method B can be evaluated. Very little extra equipment (other than that required for automatic tracking) is needed for Method B which is, therefore, more universally applicable. It is, however, likely to be a more lengthy process and although the basic parameters can be estimated analytically, optimization of various procedures can best be evaluated using "brassboard" equipment with manual controls. It is, therefore, a logical experiment for the CNRL and a natural precursor to the establishment of continuous real time wide band data links between the shuttle and the ground station via TDRS.

It should be noted in Method B that the frequency search bandwidths and signal detection thresholds must be set so that the CNRL does not lock up on TDRS antenna sidelobes, but assuming that the latter are at least 20 dB below the main lobe level, these adjustments should not be critical. Also, since the ERP from the CNRL main beam is considerably higher than that of the beacon, the frequency search bandwidth can be much wider, thus reducing (or perhaps eliminating) the time for frequency search. A number of angular search patterns are possible, including a rectangular (similar to a TV raster) pattern, a plain spiral pattern, or a weighted spiral pattern to ensure maximum time at the maximum acquisition probability position. The angular coverage and the bandwidths required can be estimated analytically but some variability should be provided in the pattern search generation unit, since the optimum will depend on the selected host vehicle orbital elements, the accuracy of the a priori relative positions, attitude uncertainty, and whether or not some estimation of Doppler shift is included.

Table 7-6. Ku-Band Acquisition Procedures (Method A)

1. CNRL instructed via UHF order wire to turn on Ku-band beacon.
2. TDRS carries out a frequency search + 0.75 MHz using an effective bandwidth of about 5 kHz and with its Ku-band antenna pointing at the estimated position of the CNRL.
3. TDRS moves antenna one 3 dB beamwidth at a time in a prescribed pattern and makes a frequency search at each position until the beacon signal is detected.
4. VCO of the TDRS locks up on signal frequency and antenna servo drives are switched from search pattern to monopulse error signals.
5. TDRS tracks beacon and transmits its carrier towards CNRL.
6. CNRL instructed via UHF orders to start acquisition cycle.
7. CNRL carries out a frequency search with antenna pointed at TDRS estimated position.
8. CNRL moves antenna one 3 dB beamwidth at a time on a prescribed pattern making a frequency search at each position until TDRS carrier is detected.
9. CNRL locks up on TDRS carrier and antenna servos are driven from monopulse error signals.
10. CNRL is now tracking TDRS in angle and frequency.
11. TDRS can continue to track CNRL beacon or can switch receiver to track CNRL communications carrier.
12. Acquisition is completed.

Table 7-7. Ku-Band Acquisition Procedures (Method B)

1. CNRL is instructed to turn on transmitter and start a prescribed search pattern about the estimated position to conduct a frequency search over the total frequency uncertainty bandwidth ( 1-1/2 MHz).
2. The TDRS Ku band carrier is turned on and the TDRS pointed in the estimated direction of the CNRL.
3. The TDRS starts a much slower search pattern moving its antenna one 3 dB beamwidth at a time, pausing long enough in each position for the CNRL to have completed at least one search pattern before the TDRS moves to the next beam pattern.
4. CNRL locks up on the TDRS carrier and tracks it thus providing a more continuous signal for the TDRS.
5. TDRS locks upon CNRL signal thus completing acquisition.

Having determined the optimum acquisition procedures, the hand-over procedures can be rapidly established and advantage taken of the wide bandwidth communications available. The next step is the test of the wideband capability by the exchange of high data rate test patterns (up to 100 Mbs) and measurement of data error rates for the test signals over relatively long periods of time and under conditions including short and long paths through the ionosphere. At medium data rates (up to 5 Mbs) a comparison of S-band and Ku-band links to/from TDRS can be made using the S-band receiver which provides a general purpose communication link in the presence of severe VHF RFI. The S-band TDRS links will have been thoroughly tested with unmanned low altitude user satellites for a period of one or two years prior to the launch of the CNRL and it can be assumed that they will represent a useful standard up to their maximum data rates capabilities.

The performance of the TDRS Ku-band link, however, will exceed that of the S-band link so that a valid comparison is not possible at the highest data rates. The object of the Ku-band tests at the higher data rates, therefore, will be to assess the absolute value of performance (namely, the data error rate as a function of data rate) and to compare this with the known or measured parameters of the link so that the combined effects of other variables, which may not be readily segregated, can be assessed. This would facilitate identification and improvement of inefficient components (such as demodulators, bit synchronizers, etc.). In conjunction with analytical and experimental work in ground based laboratories, it will ensure development of a continuous real time wide band data link suitable for spacecraft/ground communications which will have been thoroughly tested and evaluated under operational conditions. The experiment will conclude with demonstrations of real-time high quality color TV transmissions from the CNRL to ground via the TDRS and comparisons of analog and digital methods of transmission.

## 7.5 EXPERIMENT/OBSERVATION MEASUREMENT PROGRAM

### 7.5.1 VHF Communications Relay Experiment

The basic measurements to be made in this experiment are:

a) Error rates for various data rates as a function of the RFI environment. It is particularly important to compare the error rates over highly industralized areas (e.g., USA and Europe) with areas virtually free of RFI, such as the broad ocean areas. The magnitude and nature of the RFI will be investigated in a separate experiment (Terrestrial Sources of Noise and Interference) using the 126 - 128 MHz signals received by the equipment used in this TDRS experiment.

b) The effectiveness of various techniques for RFI reduction (e.g., antenna directivity, spread spectrum techniques, RFI cancellation, etc.) with the apparent "optimum" configuration for a given RFI environment. It is probable that there will be a number of "optimum" configurations, each for a specific RFI environment and these will be compared in situ over a number of orbits. As a hypothetical example, it is assumed that the RFI environment over the USA consists of a large number of comparatively low power emitters distributed over the whole of the 126 - 128 MHz band, whereas it is possible that when over Europe the problem is confined to a few high power emitters. The astronaut would then determine that his "best" configuration used the maximum amount of bandwidth spreading over the USA but the least amount of spectrum spreading (combined with careful choice of frequency) was "better" over Europe.

The astronaut would, therefore, reconfigure the system of Figure 7-4 to connect Receiver No. 5 to the same antenna as Receiver No. 3 and request the use of two VHF channels from the TDRS, one with maximum process gain and one with minimum spectrum spreading, setting the receivers and demodulators accordingly. The comparative error rates would then be recorded over several orbits to decide which was statistically optimum in a variety of RFI environments with particularly interest over the USA and Europe.

There is no requirement for special Truth Sites, but it may be convenient to activate appropriate STADAN sites and track the CNRL to provide amplitude and frequency calibration. No special orbit constraints are imposed if the Laboratory passes over the malor potential RFI emitters during the sortie. The items to be displayed, recorded and/or transmitted to ground are:

1) Equipment configuration status (receivers, antennas, RFI cancellation, etc.)

2) Equipment parameters (bandwidth, frequency, etc.)

3) Signal parameters (data rate, amount of spread spectrum, satellite ERP)

4) RFI environment (amplitude/frequency distribution and duration)

5) Performance (error rate and duration)

6) Time.

In addition, some qualitative voice tests may be made using Delta modulation/PSK, Pulse Duration Modulation/PSK, and/or Narrow Band FM Demodulators.

7.5.2 Ku-Band Communications Relay Experiment

The major observations and measurements to be made are:

a) The total time for acquisition of the TDRS by the CNRL and vice versa with various combinations of parameters and equipment configurations. The two major configurations are with and without a Ku-band beacon on the CNRL. It is possible that the TDRS may be fitted with a Ku-band beacon and in this case four basic configuration combinations are possible.

For each of these configurations, a number of parameters may be varied such as :

- Type of angular scan (e.g., rectangular, spiral, weighted spiral)
- Bandwidth, frequency sweep range and sweep rate
- Angular aperture scanned, scan rates.

As a result of these experiments it will be possible to trade-off the actual reduction in acquisition time as a function of equipment complexity, in a systematic manner under actual operational conditions. The best procedures for subsequent flights can be prepared so that later equipment can be automated to minimize astronaut time when the equipment is used in a service (rather than an experiment package) role.

b) Data error rates for identical test signals (1 Mbs and 5 Mbs) at S-band and Ku-band (particularly for long paths through the ionosphere) to and from TDRS

c) Data error rates at Ku-band using 20 Mbs, 50 Mbs, and 100 Mbs data rates

d) Transmission (at Ku-band) of color video material test patterns to and from ground via TDRS

e) Transmission of color TV (USA broadcast standards) of astronaut activities to and from ground via TDRS.

## 7.6 INTERFACE, SUPPORT AND PERFORMANCE REQUIREMENTS

### 7.6.1 VHF Communications Relay Experiment

The major environmental requirements for this experiment are concerned with the design of equipment to be used in the space environment. The antenna structures and equipment which may be mounted on or near the antennas (e.g., preamps, diplexers) will have to be designed to withstand the space environment. In particular, diplexers may be required to be pressurized (to avoid multipacting problems), but this is not difficult for the duration of the intended missions. Equipment located in the pressurized module should be capable of surviving sudden pressure drops and must on no account present a hazard under these conditions. High power equipment such as the VHF transmitter should be safety checked in a simulated space environment.

It is assumed that the experiment will be conducted in conjunction with the TDRS ground station which will allocate one of the two TDRS forward links for the purpose of the experiment and two or possibly three return channels. Some multiplexing will be needed on the forward channel to provide an order wire (or voice) and one or two test patterns on a single forward link, leaving the other to handle the general TDRS traffic for the duration of the mission. Two wide band (spread spectrum) signals with orthogonal codes can be readily combined and the addition of a third (narrow band channel) appears feasible with reduction of power output from 27 dBw (for two channels) to 25 dBw (for three channels). This is desirable in order to maintain contact with the ground station which is simultaneously transmitting a narrow band signal without spread spectrum and the same signal with band spreading to occupy the total available bandwidth. Alternatively, the S-band link may be used to provide voice communication with the ground station via TDRS.

Table 7-2 shows that in the absence of RFI, excellent link margins can be obtained for the VHF forward and return links at the maximum specified data rates of 1000 bps and 10,000 bps and also for voice at an articulation index (AI) of 0.3.

The circuit performance is thus dominated by RFI conditions and as can be seen from Table 7-5, barely acceptable margins are available in the CNRL-to-TDRS link even with the maximum theoretical process gain from spread spectrum technology without some RFI cancellation technique.

In the forward link (TDRS to CNRL) the margins are negative even using a highly directional VHF antenna in the CNRL (+15 dB front-to-back ratio). It is apparent that an RFI cancellation system is required at the CNRL which will produce better than 20 dB of cancellation in the worst RFI environment. This appears possible with reasonable front-to-back ratios in the upper and lower hemisphere coverage antennas but further studies in this area are required.

The Yagi antenna shown in Figure 7-4 is used to obtain a good front-to-back ratio when pointed at the TDRS for maximum rejection of ground based RFI and provides a suitable performance standard against which the hemispherical coverage antennas can be compared. This capability may be combined with the antenna system of the RF Propagation experiment if the latter is modified to provide computer-directed pointing. The pointing requirements ($\pm 10$ degrees, $3\sigma$), are easily met since the antenna beamwidth is about 50 degrees. The major problem is the difficulty of pointing the Yagi in the direction of the TDRS when the shuttle is in the normal position for the majority of the early CNRL experiments. It may be possible to roll the shuttle for a short comparison of the standard (highest performance) antenna system with the hemispherical coverage antennas. Further investigation of the capabilities of the Yagi antenna is required to determine whether its use can be justified in early experiments.

### 7.6.2 Ku-Band Communications Relay Experiment

At S-band a number of travelling wave tube amplifiers (TWTA) have been designed for long life in the space environment, but the Ku-band equivalents are not available. A 35 watt TWTA (WJ-1049) has been designed for use in aircraft and this could be readily converted for space use by the addition of a suitable pressurized container. However, for the time frame of interest it is expected that a number of space qualified Ku-band TWTAs will have become available for other operational or experimental space programs (e.g., Domestic Satellite).

The other major items of concern which may cause difficulty unless specifically designed for the space environment are the Ku-band and S-band diplexers and the antenna pedestal. However, diplexer problems can be solved by pressurization and it appears that the antenna drives designed for the TDRS may be readily adapted for use in the CNRL.

Since RFI is not expected to be a significant problem at S-band and Ku-band, adequate link budgets can be readily obtained even with very conservative noise figure for the TDRS receivers. It is assumed that the CNRL will use all solid state parametric amplifiers at S-band and Ku-band.

Table 7-8 shows that adequate link margins can be obtained in a 100 MHz bandwidth at Ku-band which should be more than adequate for a single high quality video channel.

The antenna pointing accuracy capability required by the host vehicle is approximately $\pm 2$ degrees, sufficient to point the S-band antenna when using this band to provide an auxiliary voice channel (e.g., in the presence of severe VHF interference), or to reduce the angular uncertainty for Ku-band acquisition. In either case, the accuracy is not very critical to the experiment and can be readily obtained by the shuttle. During actual video transmissions or measurement of performance at high data rates, much greater pointing accuracy will be obtained by the use of automatic tracking of the TDRS. It is assumed that the TDRS ground station will provide all of the necessary support for the Ku-band communications relay experiment.

Table 7-8. Comparison of Ku-Band and S-Band Link Margins

| | TDRS to CNRL | | CNRL to TDRS | |
|---|---|---|---|---|
| | Ku-Band | S-Band | Ku-Band | S-Band |
| Frequency | 14 GHz | ~2070 MHz | 15 GHz | ~2250 MHz |
| Transmitter Power(watts) | 35 | 13 | 15 | 17 |
| Antenna Gain (dB) | 44 (5 ft) | 28 (5 ft) | 48 (8 ft) | 32 (8 ft)[2] |
| ERP | +52 dBw | +41 dBw | +63 dBw | +49 dB dBw |
| Space Loss (dB) | -207 | -191 | -207 | -191 |
| Polarization Loss (dB) | -1 | -1 | -1 | -1 |
| Receiver Antenna Gain (dB) | 48 | 32 | 44 | 28 |
| Signal Level | -108 dBw | -119 dBw | -101 dBw | -115 dBw |
| Noise Density for 300°K (dB/Hz)<br>1200°K (dB/Hz) | -204 | -204 | -<br>-198 | -<br>-198 |
| Carrier to Noise Density Rate (C/No) dB/Hz | +96 | +85 | +97 dB | +83 dB |
| S/N ratio 100 MHz | 16 dB | - | 17 dB | - |
| S/N ratio 5 MHz | - | 18 dB | - | 16 dB |
| Margin $10^{-6}$ ErrorRate 100 Mbs | +4 dB | - | +5 dB | - |
| Margin $10^{-6}$ Error Rate 5 Mbs | - | +6 dB | - | +4 dB |

## 7.7 POTENTIAL ROLE OF MAN

### 7.7.1 VHF Communications Relay Experiment

The astronaut will play a vital role in the following areas:

a) To reconfigure equipment for various phases of the experiment, and to take most advantage of unusual events (such as unexpectedly heavy RFI)

b) To compensate for, or take advantage of, changes in schedules of other experiments

c) To coordinate CNRL activities with ground personnel (e.g., request changes in TDRS test signals, channels, etc.)

d) To monitor routine measurements for adequate but not excessive recording of data

e) To monitor anomalous readings, diagnose cause and take appropriate action if necessary (e.g., replace units or reconfigure experiment)

f) To make real time changes of parameters to optimize experiments with changes of RFI environment

g) To optimize the use of the limited time available over the areas of heavy RFI, dependent on the levels found in previous passes

h) For subjective tests on voice circuits during heavy RFI.

Crew skills required include general background in communications technology (at the level of a senior technician).

### 7.7.2 Ku-Band Communications Relay Experiment

As in the VHF experiment, the major role of the astronaut will be to reconfigure the equipment for various phases of the experiment, to coordinate with ground personnel, and to reschedule experiments because of necessary changes in other experiments which may require assistance from the communications links via the TDRS. For example, the Laser Communication experiment and the Landmark Tracking experiment may require the real time use of video or high speed data links to the ground or the S-band link may be needed for voice communications with ground personnel. Thus, rescheduling or reconfiguration decisions may have to be made to support other CNRL experiments.

The astronaut may also wish to change some of the acquisition parameters as a function of early experiments which have indicated a need for either greater probability of acquisition or a shorter acquisition time. Once the optimum acquisition parameters have been well established and the standard tests have been run, the astronaut will provide a communications service for other experiments or use the TV camera to transmit appropriate video material.

The crew skill requirements are identical to that described in Section 7.7.1.

## 7.8 EXPERIMENT EVOLUTION

### 7.8.1 VHF Communications Relay Experiment

The VHF experiment is recommended for inclusion in the first CNRL flight payload to provide the earliest start on a systematic approach and the most rapid optimization for VHF forward link hardware operating in the RFI environment. However, completion of the optimization may not be achieved until the second or third CNRL flight. The optimum system will be used to provide routine voice and low rate data communications and a test data bit stream to continuously monitor (quantitatively) the performance of the chosen configuration in the changing RFI environment. A typical configuration may resemble Figure 7-4 without the Yagi antenna and without Receivers No. 1 and No. 2 and their associated equipment. This configuration would continue to measure the RFI level using Receiver No. 4 which would also supply the RFI cancellation subsystem. Receiver No. 5 would be used to provide routine communication services and Receiver No. 3 would provide a digital test signal, code division multiplexed on the same TDRS carrier as the communications link. Ultimately, Receiver No. 3 would be omitted.

### 7.8.2 Ku-Band Communications Relay Experiment

The first CNRL flight with the Ku-band communications relay experiment equipment may possibly be sufficient to optimize the acquisition procedure, unless there is a persistent schedule conflict with other experiments (which cannot be presently foreseen) or some equipment difficulty. The second flight, therefore, could be devoted to side-by-side

comparison of the S-band and Ku-band links and the first Ku-band tests at very high data rates. Later flights may use Ku-band equipment to perform comparative tests of Ku-band and VHF links to measure dispersion effects at very low grazing angles with the upper part of the ionosphere. The ultimate use of the Ku-band communications relay equipment will be to send high rate data and video data to the ground, including real time TV records of extra-vehicular and other spacecraft activities.

## 7.9 SRT REQUIREMENTS

None.

## 7.10 ACKNOWLEDGEMENTS

### 7.10.1 Related Experiments

| Experiment | Principal Investigator and Association |
|---|---|
| Data Relay | R. Pickard, Goddard Space Flight Center |
| Wideband Narrow Beam Antenna Acquisition and Tracking | E. Pfarr, McDonnell-Douglas Astronautics |
| Low-Noise 60 GHz Parametric Amplifier | Dickens, Westinghouse Space Systems |

### 7.10.2 References


1. Goddard Space Flight Center RFP 20388/24S (TDRS).
2. TDRS User Requirements, D. R. Lord, 21 May 1971.
3. Satellite Communications to Mobile Platforms, Lebow et al, Proceedings of the IEEE, February 1971.

# EXPERIMENT 8

# ON-BOARD DATA PROCESSING

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# 8. ON-BOARD DATA PROCESSING

## 8.1 INTRODUCTION

Unlike the remaining experiments described in this report, the investigative area of on-board data processing does not lend itself to the definition of one or two explicit point experiments. As a consequence, rather than focusing attention on one of numerous and interesting concepts, all of which have considerable merit, descriptions will be presented of each one. The descriptions include discussions of background and status, and a definition of the objectives. A discussion of proposed additional effort on these topics replaces the details experiment plans and related data furnished for other experiments.

## 8.2 EXPERIMENT OBJECTIVES

Successful implementation of the proposed series of experiments will demonstrate the feasibility of providing improved Comm/Nav services through the introduction of more sophisticated satellite communication equipment. The specific advantages sought are:

a) Alleviation of RF interference

b) Reduction in multipath effects

c) Make practical use of Doppler frequency shift

d) Facilitate direct small user control

e) Enhanced message privacy.

Twelve candidate processing concepts have been identified for demonstrating various potential improvements within the above five areas; they are shown in Table 8-1. These concepts are each described in the following section.

## 8.3 DISCIPLINE BACKGROUND AND STATUS

The general approach to providing a satellite communication repeater service is to equip the spacecraft with a back-to-back broad-band receiver-transmitter combination. A degree of frequency offset is used between the receive and transmit assignments to preclude ring-around regenerative oscillation. The required frequency translation is obtained by mixing and

Table 8-1. Candidate On-Board Data Processing Concepts

| Candidate Point Experiment Title | Objective Category | | | | |
|---|---|---|---|---|---|
| | RFI Alleviation | Multipath Reduction | Doppler Extraction & Compensation | Small User Control | Improved Privacy |
| Adaptive channel interconnections and analysis | X | | | | |
| Selectable re-modulation | X | | | | |
| Optional redundant transmission | X | | | | |
| Adaptive ERP control | X | | | | |
| Movable notch filter | X | | | | |
| Frequency diversity and voting | | X | | | |
| Doppler compensation and position location | | | X | | X |
| Spread spectrum translation | | | | | X |
| Spatial beam tracking | | | | | X |
| Multiple satellite network control | | | | X | |
| On-demand frequency translation | | | | X | |
| Store and forward | | | | X | |

filtering, or by unequal down and up conversion ratios. In some signal conversion processes the upper and lower band edges are inverted (translated).

## 8.4 EXPERIMENT DESCRIPTIONS

The following sub-sections present a description of the concept, operational advantages and general implementation for each experiment.

### 8.4.1 Adaptive Channel Interconnection and Analysis

Typical general purpose communication satellites incorporate one or more segments of their frequency band that are subdivided into a number of contiguous, or semi-contiguous, equal width channels. This is frequency division multiplexing (FDM) and is analogous to the arrangement of carrier telephone voice channels.

Because the satellite will almost always be operating on an assigned and exclusive portion of the frequency spectrum, co-channel interference from other services should be minimal. However, this is not true of harmonic and intermodulation interference sources. Other spectrum users operating at frequencies that are integer sub-multiples of the satellite frequency assignment will generate potentially troublesome harmonic components that can degrade or render one or more of the satellite service channels unusable. In general, such interference is sporadic rather than continuous. This is a particularly acute problem for low-orbit satellites when over-flying a harmonic source.

#### 8.4.1.1 Concept

It is suggested that the satellite incorporate facilities for adaptively re-configuring channels to compensate for such effects and supplement this adaptive capability with facilities for accumulating data and hopefully identifying the origin of the interfering source.

As a model for describing the proposed arrangement for the experiment, a simple communication satellite having 12 FDM 4 kHz wide voice channels, using frequency inversion and spacing for input-output isolation, as shown in Figure 8-1, has been assumed.

The suggested scheme would operate in the following manner: When an interfering signal seriously degrades or interrupts a user channel, the user would signal his desire for a modified assignment using the

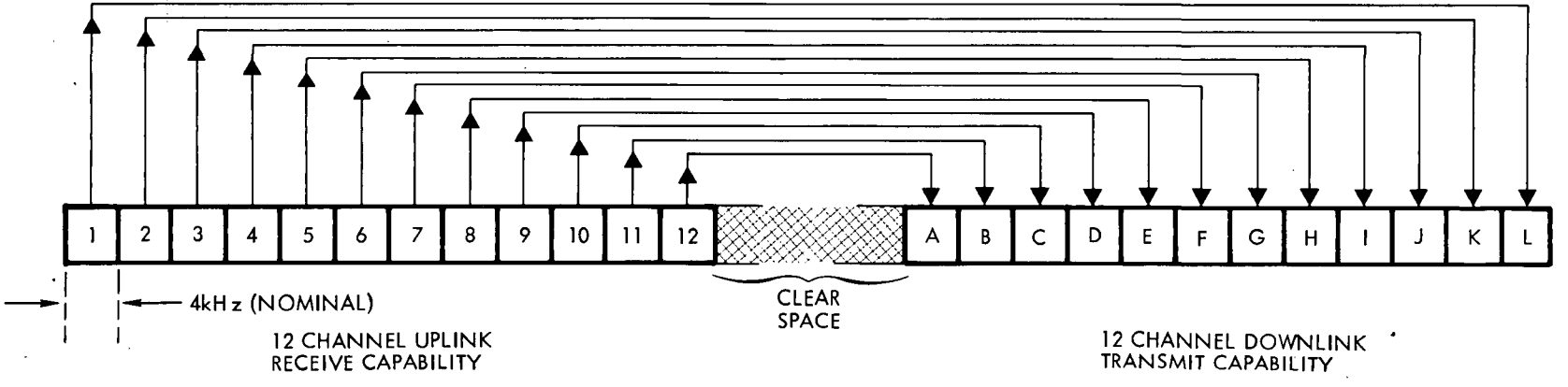



Figure 8-1. Representative Communication Satellite Channel Configuration

common service channel (CSC). On receipt of this service request, the internal logic control circuitry would initiate monitoring of the troublesome channel and search its remaining channels for a clear channel. It would then interconnect the selected clear channel with the "good" leg of the original service uplink-downlink pair and advise the requestor of the new assignment. If all remaining channels were occupied, the present user would be assigned a waiting number and his connection order executed when a line became free and all lower waiting number orders (if any) had been executed. Figure 8-2 illustrates the functional logic required to implement this approach.

The monitoring facilities proposed would include a universal demodulator/modulator assembly, a magnetic tape recorder and a microwave spectrum analyzer. On receipt of a re-assignment request, the control logic would command the matrix switch to connect a demodulater between the defective channel and the magnetic tape recorder and initiate the spectrum analyzer. The analyzer would electronically sweep across the complete uplink and downlink bandwidth and feed the tape recorder with a spectral power density profile. A ground command from the satellite management ground station would initiate slow speed transmission of the data stored in the tape recorder for detailed analysis using the ground station's computers. The repertoire of commands would provide for moving the center frequency and sweep width of the spectrum analyzer viewing region to provide fine detail for any selected channel.

### 8.4.2 Selectable Re-Modulation

Existing terrestrial communication links comprise two or more cooperating radio stations that operate on the same frequency and use compatible modulation schemes.

There are an increasing number of space applications where it would be highly advantageous if a satellite user could select the type of modulation to be used for his particular down link signal. For example, this capability would allow an aircraft using UHF-AM equipment to communicate with a user having UHF-FM equipment. When combined with the additional facility for on-demand frequency translation, it opens up some totally new service possibilities.

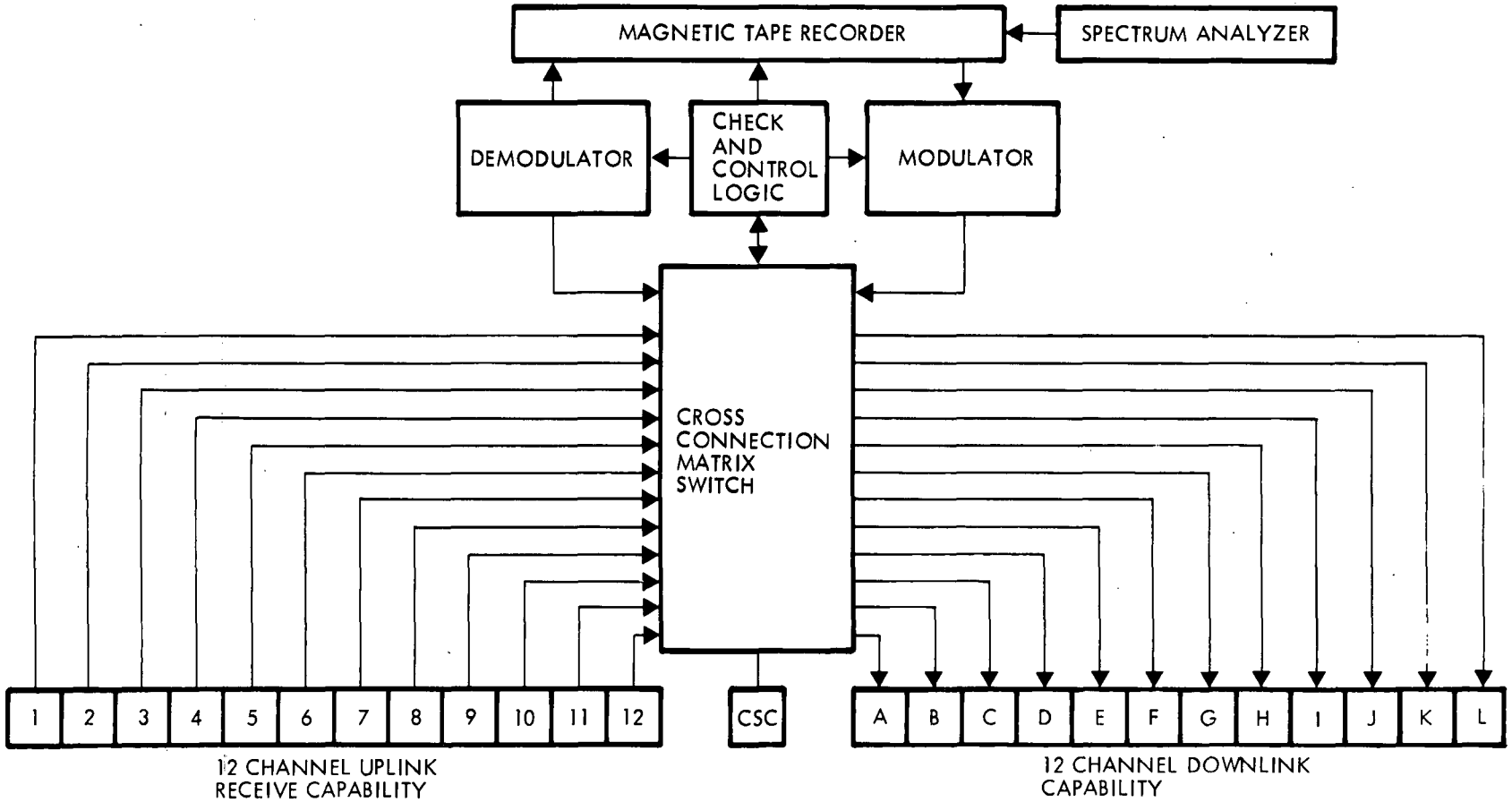



Figure 8-2. Candidate Adaptive Channel Interconnection Concept

8.4.2.1 Concept

The suggested method of implementation would involve locating a bank of universal modulators, together with the necessary control logic and memory capacity, in the spacecraft. The selection of modulation would be effected in the spacecraft, by decoding commands initiated by the users. It appears entirely feasible to permit these modulation selection commands to be sent within the user's regular channel using his normal transmitter, although some special form of modulation or signal coding will be needed to ensure that satisfactory recognition statistics are achieved. An alternative concept would be to make use of a common service channel for all user modulation selection commands. This has the disadvantages that it entails two-channel capability at each user station, it may involve delays in order execution, and it wastes some channel space that could otherwise be dedicated to user-to-user communication.

The general configuration of the spacecraft equipment needed to implement this concept is illustrated in Figure 8-3. The proposed scheme would operate in the following manner: The phase-lock loop of the signal processing sub-system would continuously sweep across the uplink input channel band. At each user signal point, the loop would temporarily acquire, strip off the modulation and apply the latter to a filter. This filter is matched to the frequency-time characteristics of the modulation-request codes. If an approved request code is detected, the filter output activates the appropriate intercepts of the modulator selection switch. This switch, or matrix assembly, then assigns the phase-locked sample of the user's carrier and the baseband information to a modulator and the downlink output bus. The code detection also results in issuing a stop command to the sweep disable switch, which latches in the disable position, thereby inhibiting the acquisition sweep generator. The sweep disable condition allows the phase-lock loop voltage-controlled oscillator (VCO) to track any instability in the user up link signal carrier, and allows the modulation request code to be sent as a pre-amble rather than continuously. The service interrupt timer monitors the presence of carrier from the user. Interruption of the carrier initiates the timer which provides an appropriate delay prior to

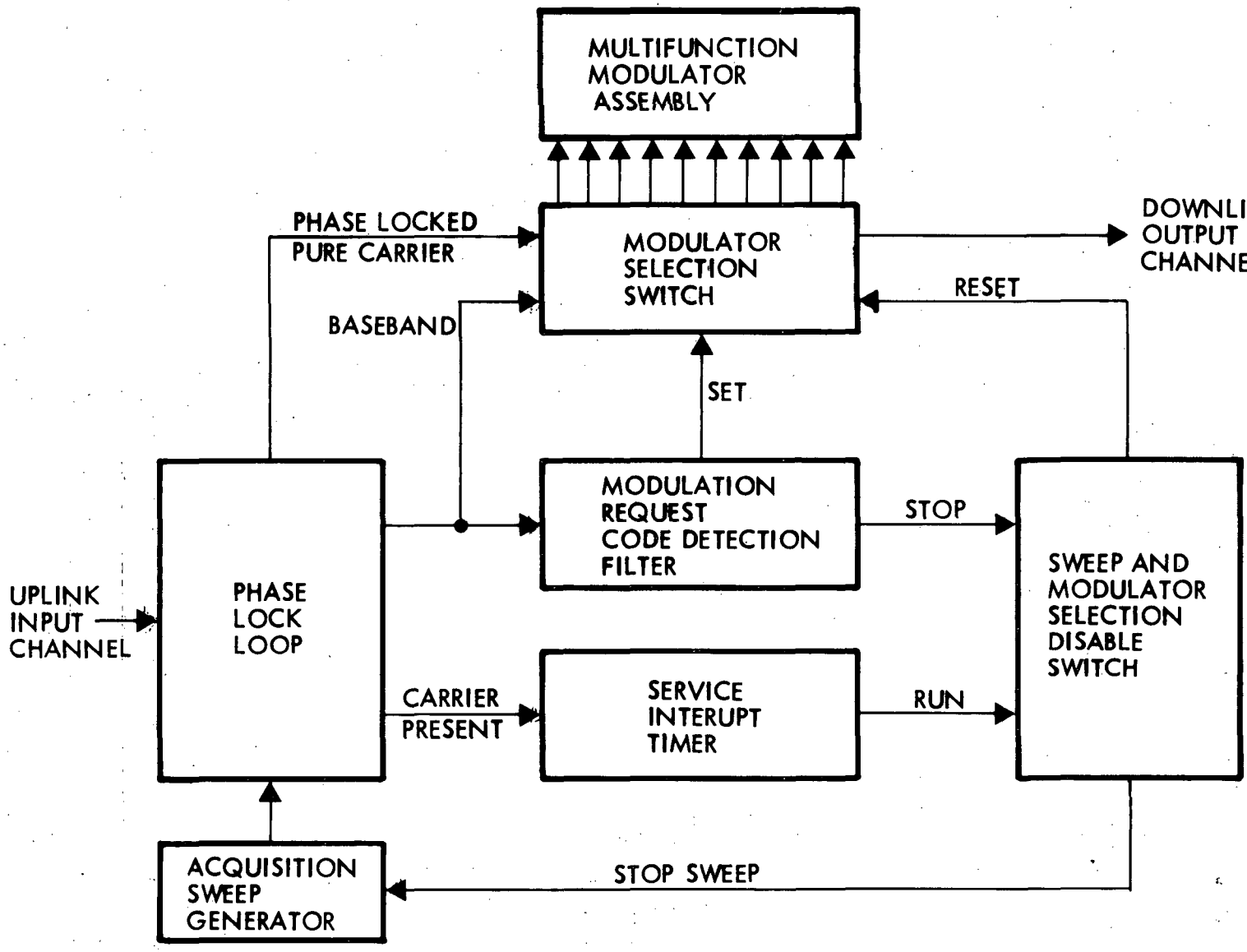



Figure 8-3. Spacecraft Configuration – Equipment Proposed for Selectable Remodulation Feature

re-enabling the acquisition sweep generator and resetting the modulator selection switch matrix to the open or quiscent condition.

The phase-lock loop then resumes the sweep across the band until it encounters the next candidate user carrier, whereupon the above process is repeated. If the modulation request code filter does not detect an approved code, a timer associated with the acquisition sweep generator administers a small pulse to the sweep integrator, unlocking the VCO and resuming the sweep. Multiple processors of the type illustrated in Figure 8-3 would be provided in each operational communications spacecraft if this scheme were implemented.

### 8.4.3 Optional Redundant Transmission

There are a number of situations in which it is essential that a critical message be repeated, but the originator cannot perform that repetition. These are generally emergencies; examples include disabled aircraft, downed pilots, sinking ships, lost explorers, police patrol cars, etc.

#### 8.4.3.1 Concept

The proposed service could be provided by equipping a satellite with a small tape recorder and the related control logic to protect and limit access: It presently appears that there should be two modes of recording access, one for all general emergency calls, and one for sensitive data. The general channel could be activated by the S-O-S Morse code sequence. This arrangement would provide for automatic tape storage of all messages that were preceded by the standard distress call, S-O-S. The accumulated messages would be retransmitted many times and also would be available for ground interrogation via an appropriate uplink command. Duplication of the recorders would prevent loss of recording ability during the ground-commanded readout period.

The protected storage channel is proposed as a means of handling civil emergency communications that require privacy, in order to protect life and property, and maintain law and order. Examples include:

- Major fires
- Riots or disturbances
- Epidemics
- Power utility overload levels
- Toxic or flammable spillage
- Radio activity (e. g., nuclear power plan run away).

Access to this data by the general public could materially hamper the civil authorities responsible for handling these problems.

Processing logic is required to recognize valid commands associated with both the record and playback modes. The functional configuration of the equipment is illustrated in Figure 8-4.

The system operates in the following manner: On receipt of an uplink emergency or distress signal, one of the several phase-lock loop processors acquires locks and tracks any subsequent carrier drift. Two such processors are proposed for distress use, one each assigned to the international frequencies of 141 and 243 MHz respectively. A group of additional processors is suggested to accommodate various civil and emergency functions on frequencies to be determined.

Each group of processors (distress and civil emergency) incorporates an assignment switch and recorder control switch. The assignment switch is activated by the carrier lock signal available from each of the phase-lock-loop processors. The presence of a carrier lock signal seizes the record channel for that processor by activating the record control switch which routes the output of the active processor to the appropriate recorder pair. The recorder assigned is established by logical decisions based on the status of the playback control logic, the fraction of tape capacity remaining, and the operational status of the recorder. As a result of these logical operations, the signal is routed and recorded on the spacecraft tape log. A timer associated with the recorder causes repeated transmission of the message for a predetermined period. At some subsequent time a ground station can transmit a coded playback command. This code will be recognized by the playback command decoder. The code serves to identify the recorder to be activated, and the downlink

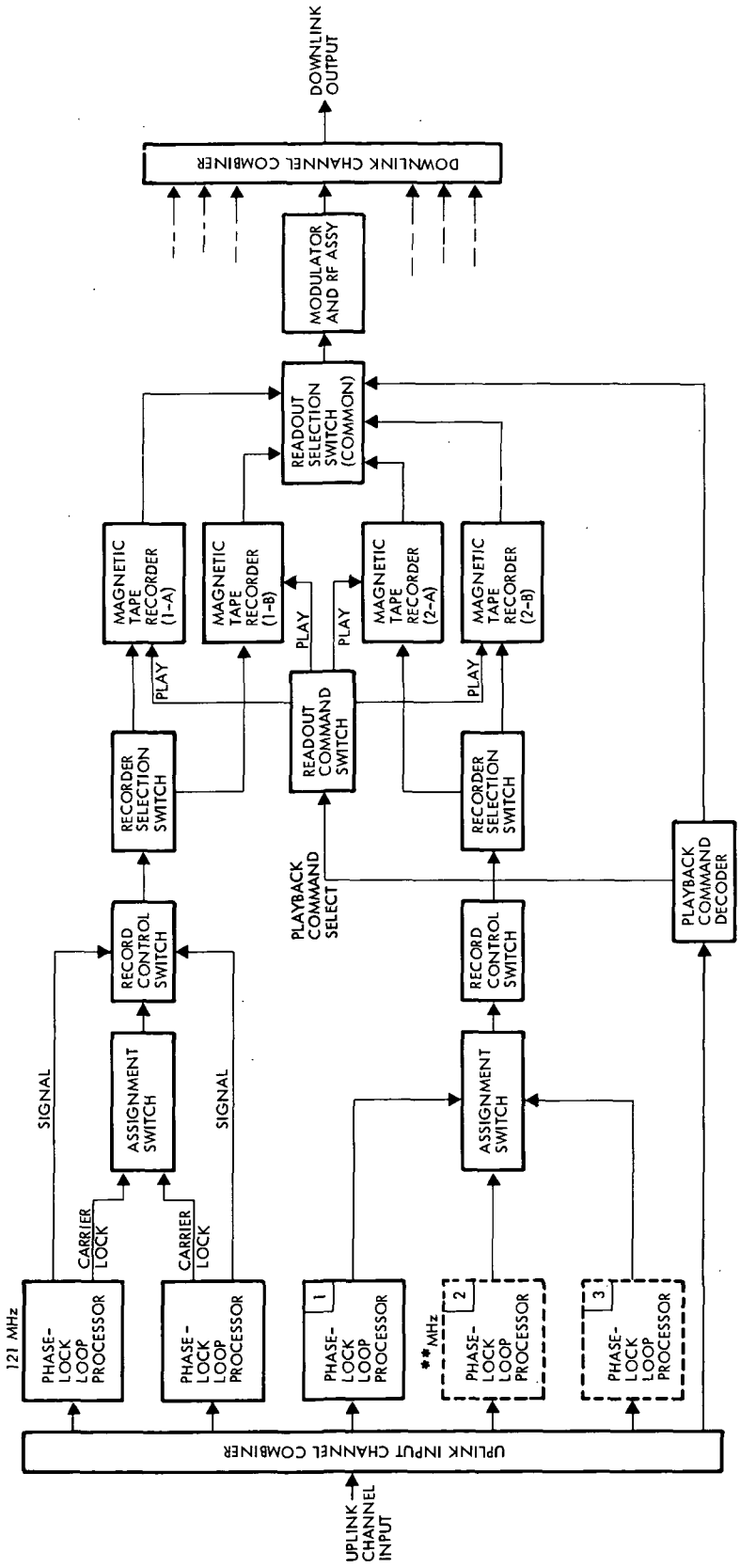



Figure 8-4. Hardware Configuration for Redundant Transmission Scheme

channel to be used for transmission. As a result, the taped message, or messages, are transmitted to the interrogating ground station, on the channel frequency he has specified.

There are a number of interesting possible variations and detailed improvements that should be investigated, including:

- Type of coding needed for protection
- Simple combining of 121/243 MHz channels
- Immediate transmission to ground of "Message Held" code
- Send acknowledgement to sender
- Combine tape recorders 1-A, 2-A and 1-B, 2-B using multiple tracks (Reference Figure 8-4).
- Automatic retransmission until uplink stop command received.

### 8.4.4 Adaptive ERP Control

The effective radiated power (ERP) needed for a user to communicate with another user via a satellite depends on the modulation form and signal-to-noise ratio (SNR) required, and on the interference environment at the receiving site. The former parameters are determined by the type of service being used, i.e., CW, FSK-Teletype, FM Voice, analog TV. The interference environment, however, is a highly variable quantity. Man-made noise in urban areas can attain levels which are three orders of magnitude above the thermal baseline due to receiver noise alone.

In a rural environment the interference is typically very low. A ship at sea, while free of urban noise, is characterized by a miniature equivalent, the representative level is between urban and rural conditions.

It is clear that the use of excessive ERP, beyond that required for satisfactory quality of reception, constitutes pollution of the communications media, which should be discouraged. The basis of this concept is to control the ERP value of each signal to provide only the required SNR to meet the specific conditions at the recipient's location. The suggested method for accomplishing this objective is a form of adaptive power control, exercised whithin the spacecraft. An added advantage is conservation of satellite electrical power and extended life.

8.4.4.1 Concept

There are two possible levels of implementation complexity; the first is simple and does not provide a feedback or self-adaptive capability, the second monitors the end result and is self-regulating. These two methods are referred to as "geographically independent control" and "automatic SNR control" respectively.

Geographically dependent control involves storing a look-up table in the satellite memory that identifies the ERP required for service to each user site. It would be based on actual measurements of the SNR obtained at these sites from the satellite. These figures would take into account the average field strength due to man-made interference sources, and the effect of the actual receive site antenna pattern, local reflections, etc. Since the site information is stored in the satellite memory, it is feasible to up-date this information as the conditions at each site become better known, or change due to local developments.

Automatic SNR control involves a degree of increased sophistication and is based on periodically measuring the actual SNR of each receiving site in real time and transmitting this information to the satellite for semi-continuous ERP control. If a multiple choice of modulation, coding, and frequencies is made available, as discussed in other sections of this On-Board Data Processing experiment, the satellite would store appropriate correction factors to allow for such changes insofar as they modify the required SNR and ERP values.

Actual control of the ERP can take several forms. The simplest results when the satellite incorporates a multibeam fixed or steerable antenna array. For this arrangement it is only necessary to vary the power distribution applied to the several beam feeds. If a single broad coverage parabolic antenna is used, it is apparent that all channels represent a potential interference source in every area. Thus, reducing any particular single channel will only effect a relatively small improvement in the resulting interference level. The situation is similar to that of automobile pollution where a little, and seemingly unimportant, effort to improve each vehicle results in a massive improvement nationwide. Perhaps the overriding reason for suggesting that this is a worth-

while area for study lies in the obvious trends of satellite antennas towards the multibeam form.

### 8.4.5 Movable Notch Filter

As more and more electronic communication services are implemented, the radio frequency band is increasingly congested and interference alleviation becomes a critical design task.

This problem can be partially alleviated by careful preliminary system analysis and frequency planning; however, new services are constantly being developed, and the basis for selecting particular operating frequencies often changes appreciably within the lifetime of the satellite, rendering the selected parameters no longer optimum. With the rapid growth of communication technology, we can expect an acceleration in these effects. What is needed is clearly a solution that is sufficiently flexible to accommodate the evolutionary changes after the design, fabrication, and launch of a communication or navigation satellite.

A movable notch filter that can be used to suppress interfering signals would appear to have valuable potential and is well worth exploring on an experimental basis.

#### 8.4.5.1 Concept

It is proposed that one or more remote controlled movable notch filters be installed in the spacecraft. This will provide the satellite ground control personnel with a highly versatile tool with which to combat a wide range of interference situations.

Notch filters have come into widespread use in HF communications, and such a feature is built into any good quality modern HF communication receiver (including receivers for amateur radio use). The earliest notch filters used a bridge-tee circuit configuration which provides a notch descent shape factor related to $4(Q)^2$, where $Q$ is the quality factor for the L-C components of the tuned circuit. However, the notch did not achieve wide popularity until the advent of the active filter. Early active filters used an amplifying device such as a vacuum tube or transistor to offset the resistive and dissipative losses in the tuned circuit components, thereby raising the effective quality factor. Because of the large intrinsic gain available from the active element, it is possible

to completely neutralize the circuit losses and attain an infinite Q factor. In practice this is undesirable because it results in unstable operation and a tendency to oscillation.

The efforts expended to achieve extreme values of circuit Q factor are a target because the width of the notch (measured in Hertz) is inversely related to the Q value, and the attenuation is related to the Q value, so that the larger the Q value, the greater the attenuation and narrower the notch. These HF notch filters were primarily used to suppress narrow band CW (Morse) stations located adjacent to a desired signal. The slow keying rates for CW transmitters result in a narrow sideband structure that can be effectively suppressed with the infinite-Q type of active filter.

For intermediate bandwidth signals the problem becomes more difficult because of the wider frequency range to suppress. Therefore, a finite rectangular shape is required rather than a very sharp notch. To provide the required width, we must limit the Q factor which

a) May extend the attenuation region across the desired signal as well as the undesired, and

b) The Q limitation inherently limits the suppression possible (attenuation).

A filter requirement of this type is a classic design problem and is usually termed a "steepest descent optimization" task.

The most common filter classes are the Butterworth, Chebychev, and Elliptic; of these, the elliptic provides the fastest transition slope between the pass and stop band regions and is, therefore, a potential candidate.

For wideband signals such as FM and television, the filtering problem becomes appreciably more difficult. Three other technical problems associated with signal separation must also be mentioned, namely, frequency stability, intermodulation and phase response. If a very narrow deep notch filter is used to suppress an unwanted signal, it will only be effective if the user can tune it so that it is superimposed on the offending carrier, and maintained it in that position. Practical experience with HF

receiver notch filters indicates that appreciable skill is required to position the notch so as to obtain the optimum performance. Design care is required in both selecting stable components and packaging them so that temperature changes do not cause the filter to drift out of the sharp null region. Even when these requirements are met, there frequently exists a drift problem associated with movement in the frequency of the interference source carrier itself. The phase response is important because the fast pass band to stop band transitions usually result in a phase response that mutilates the desired data in the pass band. This is particularly true of TV signals which are sensitive with respect to phase linearity.

A study of these fundamental limitations led TRW to develop a special tracking notch filter (Reference 1) based on the proven phase-lock loop principle. A representative circuit arrangement is illustrated in Figure 8-5. The phase-lock loop and associated filters are used to develop an estimate of the undesired signal which is then subtracted from the composite (desired plus undesired) to suppress the undesired signal. The characteristics of the filter are designed to match the spectral signature of the undesired signal. The phase-lock loop (PLL) configuration acquires and tracks any frequency excursion of the interfering signal. The PLL furnishes a phase-locked replica of the unwanted signal carrier, which is subsequently combined with the modulation from the unwanted signal carrier, which is subsequently combined with the modulation from the unwanted signal in a balanced modulator to obtain a replica of the original interference signal, but convolved with the matched filter characteristic. The replica, or estimate of the original interfering signal is then subtracted from the composite input by summing these two components via the negative and positive inputs of an operational amplifier. The residual signal continues to be processed by the filter, resulting in the normal asymptotic approach to perfection associated with feedback systems.

This filtering technique was applied to the Apollo-12 color TV link and was demonstrated to reduce TV interference from a 1.024 MHz subcarrier telemetry signal and a 1.24 MHz analog voice subcarrier signal by 20 to 25 dB. In this situation there was a significant spectral overlap in the desired and undesired signals (see Figure 8-6).

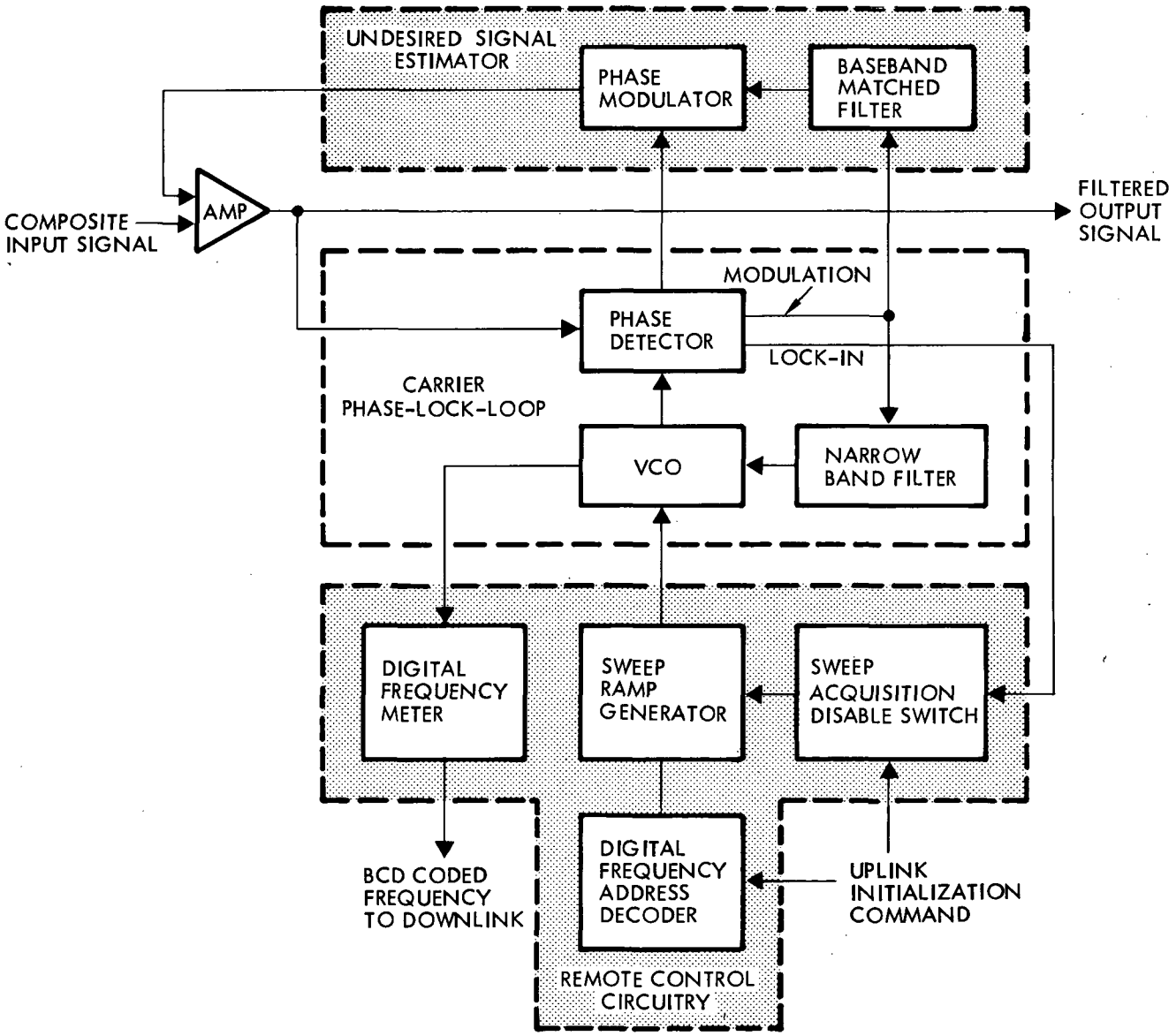



Figure 8-5. Proposed Basic Scheme for Movable Notch Filter Feature

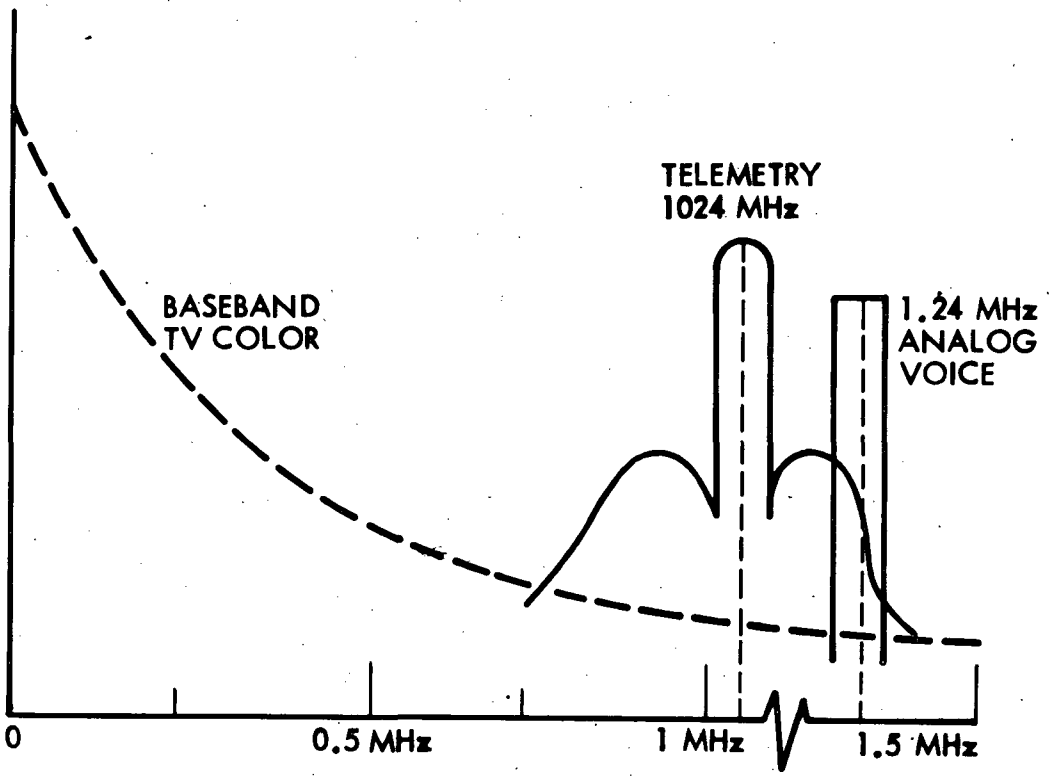



Figure 8-6. Input Signal Spectrum Processed by "APEX" in Apollo 12 Color TV Demonstration to NASA

Subsequent to these tests performed in 1969, TRW has further refined and improved the "APEX" technique under company funded and contract studies (References 4 and 5). These efforts have resulted in a number of patent disclosures (References 2 and 3). The performance features include:

General

- Separates a low level CW signal from an adjacent high level interfering signal
- Detects low level radar or telemetry signals in overlapping high level FM or TV signals
- Protects receivers in proximity to high power (firendly) transmitters, reducing inter-service interference
- Counteracts swept FM or CW jamming signals.

Specific

- Separates two FM stations only 100 kHz apart with a 1000:1 power difference

- Provides for 100,000:1 (50 dB) suppression of unwanted FM signals, or 10,000:1 (40 dB) suppression of unwanted TV signals overlapping a desired radar or telemetry pulse signals.

The original version of APEX was, of course, designed for use on the ground, at a NASA receiving station. For the proposed application on-board a satellite, it will be necessary to make some changes and additions to facilitate effective ground control. These are identified as remote control circuitry in Figure 8-5.

In operational use, the ground station crew can move the filter to the frequency location of the interfering carrier by sending a digitally coded address word over the command uplink. This word is interpreted as a "Go-To" frequency command by the digital frequency address decoder. A simultaneous signal is applied to the sweep acquisition disable switch to prevent the PLL attempting to lock onto any intermediate signals and negate the "Go-To" command.

A digital frequency meter continuously monitors the actual frequency of the voltage controlled oscillator (VCO). The values of the frequency meter output and requested address code are compared in a simple code coincidence circuit. When the values agree within an acceptable tolerance, the sweep acquisition switch is enabled and the PLL takes over control to acquire phase lock with the carrier of the offending signal and initiate the estimation and subtraction process.

Use of the PLL for zeroing-in on the target carrier frequency alleviates the accuracy requirements for the system and accommodates dynamic changes in the target transmitter's carrier frequency. A spectrum analyzer allows the ground control personnel to determine where to place the filter and monitor its effectiveness.

### 8.4.6 Frequency Diversity and Voting

In a number of realistic operational situations involving the use of communication-navigation satellites, it may be advantageous to provide facilities for frequency diversity and/or diversity with voting. Multipath effects (and unique interference situations) are cases in point, where specific but non-obvious combinations of terrain features and satellite-to-

ground station (or aircraft, ship, etc.) geometry cause a drastic deterioration in user service. Since such effects are wavelength dependent, it is possible to circumvent the degradation by a judicious shift in link operating frequency. With a modest increase in sophistication, a voting arrangement can be added to alternative frequencies to select one having the best demonstrated performance. Somewhat similar systems, involving spatial diversity and voting signal selection, are presently used in quite a number of terrestrial communication services; for example, the Chicago police network.

8.4.6.1 Concept

Practical implementation of a scheme using frequency diversity imposes some important conditions on the associated ground terminals. First these terminals must be equipped to receive all the multiple frequencies it is planned for that terminal to use, although not necessarily the full capacity of the satellite. Second, the system must provide a common service channel (CSC) or channels, to accommodate transmission of the frequency shift instructions. If multipath interruption of individual channels is the basis for the proposed improvement, we must provide a C.S.C. concept that will not fail for the same (multipath null) reasons.

A potential solution to the complexities associated with central control and the spectrum wastage resulting from a CSC is to provide dual frequencies for all users on a continuous basis. To prevent a drastic reduction in the user capacity of the satellite, single sideband (SSB) modulation would be required. For this approach, the total satellite service bandwidth would be divided into approximately twice the number of channels appropriate to double sideband. Each ground transmitter would simultaneously transmit two SSB signals with a frequency separation equal to one-half the satellite service bandwidth. The receiving terminal would incorporate a signal combiner or voting switch to make optimum use of the two signal samples obtained. However, the use of SSB is presently restricted to amplitude modulation. FM-SSB modulation techniques have been investigated (Reference 6) but operational systems of the type proposed have not yet been developed or demonstrated to be feasible.

### 8.4.7 Doppler Compensation and Position Location

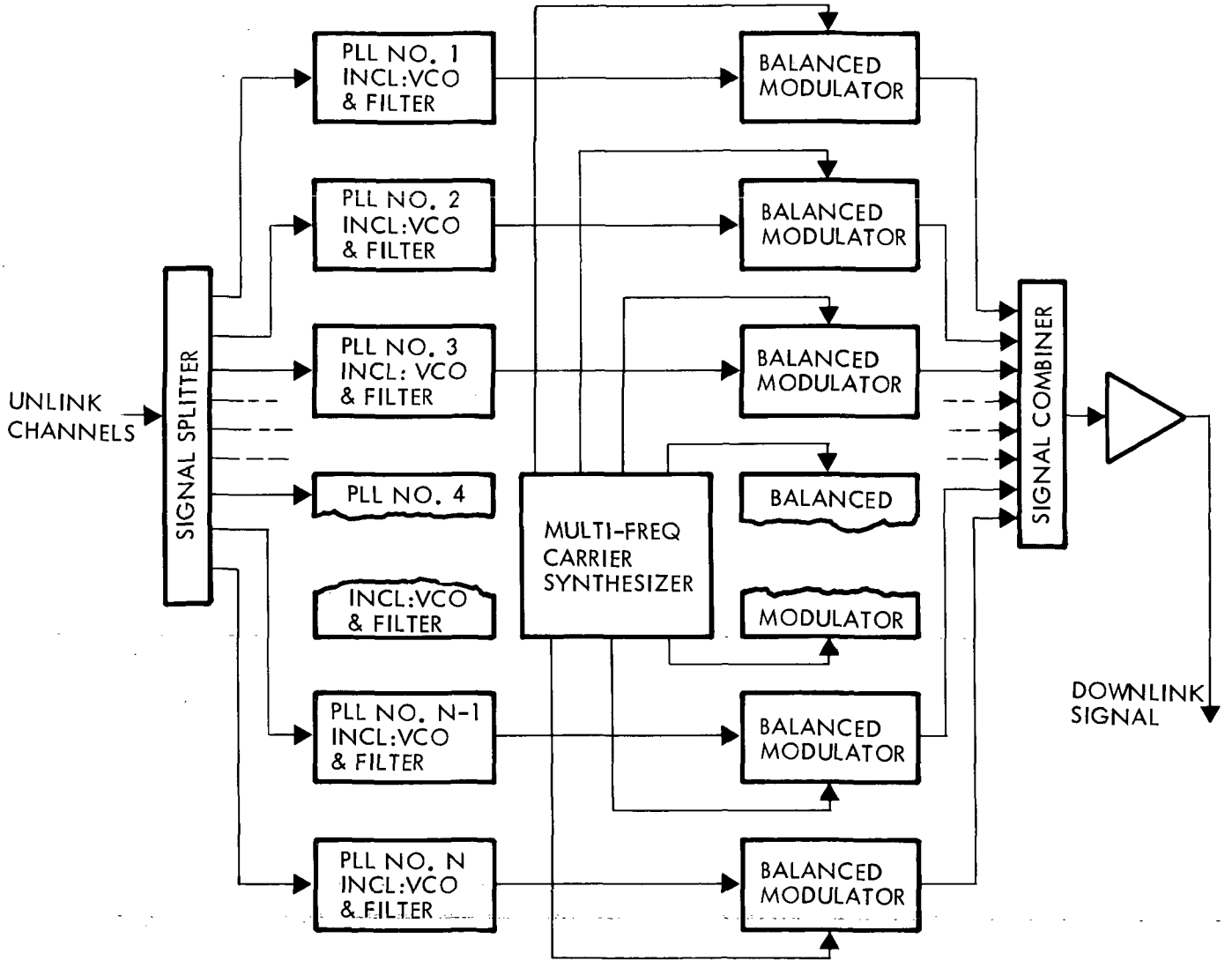
The motion of orbiting, non-synchronous, satellites produces a significant frequency shift in the spectra of signals sent via the satellite. These frequency shifts are undesirable because they must be accommodated within the band allocated for the satellite service, and thus detract from that remaining for useful communication purposes. Given a knowledge of the satellite ephemeris, it is possible to compensate for the Doppler by appropriate signal processing.

The Doppler history is a function of the specific geometry defined by the location of the source and receiving terminals and the satellite orbit. It follows that one can establish the location of a geographically uncertain terminal by appropriate processing of the Doppler signal. When both the source-to-satellite and satellite-to-receiving terminal paths are time dependent, it becomes more difficult to derive the location of either. If a Doppler compensation facility is incorporated in the satellite to counteract the source-to-satellite Doppler effect, the location of the receiving terminal may be readily obtained (or vice-versa).

#### 8.4.7.1 Concept

The most satisfactory method of compensating for satellite motion induced Doppler on the uplink is to strip off the modulating information content and use this to remodulate a highly stable on-board oscillator. One phase-lock loop (PLL) circuit will be required for each user channel, but since a complete PLL processor is presently available as one integrated circuit element, this is neither a significant risk, cost, size, or weight problem.

Since a reasonably large number of new stable channel carrier frequencies must be generated, a common frequency synthesizer is proposed. The remodulated signals would be combined and processed via the regular wideband travelling wave tube (TWT) or solid state satellite power amplifier. The general configuration proposed is illustrated in Figure 8-7. A supplementary advantage accrues because this scheme also compensates for drift in the carrier frequencies of the user terminal transmitters. Figure 8-8 depicts the effect of this proposed compensation technique on the downlink frequency spectra.




KEY: PLL = PHASE-LOCK LOOP
WBPA = WIDE BAND POWER AMPLIFIER

Figure 8-7. Configuration for Proposed on-Board Doppler Compensation Processing

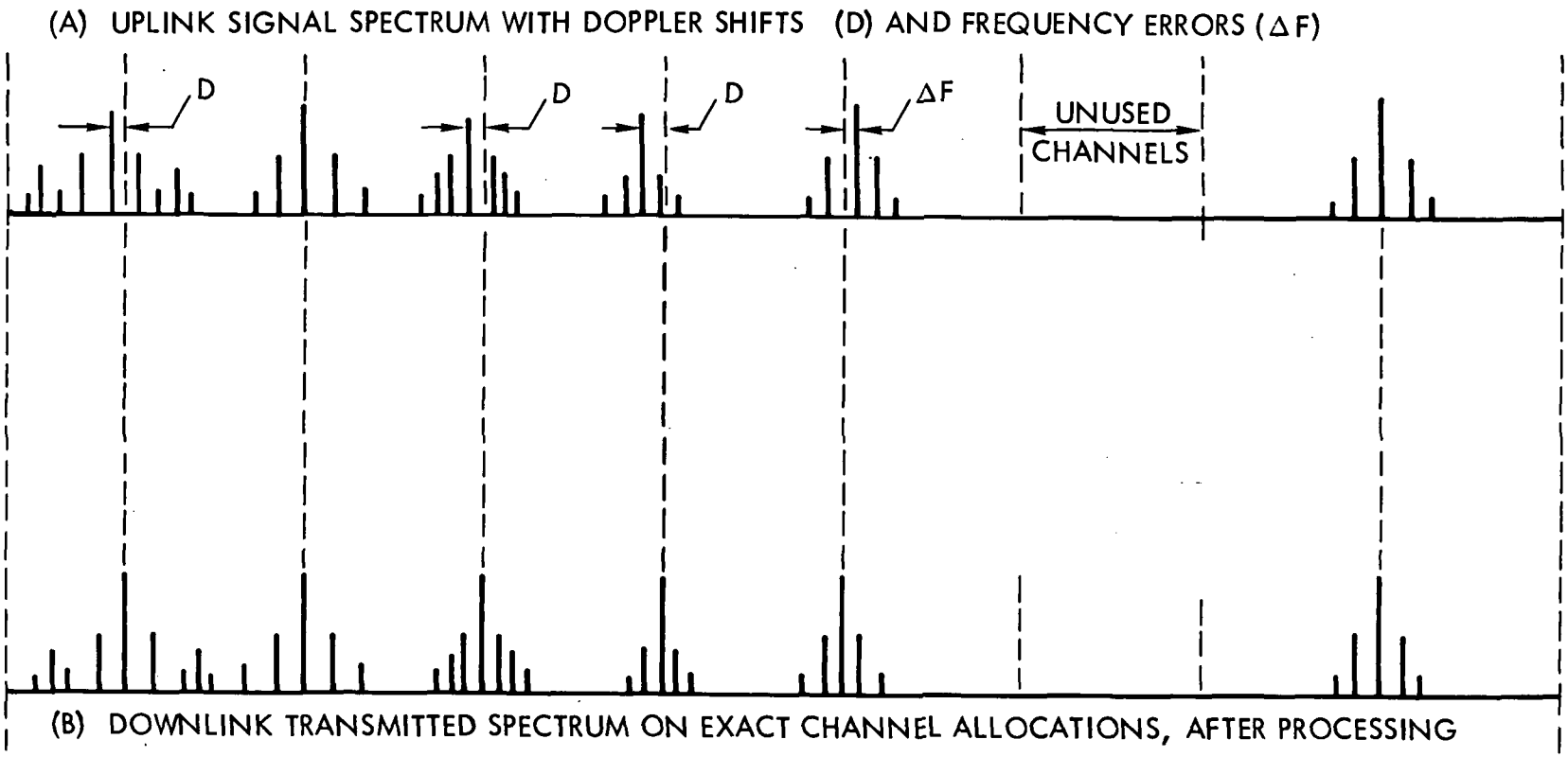



Figure 8-8. Effect of Proposed Doppler Compensation Scheme

### 8.4.8 Spread Spectrum Translation

During the last few years message security has become increasingly important to civil and commercial organizations. The solution generally adopted is to code the information prior to modulation at the sending point and decode it after detection at the receiving site. The most powerful protection is afforded by digital algorithms after analog-to-digital (A-D) conversion of the raw information signals.

Since these coded signals can angle modulate the user's carrier, modification to the satellite repeater design is only necessary if the A-D conversion, sampling and coding processes have caused the total data rate to be expanded beyond the satellite channel capacity.

In this description we would like to address a somewhat different problem. There are cases, however, in which it is desirable to have uncoded sources transmitting signals via the uplink, but would like the downlink transmissions to be coded for increased privacy. Such a service can be provided by appropriate addition of some on-board signal processing equipment.

#### 8.4.8.1 Concept

The sending ground station contacts the Communication satellite and establishes entry authority via its user number. It prefixes its message with a code word indicating that message privacy is desired. The satellite on-board processing equipment recognizes this code and reconfigures the payload electronics to accommodate the necessary changes.

There are a variety of methods that can be employed to achieve the desired privacy, including:

- Spectrum inversion
- Spectrum segmentation and transposition
- Subcarrier structures
- Frequency hopping
- Pseudo random noise coding

Evaluation and comparison of these and other techniques must take into account the characteristics of the raw data that is to be encoded

and the nature of the application. Such an evaluation is beyond the scope of this initial discussion, but is recommended for future in-depth investigations.

8.4.9 Spatial Beam Tracking

The combined requirements to reduce radio frequency interference, increase data rates, and improve message privacy suggest the use of narrow beam tracking antennas, with on-board control logic. A multiplicity of such pencil beam antennas would permit the satellite to cross link a number of geographically small service areas. Because the coverage areas are small the radiation is restricted, alleviating RFI. If the sum of the beam areas is small compared with a hemisphere, the increase in link gain is significant, which in turn allows higher data rates, and better overall service efficiency; fundamentally, because only RF power illuminating the collecting antenna aperture of the intended recipient is useful.

Clearly, a maximum performance in terms of both interference reduction and bit error rate will be obtained if the individual beam footprints are of minimal size. A lower limit is established by overall attitude stability of the satellite, including any stable platform within it, to support the antennas. For the purpose of preliminary sizing, a 1-sigma stability value of 0.1 degree, and Gaussian error distribution statistics may be assumed, giving the following error expectation:

| Magnitude of single plane error (degrees) | 0.1 | 0.2 | 0.3 | 0.4 |
|---|---|---|---|---|
| Probability that value will be exceeded | 0.32 | 0.046 | 0.0027 | 0.00006 |

The importance of any specific angular value of antenna misalignment is a function of the antenna beam width. If the antenna is misaligned by half its 3 dB beam width value, then clearly the related communication link will experience a -3 dB signal loss. By combining the assumed stability statistics with a selected beam pattern, the statistics may be expressed in terms of link loss.

It is convenient to define the 3 dB beamwidth of the antenna in terms of the 1-sigma stability. In order to appreciate the physical and operational significance of the stability and beamwidth, it is advantageous to translate them into footprint diameters and linear offsets. From a synchronous orbit altitude the footprint offset caused by a 0.1 degree shift in boresight in a single plane (nadir condition) is approximately 40 miles.

Table 8-2 summarizes the expected performance for several values of beamwidth on the foregoing basis. The data presented in the table has been plotted parametrically in Figure 8-9 to provide loss versus probability curves for various rationalized values of beamwidth.

Thus far three important factors have been neglected: the increase in absolute antenna gain due to reduced beam width, the physical size and practicability of antennas having the orders of beamwidth examined, and the beam pointing implications. For a conventional parabolic dish reflector, the gain is generally inversely proportional to the square of the beam width. Since the performance of a communication link depends on the minimum signal-to-noise ratio (SNR) rather than the variation (providing the changes are of modest rate), the channel loss-probability of occurrence relationships of Figure 8-9 must be corrected by the gain advantage. The following gain values are anticipated for a 10 GHz parabolic dish:

| Desired beamwidth (degrees) | 0.1 | 0.2 | 0.3 | 0.4 | 0.6 |
|---|---|---|---|---|---|
| Required dish diameter (feet) | 68 | 34 | 23 | 17 | 11-1/2 |
| Expected gain (dB) | 64 | 58 | 54.6 | 52 | 48.6 |
| Increase in gain relative to 6-sigma case (dB) | +15.4 | +9.4 | +6.0 | +3.4 | REF |

Combining the above gain improvements the compensated loss statistics shown in Figure 8-10 are obtained. For a highly reliable system, it appears clear that a compromise on beamwidth (i.e., privacy) must be made to limit the downside risk. The 6-sigma situation will provide a system for which there is less than $10^{-4}$ probability of experiencing a link loss due to antenna misalignment of more than 6 dB. The associated antenna footprint would be under 250 miles in diameter.

Table 8-2. Effect of Antenna Misalignment

| Platform Misalignment (Degrees) | Footprint Shift (Miles) | Probability of Occurrence (Percent) | Anticipated Misalignment Loss Due to Antenna Off-Boresight (dB) | | | | |
|---|---|---|---|---|---|---|---|
| | | | BW = 1 | BW = 2 | BW = 3 | BW = 4 | BW = 6 |
| 0.1 | 38.6 | 32 | 16.8 | 3.0 | 1.6 | 0.8 | 0.4 |
| 0.15 | | 13.4 | - | 8.0 | 3.0 | 2.0 | 0.8 |
| 0.2 | 77 | 4.6 | - | 16.8 | 6.0 | 3.0 | 1.4 |
| 0.25 | | 1.24 | | 730 | 10.8 | 5.2 | 2.0 |
| 0.3 | 116 | 0.27 | - | - | 16.8 | 8.4 | 3.0 |
| 0.35 | | 0.04 | - | - | 30.0 | 12.0 | 4.4 |
| 0.4 | 154 | 0.006 | - | - | - | 16.8 | 6.4 |

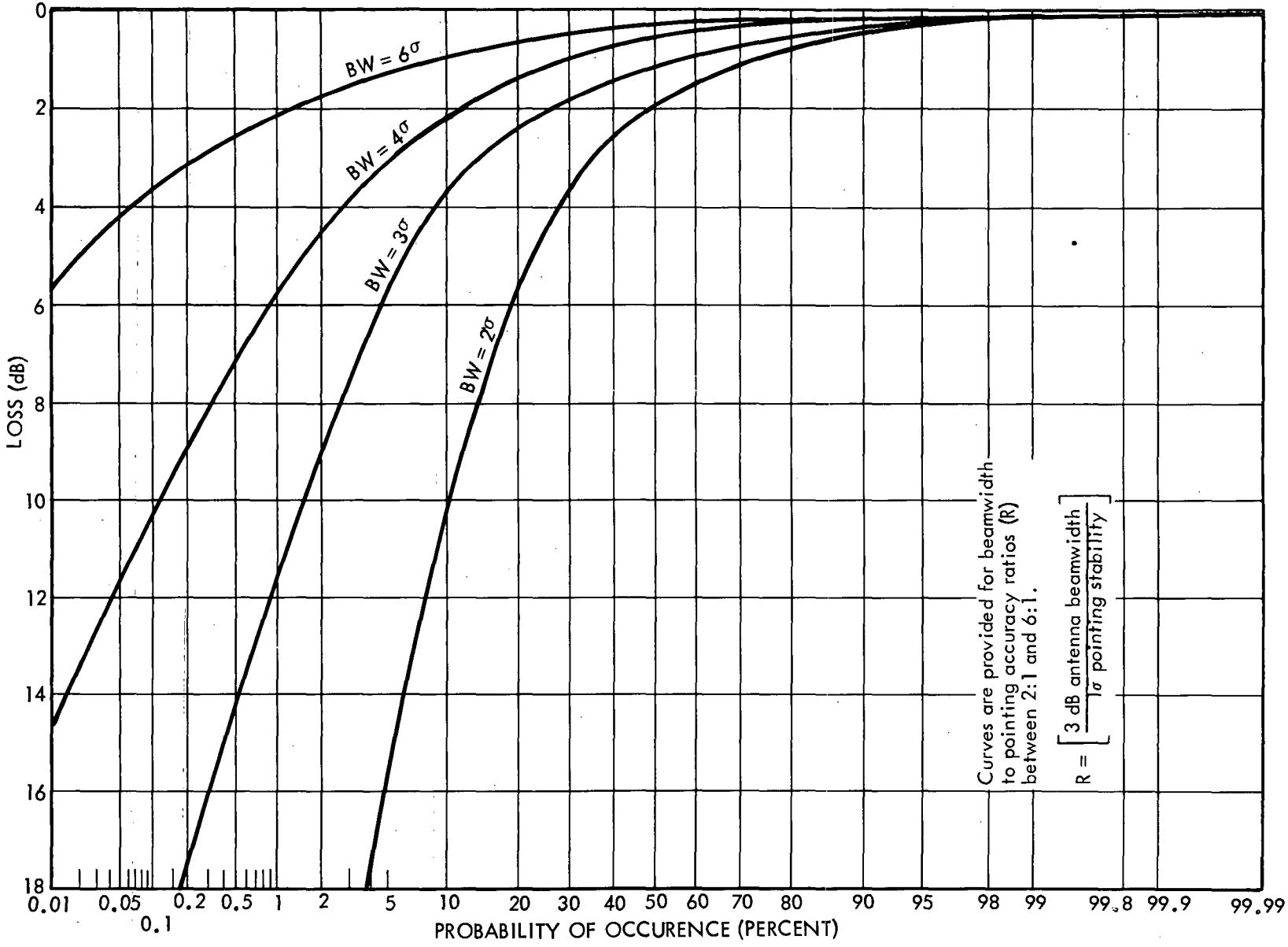



Figure 8-9. Signal Loss versus Probability of Occurrence

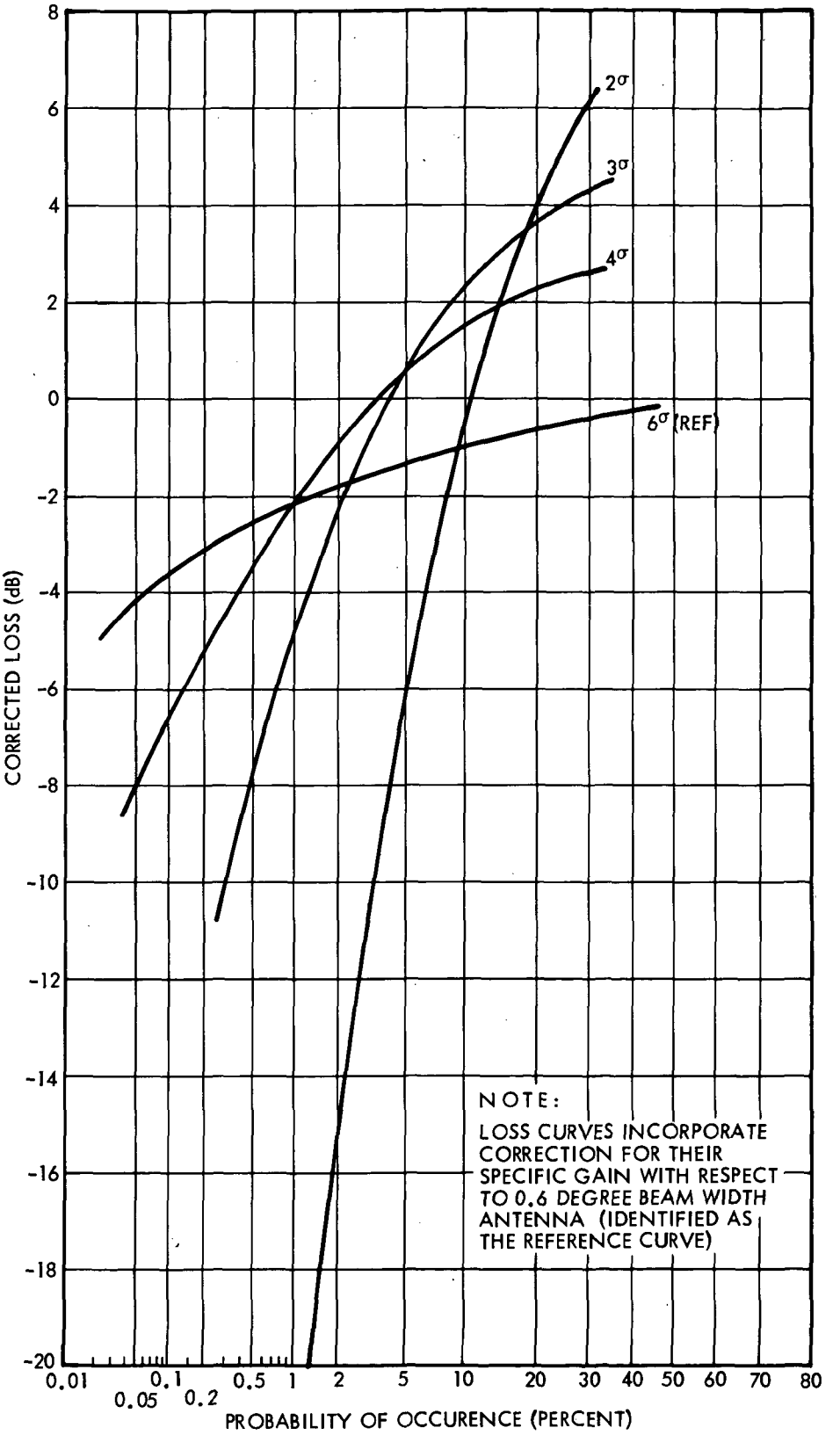



Figure 8-10. Corrected Signal Loss Versus Occurrence Statistics

8.4.9.1 Concept

For a multiple user service, the use of individual dedicated parabolic dish antennas, one for each channel, would drastically limit the overall satellite channel capacity.

A Luneburg lens with a fixed matrix of feeds would, in theory, provide the desired flexibility, but for the beamwidth values of interest (≈0.6 degrees) the required X-band waveguide feeds could not be accommodated on the available hemispherical surface. The alternative is a multichannel electronically steered array.

There are three basic approaches, namely,

a) Digital phase shifter type

b) Butler matrix array

c) Self-steering or adaptive type.

Recently there has been considerable work on these approaches (References 7, 8, 9, 10). Hughes Aircraft and Airborne Instruments Laboratory have built demonstration and engineering models under NASA contracts for application in the tracking and data relay satellite (TDRS). The results of these efforts are summarized in Table 8-3.

Although the use of such an array was found to be too expensive, heavy, power consuming, and sophisticated for the early TDRS operational needs, it nevertheless represents an important tool for improved spacecraft performance.

It is proposed that a Comm/Nav experiment be performed to evaluate these hardware developments in space by testing and refining an electronically steered array.

The key to successful application of these devices lies in the judicious integration of a highly versatile on-board signal processor with a large matrix array. The objective is to provide facilities for synthesizing a large number of independently steerable beams.

Table 8-3. Multichannel Electronically Steered Array Characteristics

| Parameter \ Contractor | Hughes Aircraft | Airborne Instruments Laboratory |
|---|---|---|
| Frequency | 7.3 GHz (receive)<br>8.0 GHz (transmit) | 2.2 - 2.3 GHz (receive)<br>1.76 - 1.85 GHz (transmit |
| Number of elements | 2 x 64 | 22 element model of final 336 |
| Total coverage cone | 30 degrees | 26 degrees |
| No. of Channels | 4 | 2 |
| Pointing method | CW pilot signals | |
| ERP | 27.8 dBw | 58 dBw |
| Total gain | 30 dB | 43 dB |
| Gain per element | 11.6 dB (min.) | 18 dB |
| RF bandwidth per Channel | 125 MHz | 10 MHz |
| Polarization | CP | RHCP |
| Noise figure | 15.2 dB (average) | 7 dB |
| Receiver power | 32 watts | - |
| Pilot Processor Power | 109 watts | - |
| Total power | 343 watts | - |
| Total weight | 180 Kg. | - |

### 8.4.10 Multiple Satellite Routing

The historic growth of terrestrial point-to-point communication has evolved from hardwire (telephone lines) through high frequency (HF) radio to microwave and now to satellites. The substitution of RF propagation for solid wires has provided much greater flexibility in overcoming natural (terrain and water) barriers. Although HF radio and microwave links have quite different advantages and limitations, feasible implementation methods were devised and were integrated with the other telephone facilities to provide a uniform service.

Thus far, communication satellites have only been used as single interchange with multiple user up and down links. It seems inevitable, by extrapolating the related developments in radio communication, that future satellite communication services will comprise a multiplicity of geostationary and orbiting vehicles, with associated mutual communication capability. Under these circumstances each satellite will assume the functions of a message routing center; if the destination of the received message is within its area of coverage, the signal will be transmitted accordingly. Otherwise it will be transferred to another satellite. The second satellite will in turn appraise the message on the same basis, until the message arrives at the designated ground point.

Although switching, routing, priority, and bookkeeping functions are well understood, and have been widely implemented for terrestrial telephone and teletype services, these features have not yet been transferred to space applications. Present communication satellites are controlled from supervisory ground terminals just as early telephone services were based on manual PBX operators. It is anticipated that just as these manual operators have been replaced by direct dialing and peripheral interconnections by customers (Carterphone ruling), so shall the ground stations relinquish their supervisory functions and satellite communications emerge as a user controlled service.

#### 8.4.10.1 Concept

It is proposed to design, assemble the appropriate hardware, and demonstrate in space, an operational message switching and routing scheme appropriate to a multi-satellite global communication service. The

general arrangement required in the switching satellite is illustrated in the accompanying block diagram, Figure 8-11.

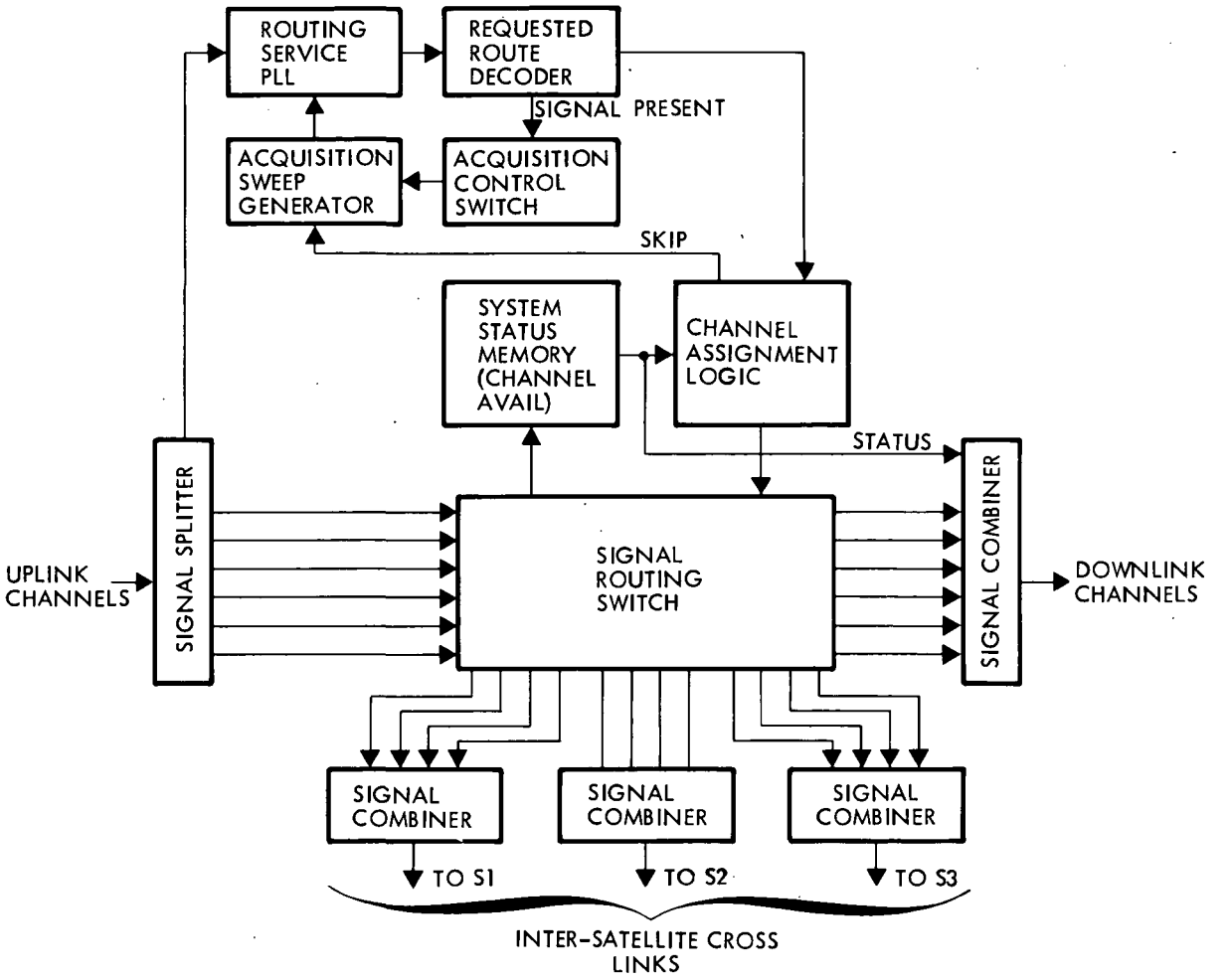



Figure 8-11. On-Board Processing for Multiple-Satellite Routing Facility

### 8.4.11 On-Demand Frequency Translation

Existing tactical communications satellites (the model for future civil satellite services oriented towards the small user) provide a communication connection between users operating in the same frequency region. There are a growing number of civil applications where it will be advantageous to permit cross-band communication. The most flexible concept would appear to involve providing a multi-band satellite RF capability with re-transmission of each individual message on a user selected frequency channel.

For example, a re-entering spacecraft could transmit to the satellite at X-band to minimize the plasma attenuation effects and prefix the message with a frequency command code that would result in re-transmission of the message data to the ground in the 216 MHz telemetry band.

This concept is related to that of selectable modulation, described in paragraph 8.4.2.

#### 8.4.11.1 Concept

Implementation will entail equipping a satellite with a group of channel frequency translators and the necessary control logic to recognize the appropriate user commands and bring the correct frequency translation into service. The complete uplink band cannot be translated because individual users will, for the most part, desire differing translation schemes. To accommodate the variety of needs, it is recommended that phase-lock loop modules be used to strip the modulation from a channel, with the output baseband data applied to an appropriate modulator. The carrier for the modulation process would be selected from the comb output of a common synthesizer. The channel commands (selected carrier frequency) would be held in a spacecraft memory unit until the transmission was completed to preclude two users selecting the same operating frequency.

The number of phase-lock loop and command decoder assemblies incorporated in any one satellite will depend on the expected rate of

command requests and permissible delay in executing orders. Since delay involves loss of message handling (traffic) revenue, it will be relatively easy to optimize the latter parameter.

The suggested functional configuration to accomplish the frequency translation is shown in Figure 8-12; a high degree of equipment commonality exists with the Doppler compensation concept described in paragraph 8.4.7.

### 8.4.12 Store and Forward

A common communication service requirement is provision for a defined delay between receipt of a message and delivery to the intended recipient. This is in contrast to the simultaneous mode. A second related characteristic is that such messages involve one way transmission rather than the bi-directional or duplex mode used in, for example, telephone practice.

From a spectrum occupany viewpoint, the store and forward (S&F) mode is quite attractive since it allows the satellite to retransmit the signal on the user's uplink frequency, using a narrow beam and/or polarization diversity without ring-around or multipath-like effects.

For a satellite that also incorporates multiple beams or a steerable antenna, the S&F mode is particularly attractive because it permits the messages to be segregated into destination-related groups and transmitted in these groups. This minimizes beam manipulation and the associated spacecraft power penalties and avoids the communication time loss while slewing the antenna.

#### 8.4.12.1 Concept

The spacecraft would incorporate a command decoder designed to recognize the user preamble code for the S&F service. Recognition would result in transmission of a command acknowledge code to the user advising him that he is "connected". Within the spacecraft, the S&F code would allocate a recorder channel of the on-board magnetic tape recorder, and load the received message.

The user's preamble would include the following information elements:

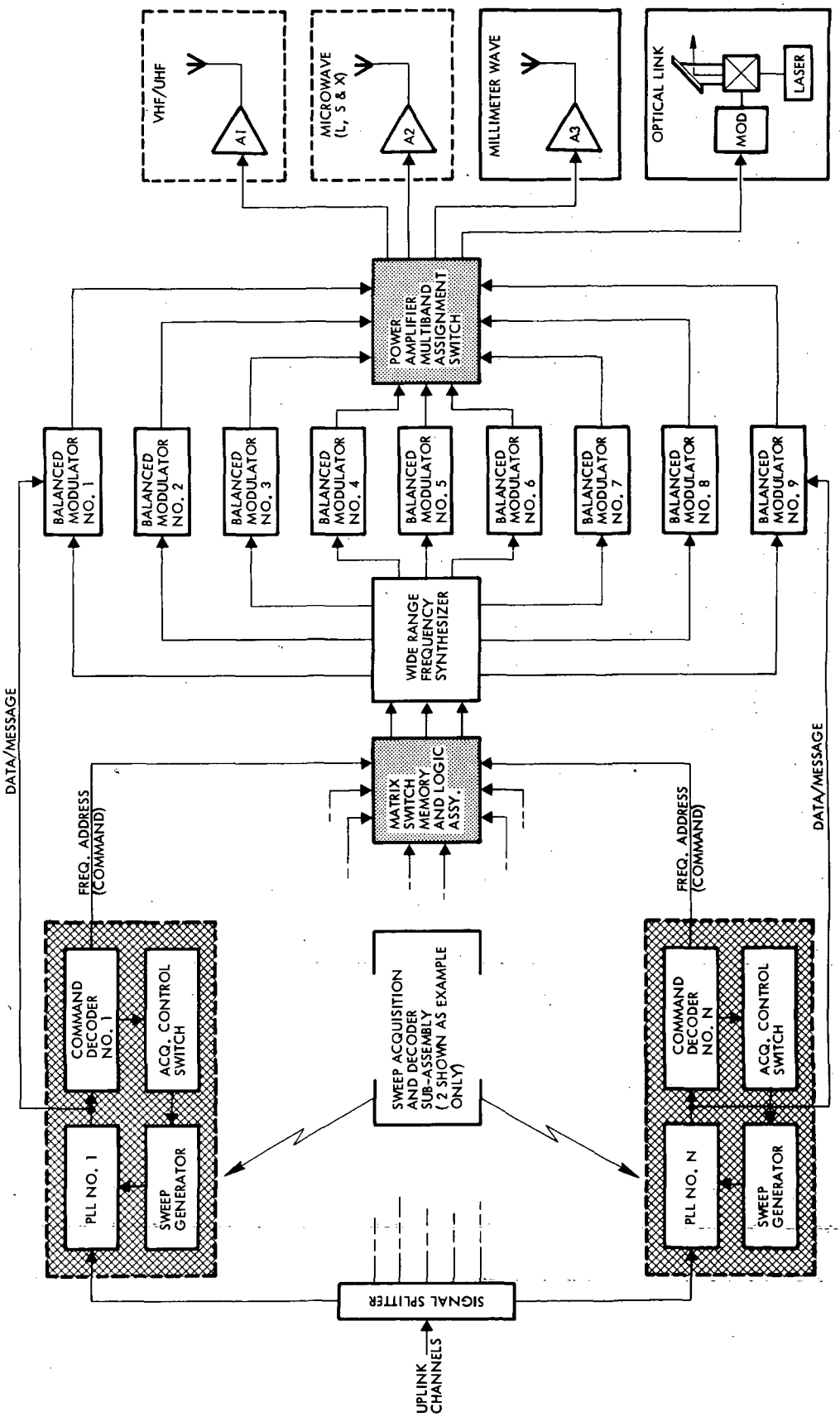



Figure 8-12. On-Demand Frequency Translation – Functional Block Diagram

- Sender identification
- Addressee's identification
- Requested delivery time.

Optional features that could be provided on an adjusted cost schedule basis include:

- Immediate replay, on demand, for sender to check message
- Hard copy to sender via satellite control ground station (FAX)
- On-board processing for coding, frequency or modulation changes, replication, and similar features described in Sections 8.4.1 - 8.4.11)
- Routing via a language translation ground facility
- Service cost estimate to sender prior to execution
- Text delete or modify option, up to (TBD) time before execution.

## 8.5 COMMONALITY

It is beneficial to examine the commonality which may be expected for the special on-board hardware needed to implement the various signal processing techniques described in Sections 8.4.1 through 8.4.12. The matrix in Table 8-4 summarizes this evaluation. It will be immediately apparent that the phase-lock loop signal processor is the most widely shared system element, followed by multipurpose modulators.

This preliminary commonality analysis is a secondary factor which must not be allowed to override the cost/benefit potential of each proposed service extension. Commonality should be used to optimize the mix of features selected for the baseline payload.

Table 8-4. Major Hardware Commonality

| Major Items of Spacecraft Hardware Needed for Implementation ↓ / On-Board Processing Feature → | Adaptive Channel Interconnection & Analysis | Selectable Re-Modulation | Optional Redundant Transmission | Adaptive ERP Control | Movable Notch Filter | Frequency Diversity and Voting | Doppler Compensation & Position Location | Spread Spectrum Translation | Spatial Beam Tracking | Multiple Satellite Network Control | On-Demand Frequency Translation | Store & Forward |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Bank of Modems with Control Logic | X | | | | | | | | | | | |
| Mag Tape Recorder | X | | X | | | | | | | | | X |
| Spectrum Analyzer | X | | | | | | | | | | | |
| Phase Lock Loop Signal Processors | | FEW | FEW | | FEW | | X | | X | X | | X |
| Multipurpose Modulator | | X | | ALL | | | | X | | X | | |
| Common Service Channel | X | | | | | X | | | | | | |
| On-Board Mini-Computer, Large Memory or Similar | | | | | | | X | | X | | | |
| Frequency Synthesizer | | | | | | | X | | | | | |
| Multi-Element Array | | | | | | | | | X | | | |
| Solid-State Switching Matrix | | | | | | | | | | X | X | |
| Multi-Band RF Equipment (Receive and Transmit) | | | | | | | | | | X | FEW | |
| Multiple Antennas | | | | | | | | | | X | X | |

## 8.6 ACKNOWLEDGEMENTS

### 8.6.1 Related Experiments

| Experiment | Principal Investigator and Association |
|---|---|
| 1. On-Board Processing | D. Spencer, TRW Systems |
| 2. Processing Repeater Applications | D. Spencer, TRW Systems |
| 3. Bandwidth Reduction and Error Control Coding | D. Spencer, TRW Systems |

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2. Amplitude and Phase Estimator (APEX), Patent Disclosure R. Y. Huang and E. Develet.

3. "Threshold Extension Technique," Patent Disclosure, M. Huang et al.

4. "Combine Filter and Phase Lock Loop Filter, A New Technique to Improve Television Reception," F. N. Stuber and M. Y. Huang, TR-7322.03-40, NASA Contract No. NAS9-10204, May 1970.

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# EXPERIMENT 9

# LASER COMMUNICATIONS

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APPENDIX A

# 9. LASER COMMUNICATIONS

## 9.1 EXPERIMENT CLASSIFICATION

This experiment will provide operational testing of a range of equipment and concepts for optical frequency communication. The unique advantages of a manned space laboratory will allow a substantial quantity of data to be obtained quickly and reliably. The data from these experiments will allow a substantial quantity of data to be obtained quickly and reliably. The data from these experiments will advance knowledge of the problems in, and device parameters for, optical communication equipment operating in a space environment.

## 9.2 EXPERIMENT OBJECTIVES

The purpose of this experiment is to refine and extend the knowledge and range of data associated with the use of lasers in space communications applications. Missions encompassed are space-to-ground, space-to-space, and space-to-airborne relay platform. Wavelengths encompassed by this experiment range from 0.53 to 10.6 microns. Goals of the experiment include the following:

a) To determine practical accuracy limitations for pointing and tracking subsystems

b) To measure transponder performance parameters under operational conditions, for various wavelength systems

c) To evaluate relative performance and reliability of competing techniques and equipment

d) To determine propagation characteristics of laser systems in free space and in the presence of atmosphere

e) To evaluate new components in a complete integrated system

f) To obtain and improve design criteria for future laser communication systems.

## 9.3 DISCIPLINE BACKGROUND AND CURRENT STATUS

Over the past few decades, the utilization of radio frequency electromagnetic propagation as a means of communication has very rapidly expanded. As this spectrum (100 kHz to approximately 30 GHz) becomes fully utilized, allocation of new bands has become increasingly difficult,

and consequently, new bands within the total electromagnetic spectrum must be developed.

Since the permissible modulation bandwidth (or data rate in the case of digital signals) is proportional to the carrier frequency, optical carriers would allow wider bandwidths than carriers within the normal radio spectrum. Further, the physical transmitting and receiving apertures required to give extremely narrow beams (and therefore the high-energy densities at the receiver of a point-to-point communications system) for an optical communications system are much smaller than the physical aperture of even a millimeter wave system. Consequently, a logical place for extending the communications spectrum is into the optical region.

Disadvantages of the optical spectrum as a communications medium lie in the high-energy absorption and scattering of the beam by particles of atomic size and larger. Variations in the index of refraction over the propagation path resulting from variations in atmospheric temperature, pressure, and density will cause beam bending, making acquisition and observation between the transmitter and the receiver extremely difficult. Random variations in temperature, pressure, and density will distort the transmitted wavefront and result in signal fading and distortion. This means that optical communication for point-to-point contact over the surface of the earth is virtually impossible except over short distances. Reliable communication at optical frequencies between two points on the earth's surface requires the use of optical wave guides connecting the transmitter and the receiver.

In spacecraft-to-spacecraft communications, the problems of absorption, scattering, phase distortion, and beam bending are negligible because of the absence of any significant atmosphere. If two satellites are moving with a relatively high velocity with respect to one another, a Doppler frequency shift proportional to the product of the carrier frequency and the relative velocity will occur; this constitutes a major technical problem for optical heterodyne systems (notably $CO_2$ wavelength) for use in links between satellites in dissimilar orbits.

Optical communication links operating at data rates of up to 1 gigabit per second and higher have been demonstrated under laboratory conditions

and over relatively short optical path lengths. Systems currently under development include the following types:

a) Mode locked, with extra-cavity pulse gating or polarization modulation (1.06$\mu$ or 0.53$\mu$)

b) CW lasing with FM subcarrier (1.06$\mu$ or 0.53$\mu$)

c) Intercavity polarization modulation (1.06$\mu$ or 0.53$\mu$)

d) Optical heterodyne detection systems (10.6$\mu$).

Technical problems which are currently being addressed include the following key areas:

a) Maximizing laser efficiency

b) Increasing the efficiency of frequency doubling of 1.06 micron energy

c) Development of modular drivers capable of achieving high modulation depth at high data rates

d) Development of very stable and/or tunable lasers

e) Laser cooling in a vacuum environment

f) Extending the lifetime of lamps for laser pumping

g) Developing techniques for simultaneous mode locking and frequency doubling for Nd:YAG lasers

h) Development of improved detectors for 1.06 micron energy

i) Development of faster modulators and detectors (mixers) for $CO_2$ lasers

j) Development of narrowband optical filters

k) Development of precision pointing and tracking systems and components.

The optical frequency demonstration experiment provides for operational testing/demonstration of equipment now under development. This testing will facilitate the application of optical communications to future needs of the nation.

## 9.4 EXPERIMENT DESCRIPTION

The basic functional configuration for this experiment is illustrated in Figure 9-1. It consists of a pair of transponder units, each having a laser transmitter, receiver, and tracker. One or both ends of the link may include an optical beacon to facilitate pointing acquisition.

Figure 9-2 illustrates several possible geometrical configurations the experiment may employ. For each case, executing an acquisition sequence to establish a two-way communication link is an essential first step. After link acquisition, high data rate transmission may be initiated.

Descriptions of the three experimental links are given below:

a) LEO to Ground. The low earth orbit (LEO) laboratory to ground station geometry is the easiest to implement and facilitates instrumentation capabilities. This link appears to be a logical first step of the experiment. The relatively short distance between the orbiting laboratory and ground station will enhance signal levels and relax requirements for transmitter power and receiver sensitivity; such relaxation appears to be desirable for the initial portions of the experiment. The LEO to ground station geometry provides an opportunity to observe atmospheric effects and statistics over a wide range of inclination angles.

b) LEO to Airborne Platform. In this configuration a balloon or aircraft is used for one of the terminal platforms. This arrangement simulates one of the operational system configurations, which utilizes an airborne platform with an RF relay to ground to avoid communication outages due to cloud cover. This experiment permits measurement of acquisition and tracking parameters with a different atmospheric path than that of Configuration A.

c) LEO to Synchronous Satellite. This experiment provides direct measurement of a satellite-to-satellite pointing and tracking system. Although it is the most difficult of the three configurations to implement, it uniquely provides a realistic and quantitative simulation of the propagation effects, background levels, distances, platform rates, disturbances, and spacecraft velocities encountered in a LEO to synchronous satellite communication link.

Three laser wavelengths are presently strong candidates for investigation: 10.6 microns, 1.06 microns, and 0.53 micron. The transponders

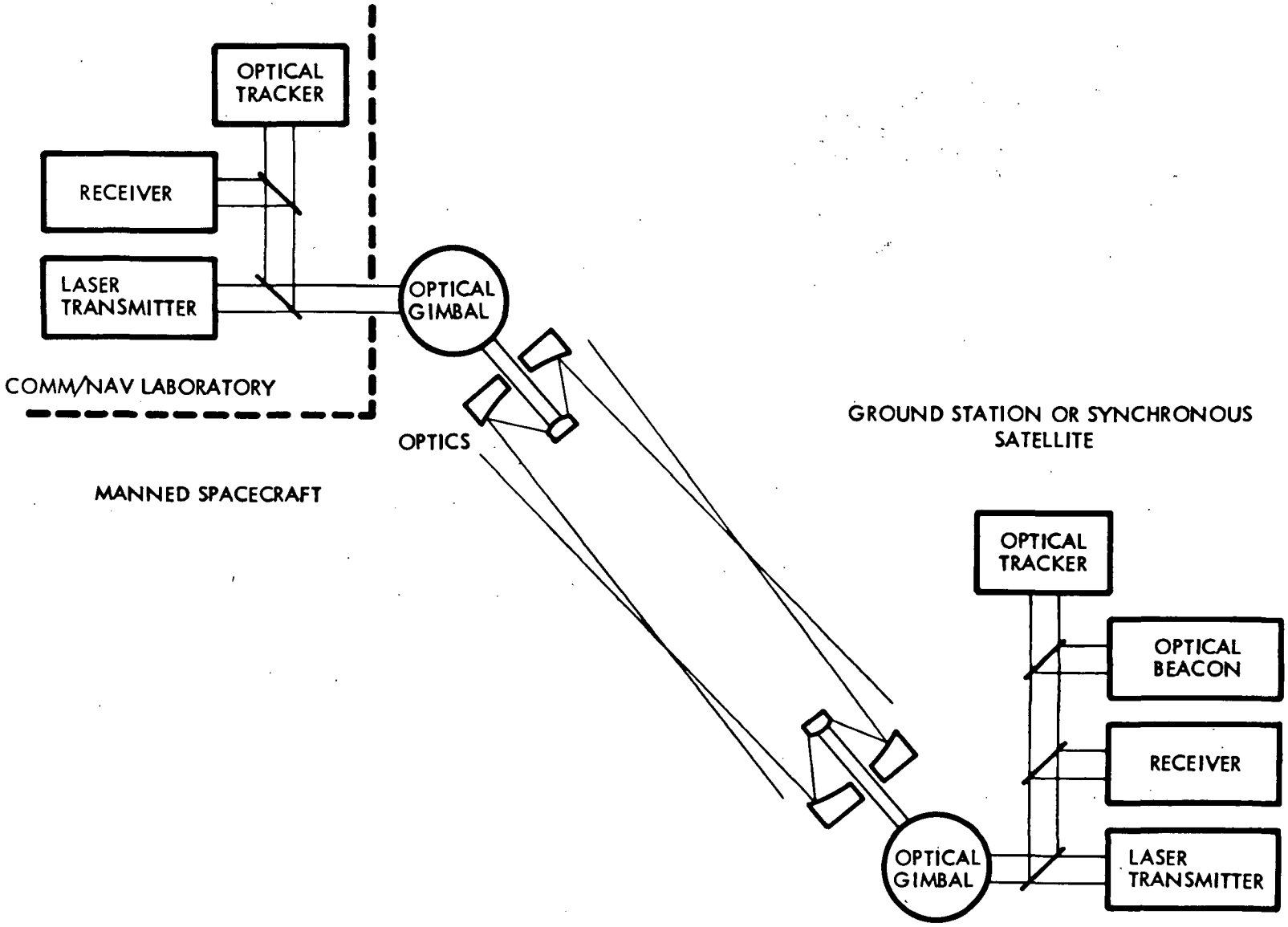


Figure 9-1. Laser Communication Experiment – Simplified Block Diagram

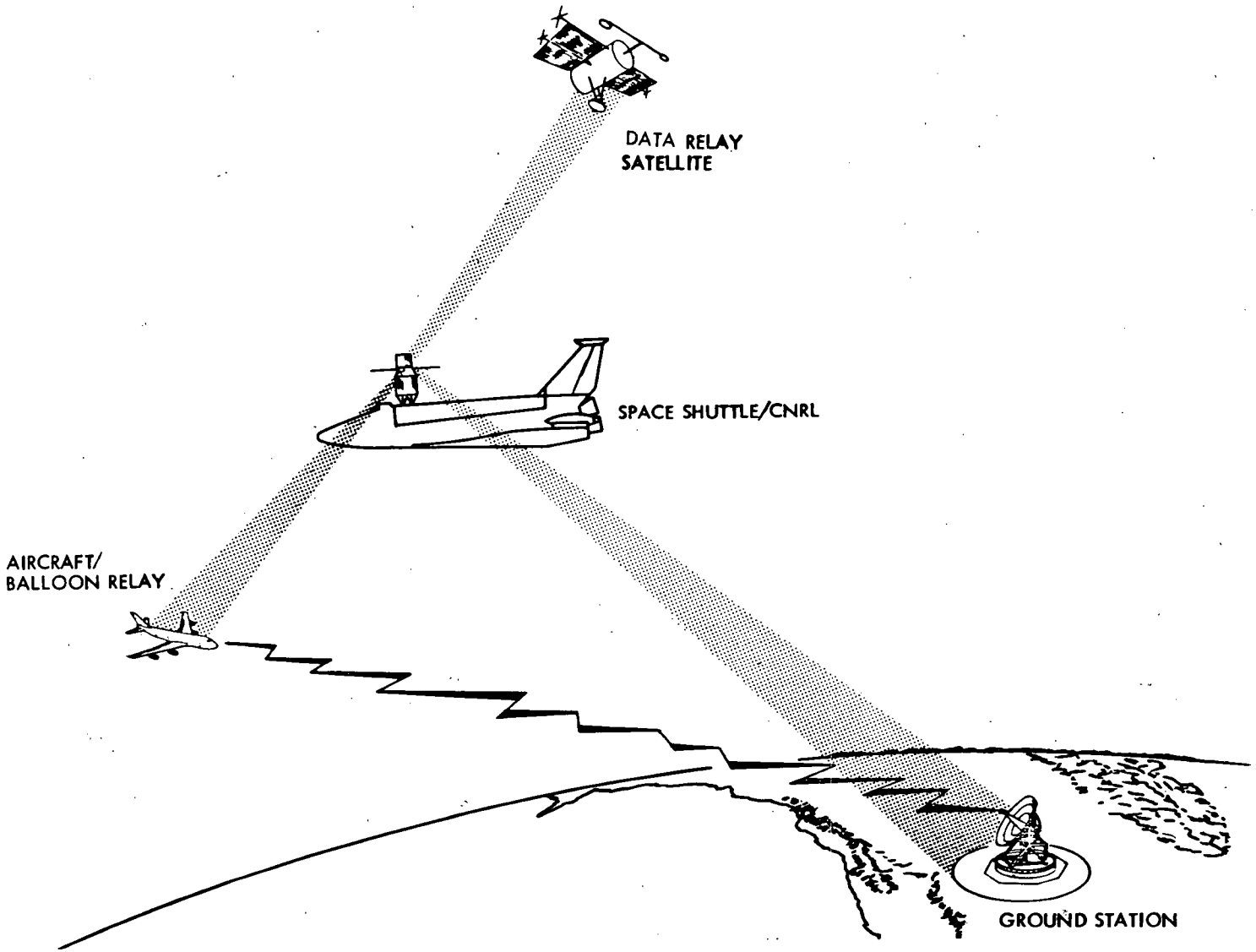


Figure 9-2. Geometry for Laser Communication Experiments

can be adaptable to these wavelengths by means of configuration changes in the optical and electronic components. A simplified block diagram is shown in Figure 9-3 for a $CO_2$ system and a Nd:YAG system. Appendix A presents a detailed description of the experiment equipment; a brief summary description of the experiment equipment is given below:

a) Optical Telescope. A reflective cassegrain telescope is recommended to provide independence of wavelength for the gimballed optics.

b) Gimbals. The gimbals provide an angular transfer system which couples a fixed input axis to that of the cassegrain telescope. Alternate gimbal concepts may also be considered. The concept shown in Figure 9-3 has the advantage that most of the system components may be located inside the laboratory compartment of the spacecraft, providing the capability to replace various components to permit experiments at different wavelengths. The telescope has a pointing coverage somewhat less than a hemisphere. Mirrors M1 through M4 rotate as a unit about the Z-axis. Mirror M4 and the telescope optics are rigidly coupled and have additional freedom of rotation about the X-axis.

c) Trackers. The fine tracker provides accurate tracking of an optical beacon at the opposite terminal and provides control signals to the telescope gimbals and vernier beam deflector. The coarse tracker provides initial acquisition tracking of the opposing terminal.

d) Beam Deflectors. Several beam deflectors are shown in Figure 9-3. One type provides a vernier pointing control with faster response and greater precision than the main optics gimbals. The other type provides a small offset pointing capability between the tracker axis and the transmitter axis. All beam deflectors have two-axis deflection capability.

e) Laser Beacon. The laser beacon provides an independent emitting source for tracking by the opposing terminal. If the laser transmitter is a suitable source, it may be possible to eliminate the need for a separate optical beacon.

f) Viewing Optics. A telescopic eyepiece may be provided in the short wavelength optics train to permit visual or television sighting along the optical axis. This will facilitate experimental procedures and data interpretation by the astronauts. A photographic camera may also be provided for recording purposes.

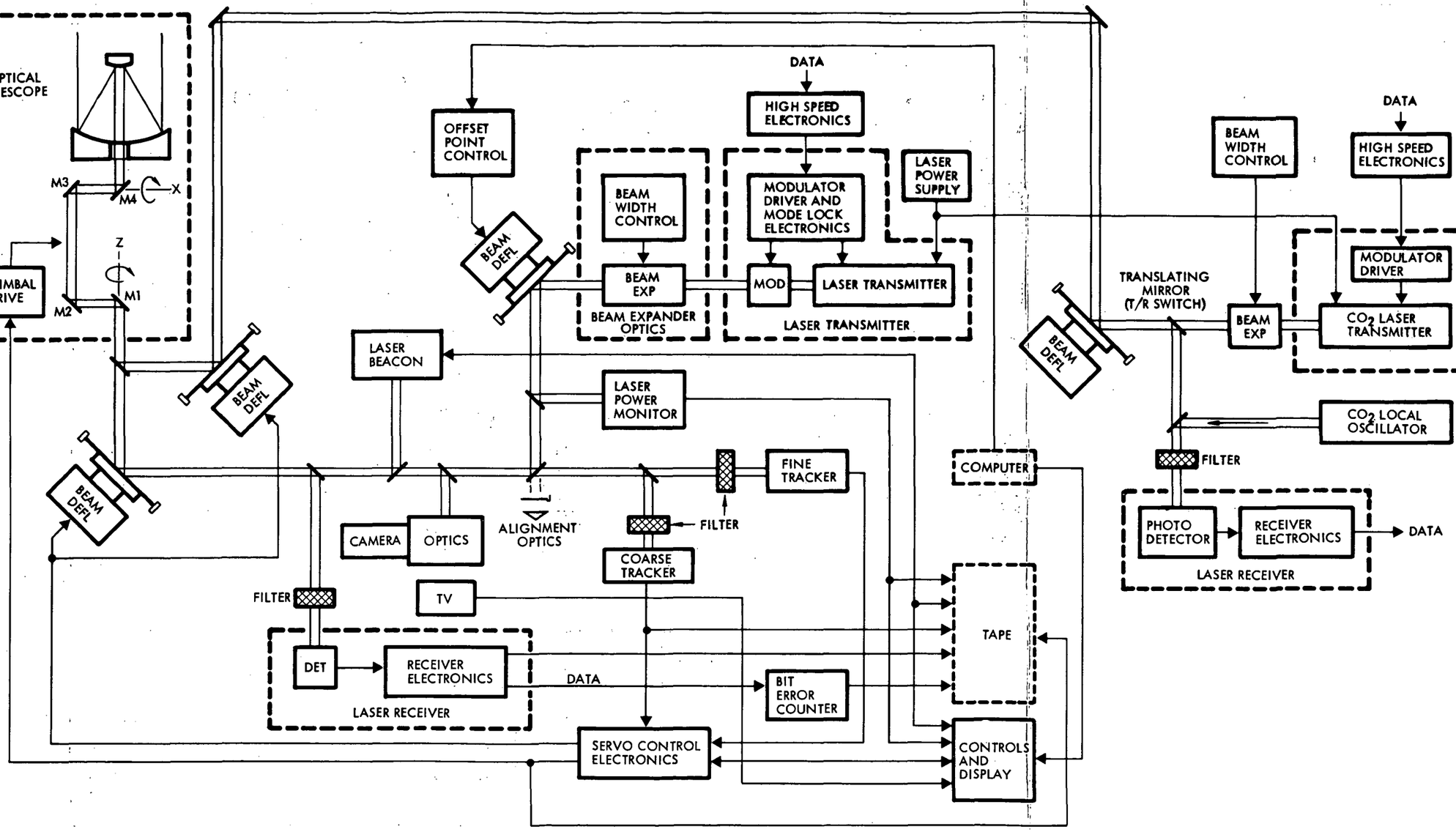


Figure 9-3. Laser Experiment — Functional Block Diagram

g) Servo Controls and Gimbal Drive. These control system components are common to experiments at any wavelength.

h) Laser Transmitter and Optics. The type of laser transmitter will vary with the wavelength of investigation. For the Neodymium wavelengths (1.06 and 0.53 micron), provisions for mode locking should be provided to permit investigation of subnanosecond pulse propagation characteristics. Non-mode locked operation with polarization modulation should also be provided. The laser transmitters should include optics for beam width control and provisions for spatially scanning the beam over a small angular range.

i) Laser Receiver. The chief function of the photo-detector is the detection of optical signals from the opposing transponder. However, it should also provide a capability to measure optical background levels within the receiver spectral band and field of view. It is not appropriate to designate the selection of detectors for each wavelength at this time.

The 10.6 micron ($CO_2$) system functions as a transmitter or as a receiver, but not simultaneously. The $CO_2$ transponder may utilize a modulated beacon or an RF transmitter for low data rate communication in the opposite direction. The Nd:YAG transponder transmits at 1.06 microns and simultaneously receives at 0.53 micron, or the converse, using dichroic beamsplitters and narrowband optical filters for wavelength separation and isolation.

The design goal of the equipment is to utilize common main optics, gimbals, optical beacons, and pointing/tracking system components for experiments at all three wavelengths. Configuration changes to permit operation at the various wavelengths of investigation will be performed with the participation of the astronaut experimenters.

Acquisition and tracking are considered to be particularly difficult and important problems for this experiment, due to the utilization of narrow beams and highly directional receivers. Moreover, the complexity of laboratory simulation of the on-orbit pointing and tracking problems emphasizes the value of experimental investigation. It is recommended that first priority be given to acquisition and tracking measurements in the planning of this experiment.

## 9.5 EXPERIMENT OBSERVATION/MEASUREMENT PROGRAM

Observation and measurement objectives for this experiment include the following:

1. Acquisition and Tracking Parameters

   a) Evaluation of the effectiveness and reliability of various acquisition and lock-on techniques in the presence of realistic signal and background levels, scintillation, platform rates, platform vibrations, velocity effects (Doppler shift and "point ahead" angle), and control system dynamics

   b) Evaluation of candidate beacon sources for acquisition and tracking

   c) Measurement of absolute pointing accuracy during fine tracking operation

   d) Measurement of offset pointing accuracy (point ahead compensation)

   e) Measurement of sensitivity thresholds for acquisition and fine tracking

   f) Measurement of atmospheric effects on tracking accuracy

   f) Evaluation of "closed loop" pointing, in which a pointing dither is used to generate correction signals at the receiver terminal. (The correction signals are transmitted back to the transmitter terminal on a return command link.)

   h) Measurement of boresight accuracy and stability between the tracker and transmitter

   i) Evaluation of the effects of various backgrounds upon acquisition and tracking

   j) Measurement or orbital limits for acquisition and tracking.

2. Propagation Parameters

   a) Atmospheric attenuation properties

   b) Scintillation phenomena associated with atmospheric inhomogeneities

   c) Far field beam pattern characteristics, with and without atmospheric effects

d) Dispersion of short mode locked laser pulses

e) Spatial coherence of received energy

f) Depolarization and possible phase or frequency shifting due to atmospheric effects

g) Reciprocity characteristics of the transmission channel.

3. Transponder Subsystem Parameters

a) Measurement of system signal and noise power in the presence of scintillation effects, propagation effects, and beam nonuniformities

b) Measurement of bit error rates under operational conditions and with various background cases

c) Evaluation of lock-on and tracking performance for the integrated transponder subsystem

d) Evaluation of effects of optical tolerances and distortions upon transponder performance

e) Comparative evaluation of various modulation types and formats

f) Evaluation of Doppler frequency tracking system.

g) Evaluation of various system components

These measurement objectives will be achieved by means of the following types of observation and data recording:

1. Recording of received signal strength as a function of time at each end of the link

2. Recording of tracker error signal time history for each tracker

3. Programmed beam scanning in a known pattern during portions of the experimentation while monitoring received signal strength

4. Recording of demodulated bit streams for bit error analysis

5. Systematic reduction of beacon power to determine threshold levels for acquisition and for tracking lock-on

6. Systematic reduction of transmitter power while monitoring bit error rate at the opposite terminal

7. Recording of background brightness levels (DC detector signals) while maintaining a photographic record of telescope field of view

8. Maintaining ground station records of spacecraft ephemeris data

9. Performing vernier adjustments of the main optics while observing image quality of a star source

10. Substitution of competing components and techniques, with repetition of parameter measurements

11. Performing stepwise variation of beam width while monitoring signal strength at the receiver

12. Variation of tracking system bandwidth while monitoring tracker error signals

13. Observation of bit error rates in the presence of various weather background conditions

14. Post-flight data reduction to separate and analyze parameters to be determined (e.g., separation of pointing error effects from attenuation effects).

In general, a search and acquisition sequence is performed to establish a two-way optical communication link. Usually, different wavelengths are used for the two directions. Following lock-on, when the beam widths have been narrowed to simulate conditions for wideband data transmission, the received signal strength is measured at each link terminal. The beams are scanned to permit measurement of intensity variations in the far field pattern. Error signals from the tracking systems are recorded to permit post flight extraction of pointing effects from propagation effects. Similarly, the transmitted power and equipment diagnostic signals are recorded for post-flight data analysis.

A preliminary summary of measurement parameters is presented in Table 9-1. These parameters will be stored on magnetic tape for later transmission to a ground station and/or post flight analysis. The time base of measurements should be accurately maintained to permit post-flight analysis of system performance.

Except for the bit error rate measurement and gimbal angle measurements, the raw data will be analog rather than digital. The total measurement period between ground station transmissions has not yet been

Table 9-1. Typical Measurement Parameters

| | Measuring Accuracy | Sampling Rate or Data Bandwidth | Dynamic Range | Number of Channels |
|---|---|---|---|---|
| 1. Receiver signal strength | 5% | 1 KHz | 200:1 | 1 |
| 2. Transmitter power | 5% | 10 Hz | 3:1 | 1 |
| 3. Tracker error signal | 1 arc sec | 20 Hz | $\pm$50 arc sec | 2 or 4 |
| 4. Beam deflector angles | 1 arc sec | 200 Hz | $\pm$50 arc sec | 2 |
| 5. Beacon output power | 5% | 5 Hz | 10:1 | 1 |
| 6. Tracker signal power | 10% | 100 Hz | 200:1 | 1 or 2 |
| 7. Transmitter beamwidth | Discrete | 1 Hz | NA | 1 |
| 8. Spacecraft attitude data | $0.5^{\circ}$ | 1 Hz | $260^{\circ}$/axis | 3 |
| 9. Telescope gimbal angles | $0.1^{\circ}$ | 10 Hz | $180^{\circ}$/axis | 2 |
| 10. Laser head temperature | TBD | 0.1 Hz | TBD | 1 |
| 11. Background brightness (1 or 2 discrete wavelengths) | 10% | 10 Hz | 100:1 | 1 |
| 12. Receiver Bit Error Rate | 10% | 10 samp/sec. | $10^{-2}$-$10^{-7}$ | 1 |

determined; twenty minutes is a preliminary estimate. For purposes of estimating data storage requirements, twenty minutes is approximately the total measurement period between ground station transmissions.

On-board computing will probably be utilized for coarse pointing of gimballed telescope. It will be necessary to compute gimbal angles for pointing toward the opposing communications terminal, based upon laboratory ephemeris and attitude reference data. The "point ahead" angle may also be computed on-board; alternatively this data could be computed on the ground and furnished to the satellite as stored commands.

Special ground stations are required for experiments involving satellite-to-ground links. For the case of a low earth orbit satellite to ground link, several ground stations are desirable to provide greater daily station contact time and a greater sampling of weather conditions. Ground station locations should provide appropriate visibility conditions for propagation measurements. In general, special orbits are not required for satellite-to-ground link measurements. It is possible, however, that special orbits might be used to facilitate use of existing or desirable ground station sites and to increase station contact time.

The beam coverage of the satellite laser transmitter is extremely small, in the range of one arc second to one arc minute depending upon the wavelength and the experiment design. However, the beam may be pointed over a wider search field. Typically, a low orbit satellite would provide a pointing capability of $\pm 45$ degrees in roll and $\pm 80$ degrees in pitch, centered about the local vertical direction.

The daily experiment operating time requirement of optical propagation experiments is approximately 10 to 15 minutes. For a low orbit satellite-to-ground station link, this running time necessitates the use of several ground stations to provide the desired station contact time.

## 9.6 INTERFACE, SUPPORT AND PERFORMANCE REQUIREMENTS

### 9.6.1 Environmental Requirements

In the present experiment concept, most of the equipment will be inside the pressurized compartment of the spacecraft. This compartment provides much better environmental control than that necessary for equipment operation. Telescope optics and gimbals will be external to the

compartment, and must be designed to operate in vacuum and over a relatively wide temperature range. These components must also resist degradation due to atmospheric exposure before launch. Reasonable control of the atmosphere in contact with the optical surfaces and coatings should be provided. Preliminary analysis indicates that the exterior components of the experiment will not require active heating or special thermal control of the interfacing structure. All components of the system must, of course, be capable of surviving the launch acceleration and vibration. The optical components which must maintain critical alignments should be mounted in a fashion which precludes mechanical resonances and high transmissability factors.

### 9.6.2 Operational Requirements

The operational requirements for this experiment are relatively straightforward, since considerable automation of data gathering is anticipated. For the low orbit satellite to ground link, experiment operating times are dictated by ground station access times. The time and pointing angles for link acquisition, on the spacecraft and on the ground, must be computed from the laboratory ephemeris data. Link acquisition will be automatic, and experimental procedures will be preprogrammed subject to selected operator controls. Prior to link acquisition, the host spacecraft must be properly oriented to provide ground station viewing during the orbital pass, and the telescope must be slewed to the precomputed direction of initial contact.

### 9.6.3 Electrical Interface

Approximately 450 watts of prime power will be required during experiment operation, most of which is required for the on-board laser transmitter. Stringent voltage regulation is not required since power converters and regulators will be incorporated, as required, in the experiment components. This power budget is predicated upon laser transmitter power levels of 0.1 watt, 1.0 watt, and 5 watts for the respective wavelengths of 0.53 micron, 1.06 microns, and 10.6 microns. These transmitter power levels are suitable for any of the candidate link geometries.

### 9.6.4 Pointing Requirements

Link acquisition in the brief available time for acquisition requires accurate initial pointing with respect to inertial references. Reasonable goals for inertial pointing accuracy are:

| | |
|---|---|
| Low Orbit Satellite Telescope | $\pm$0.5 degrees |
| Ground Station Telescope | $\pm$1 arc minute |
| Cooperative Synchronous Satellite | $\pm$0.1 degrees |

The optical frequency demonstration experiment requires the availability of an equipment location having an unobstructed field of view. The precision pointing of very narrow beams will require that platform vibrations and shocks be kept at a low level during experiment operation in order to minimize jitter; therefore, spacecraft thruster operations may disrupt the experiment.

### 9.6.5 Ground Facility Requirements

Ground facilities must provide the following instrumentation and support functions:

a) A transponder system of the type illustrated in Figure 9-1

b) Instrumentation to measure and record the parameters listed in Table 9-1

c) Instrumentation to measure spatial coherence of received energy and the width of received mode locked laser pulses

d) Computing capabilities to establish link acquisition and ground station handover data

e) Data processing and display equipment to permit real time monitoring and control of the experiment

f) Data processing equipment and software to process recorded data and spacecraft telemetry data between orbital passes

g) Voice communication link to the spacecraft.

### 9.6.6 Other Support Facilities

For the case of satellite-to-satellite link experiments, or satellite-to-high altitude platform experiments, a dedicated laser transponder is

required for the opposing link terminal. In general, this transponder will resemble that of the orbiting laboratory except that less flexibility is required. A single wavelength transmitter and/or receiver would be provided for the experiment, with relatively little instrumentation. Computing functions and mission control would, of course, be provided by ground based tracking stations.

## 9.7 POTENTIAL ROLE OF MAN

Considerable analysis will be required to optimize the balance between automated/programmed functions and those which will be performed manually. Typical functions that might be performed by crew personnel are:

a) Physical configuration changes to prepare for experiment variations (e.g., replacement of various experiment components to permit operation at a different wavelength)

b) Electrical switching and cable connection

c) Monitoring of oscilloscopes and other displays to provide voice link information to mission control

d) Equipment functional verification prior to initiation of experimental procedures

e) Diagnostic testing and component replacement in the event of a malfunction

f) Obtaining data from other sensors for correlation with experimental results.

Skills required for personnel monitoring or controlling the experiment are principally those associated with interpreting displays and performing appropriate control functions. Some familiarity with optical alignment methods will be helpful. Special training may be needed to insure personnel safety, although it would be preferable to preclude safety hazards in the design of equipment components.

## 9.8 EXPERIMENT EVOLUTION

The evolutionary growth of this experiment is developed below according to the applicability of each of three laboratory configurations.

Early Laboratory. Low orbit satellite-to-ground link will be employed for investigation of atmospheric propagation effects. May be restricted to direct detection systems to avoid Doppler shift problems associated with heterodyne receivers.

Growth Laboratory. This phase will include operations between the low orbit laboratory and an airborne relay platform. A cooperative synchronous satellite is desirable for this phase to examine free space propagation effects. Pointing and tracking capabilities should be upgraded to accommodate the narrow beamwidth requirements of a satellite-to-satellite link.

Total Laboratory. The third and final phase should provide the flexibility to operate with all of the link geometries of interest and with any of the candidate wavelength systems. In addition, the on-board instrumentation should be significantly more sophisticated than that of the earlier labs. In the Total Laboratory, it appears that experiments in the Optical Frequency Propagation Class would be performed as part of the Laser Communications experiments. Thus, equipment design for the Total Laboratory will be dictated primarily by optical link demonstration requirements.

Technological progress will, of course, play a major role in determining experiment evolution. Key problems which may impact experiment emphasis are:

a) Doppler Shift Compensation. The development of techniques to compensate large Doppler shifts would shift experiment emphasis toward heterodyne detection systems.

b) Pointing and Tracking. Improvements in pointing and tracking technology would tend to shift emphasis toward shorter wavelength systems which are capable of achieving very narrow beams with small apertures.

c) Detector Technology. Development of high efficiency infrared detectors with high internal gain would tend to decrease interest in 0.53 micron systems.

## 9.9 SRT REQUIREMENTS

Supporting research and technology for laser communication experiments should include development of precision acquisition and pointing

equipment, and development of high efficiency, low noise detectors for 1.06 micron receivers. SRT in high efficiency laser transmitters currently underway should be continued.

## 9.10 ACKNOWLEDGEMENTS

### 9.10.1 Related Experiments

The following experiments were considered in formulating the candidate experiment described herein:

| Experiment | Principal Investigator and Association |
|---|---|
| 1. $CO_2$ Laser System Development (RTOP) | N. McAvoy, Goddard Space Flight Center |
| 2. Nd Laser System Development | M. Fitzmaurice, Goddard Space Flight Center |
| 3. Neodymium Laser System Development (RTOP) | Research and Technology Operating Plan, Goddard Space Flight Center |
| 4. Development of a Nd:YAG Laser and Laser Altimeter | Randall, Marshall Space Flight Center |
| 5. Near-Earth Laser Communication System | D. Lilly, Manned Spacecraft Center |
| 6. Optical Frequency Demonstration | Blue Book Vol. V, Jan. 1971 |
| 7. Acquisition and Tracking System Exercises | R. Dishington, TRW Systems Group |
| 8. Acquisition and Tracking Parameter Experiments | R. Dishington, TRW Systems Group |
| 9. Optical PCM Communication Experiment | T. Kinsel, Bell Laboratories |
| 10. Laser Space Communication Experiment | Goodwin, Hughes Aircraft |

### 9.10.2 References


1. "Deep Space Communication and Navigation Study," Vol. II, Communication Technology, NAS5-10293, Bell Laboratories, May 1968.

2. "Optical Space Communication," R. S. Kennedy and S. Karp, NASA, SP-217, August 1968.

3. Proceedings of the IEEE Special Issue on Optical Communications, Vol. 58, October 1970.

# APPENDIX A

# EXPERIMENT EQUIPMENT DETAILED DESCRIPTION

## 1.0 INTRODUCTION

This experiment class encompasses a number of candidate point experiments. Three wavelengths (0.53, 1.06, and 10.6 microns) and various link configurations (space-to-space, space-to-ground, and space-to-airborne relay platform) are considered. The experiments will investigate laser transponder performance, acquisition and tracking parameters, propagation effects, and component performance.

Equipment requirements have been selected with the goal of accommodating all of the planned specific experiments. Thus, for example, transmitter power requirements are based upon the most stringent link configuration, rather than identifying separately requirements for each individual case. This not only simplifies the statement of equipment requirements, but results in requirements which are typical of the operational systems of greatest interest.

The data rate requirements presented herein represent goals for an operational system, based upon a combination of user requirements and consideration of present technology limitations. When more definite plans are developed, it may prove desirable to relax these requirements for the initial experiments.

Many equipment parameters cannot be firmly established at this time, due to the rapid changes in technology. In some instances, competing alternate techniques and concepts are available, although meaningful tradeoffs are difficult before component characteristics are verified. These cases are discussed in the review of component technology status. Periodic review of the equipment requirements will be required to complete the specifications and to update present estimates of performance characteristics.

## 2.0 POINTING AND TRACKING SUBSYSTEM

All of the Laser Communication experiments require a pointing control system to accurately direct the optical line of sight toward the opposing terminal. The most attractive concept for precision pointing is to track an "optical beacon" which is part of the opposing terminal. Inertial reference attitude data is used for initial coarse pointing before acquisition of the optical beacon by the tracking sensor.

The most stringent pointing and tracking requirements arise in the low earth orbit (LEO) to synchronous altitude space-to-space link. Requirements based upon this link are summarized in Table 2-1.

Table 2-1. Pointing and Tracking Requirements

| Requirement | $CO_2$ System (10.6$\mu$) | Nd:YAG System (0.53 & 1.06$\mu$) |
|---|---|---|
| Pointing Freedom | $\pm 50^\circ$ x $\pm 90^\circ$ (typ) | $\pm 50^\circ$ x $\pm 90^\circ$ (typ) |
| Pointing Accuracy ($1\sigma$) | 8 $\mu$rad | 1 $\mu$rad |
| Maximum Slew Rate | $0.2^\circ$/sec | $0.2^\circ$/sec |
| Max. Angular Accel. | 35 mrad/sec$^2$ | 35 mrad/sec$^2$ |
| Initial Pointing Uncertainty | $0.2^\circ$ to $0.5^\circ$ | $0.2^\circ$ to $0.5^\circ$ |
| Allowable Acquisition Time | <20 sec | <20 sec |
| Background Radiance (Maximum) | 30w/m$^2$ sr micron | 100w/m$^2$ sr micron |
| Platform Disturbance | TBD | TBD |
| Optical Beacon Characteristics | TBD | TBD |

## 2.1 POINTING AND TRACKING COMPONENTS

The major components of the pointing and tracking system and their preliminary parameter values are summarized in Table 2-2.

Table 2-2. Functional Characteristics for Pointing/Tracking Components

| Component/Parameter | Performance Requirement |
|---|---|
| 1. Gimbals | |
| Angular Freedom | $\pm 50^{\circ}$ by $\pm 90^{\circ}$ |
| Resolution/Accuracy | $\pm 100$ μrad |
| Slew Rate | $0.2^{\circ}$/sec |
| Control Bandwidth | ~1 Hz |
| 2. Coarse Tracking Sensor | |
| Dynamic (search) FOV | $1^{\circ}$ by $1^{\circ}$ |
| Accuracy ($1\sigma$) | $\pm 200$ μrad |
| Tracking Bandwidth | ~1 Hz |
| Search Time | <10 sec |
| Sensitivity | TBD |
| False Target Rejection | Must reject moon, planets, stars, sunlit clouds. |
| 3. Fine Tracking Sensor | |
| Dynamic FOV | $\pm 300$ μrad |
| Accuracy ($1\sigma$) | 0.5 μrad(Nd:YAG) /4 μrad($CO_2$) |
| Tracking Bandwidth | ~100 Hz |
| Sensitivity | TBD |
| 4. Fine Pointing Beam Deflector | |
| Deflection Range | $\pm 200$ μrad |
| Precision | $\pm 0.2$ μrad |
| Frequency Response | ~100 Hz |
| Spectral Range | Must accommodate Xmtr, rcvr and beacon. |
| Typical Beam Diameter | 1 inch |
| Beam Polarization | Arbitrary, should not effect deflection. |
| Mechanical Disturbance Generation | Must not cause significant pointing errors. |
| 5. Servo Electronics | |
| Type | Type II servo loop |
| Gain Constant | ~$3.5 \times 10^{4}$ $sec^{-2}$ |
| Bandwidth | ~100 Hz |

## 2.2 OFFSET POINTING/TRACKING REQUIREMENT

"Point ahead" compensation is needed for link configurations involving a LEO satellite, to compensate for the finite speed of light and the relatively high orbital velocity normal to the optical line of sight. The magnitude of the point ahead angle is approximately 70 microradians in the maximum case, and the rate of change is extremely slow (~0.05 $\mu$rad/sec or less). Point ahead compensation may be implemented in two distinct ways: a) by offset tracking, or b) by incorporating an offset pointing beam deflector in the transmitter assembly. In the former case, offset pointing is a requirement for the pointing and tracking system. In the latter case, it is a function of the transmitter unit. Further study of the design tradeoffs is needed to determine a preferred implementation of the point ahead function.

## 2.3 STATE OF THE ART

The individual components of the pointing and tracking system require relatively little new development. Reference 1 provides a good description of useful optical components and techniques. References 2 and 3 describe precision pointing gimballed platforms and controls for space applications. The star trackers described in References 2 and 3 could be adapted to track an optical beacon, rather than a star, without major modification.

One component which may require further development is the fine pointing beam deflector. Various types of beam deflectors are available which satisfy some of the requirements (see Table 2-2), but none meeting all of the requirements has been described in the open literature.

The major effort required in the pointing and tracking system area is a comprehensive system design and integration. Perkin Elmer Corporation (Reference 1) has developed a brassboard demonstration system under NASA/MSFC funding, demonstrating many of the fine pointing parameters. Testing of this system is continuing presently under Air Force funding. This system, however, does not emphasize tracking system acquisition.

An Air Force procurement is anticipated in the last quarter of CY 1971 for the development of a brassboard laser communication pointing and tracking system. The requirements for this system will be based upon

a Nd:YAG laser communication system (either 0.53 or 1.06 microns). Once again, the acquisition problem will not be emphasized.

Reference 4 discusses possible techniques for achieving acquisition. These techniques require no new technology, but do require further engineering development. At present, there is no general consensus on the preferred acquisition concept. Logical steps in developing the acquisition system would include the following:

1) Requirements and analysis and definition.

2) Concept tradeoff studies.

3) Hardware design and test.

## 2.4 MAJOR TRADEOFFS

Many significant tradeoffs involving the pointing and tracking subsystem have not yet been analyzed and resolved. Examples of these tradeoffs are briefly described below:

1) Optical Gimbal Concept. Three concepts have been suggested for steering the line of sight:

   - Mount the complete transponder and telescope on a gimballed platform
   - Use a body-fixed transponder and telescope, with a gimballed deflection mirror in front of the telescope
   - Utilize a body-fixed transponder with a gimballed telescope and angle coupling system

   Each of these concepts has specific advantages and disadvantages, dependent upon experiment requirements, which must be evaluated.

2) Beacon. Tradeoffs relating to the optical beacon selection are described in Section 6.0. The acquisition and tracking system must be compatible with beacon signal characteristics. These tradeoffs include beacon wavelength selection, operating mode (pulsed vs. continuous), coding or modulation type, possible combining of beacon and transmitter functions, etc.

3) Acquisition Sequence. The principal tradeoff in the acquisition sequence selection relates to beam scanning vs beam broadening techniques (see Reference 1).

4) Pointing Control Loop. A concept known as "closed loop pointing" offers potential system advantages. In the closed loop method, the transmitted beam is spatially scanned with small angles (less than the beamwidth) to produce variations in carrier power at the receiver; these variations are processed to determine pointing error signals, which are fed back to the transmitter. A comprehensive analysis of this concept has not been reported in the open literature on laser communication systems.

## 3.0 OPTICS

The optics for the laser communications experiments include the following elements:

1) Telescope optics

2) Filters

3) Beam handling optics

4) Alignment optics

5) Viewing and camera optics

6) Beamwidth control optics.

Applicable requirements for these components are listed in Table 3-1.

## 3.1 OPTICS REQUIREMENTS RATIONALE

The requirements for the telescope optics are based upon considerations presented in Reference 5. Briefly, the major considerations include:

1) Aperture Size. The aperture size is determined by the energy collection area needed to support a data rate of 1 Gb/s, with available transmitter power and receiver efficiency, in a LEO to synchronous altitude space-to-space communication link.

2) Optical Quality. The optical quality requirement is based upon the relationship of antenna gain vs wavefront error presented in Reference 1.

3) Field of View. The field of view is based upon the dynamic field of view (FOV) of the coarse tracking sensor, which in turn is based upon the assumed inertial reference uncertainties of the spacecraft platform. Aberration tolerances may be relaxed for field angles beyond ~0.1 degree.

Table 3-1. Optics Functional Characteristics

| Component/Parameter | Performance Requirement |
|---|---|
| 1. Telescope Optics | |
| Function | To collect energy for the receiver and tracking sensors, and to collimate energy for the laser transmitter. |
| Aperture Size | 1 to 2 ft. diameter aperture. |
| Type | Folded cassegrain (preferably all reflective). |
| Achromatism | Must accommodate wavelengths of laser transmitter, laser receiver and beacon. |
| Optical Quality | $\lambda/20$ rms wavefront error for shortest wavelength of transmitter/receiver. |
| Relative Aperture | ~f/5 |
| Transmission Efficiency | ~0.8 |
| Active Field of View | ~0.5 degree |
| 2. Filters | |
| Function | To provide rejection of background energy by spectral discrimination. |
| Type | Narrowband transmitting, with specific type to be determined. |
| Spectral Width | ~1Å for 0.53$\mu$ and 1.06$\mu$ system<br>~400Å for $CO_2$ systems |
| Peak Transmission | >0.5 at design wavelength |
| Angular Acceptance | Less than 0.1 degree for receiver and fine tracker; up to ~5 degree for coarse acquisition tracker. |
| Temperature Range | To be determined. |
| 3. Beam Handling Optics | |
| Function | Relay lenses, beam splitters, energy redistribution elements (e.g., axicon described in Reference 1), polarizing elements, folding mirrors, etc. |
| Specific Requirements | TBD (Example parameters: alignment stability, transmission/reflection efficiency, polarizer extinction ratio, temperature range). |

continued

Table 3-1. Optics Funtional Characteristics (continued)

| | |
|---|---|
| 4. Alignment Optics | |
| Function | To permit in-flight check of focus adjustment and boresight alignment. |
| Boresight Alignment | Relative alignment between transmitter and fine tracker should be measured to 1/10 of beamwidth. |
| Focus Adjustment | Focus errors greater than $\pm 2\lambda f^2$ should be sensed, where $\lambda$ and f are the wavelength and relative aperture of the system. (Note: the shortest wavelength of interest should be used for $\lambda$). |
| 5. Viewing and Camera Optics | |
| Function | To permit the Space Lab crew to view and record the telescope field of view during various experimental procedures. |
| Optical Magnification(s)<br>Spectral Transmissivity<br>Visual & Photographic Resolution<br>Maximum Attenuation of Received Energy<br>Eye Relief and Human Factors<br>Film Type<br>Operation During Transmit/Receive Mode | To Be Determined |
| 6. Beam Expander Optics | |
| Function | To provide variable beam divergence control for the laser transmitter and the optical beacon, in order to facilitate acquisition. |
| Type | Afocal beam expander with variable element separation. |
| Typical Input Beam Size | ~1/4 in. diameter |
| Typical Exit Beam Size | ~1 in. diameter |
| Input Beam Characteristics: | |
| Laser Transmitter | $TEM_{oo}$ Wave, Gaussian Dist. |
| Optical Beacon | ~3 mrad divergence, Gaussian Dist. |
| Output Beam Divergence: | |
| $CO_2$ Laser Transmitter | Diff. limit to ~200 arc-sec. |
| Nd:YAG Laser Transmitter | Diff. limit to ~50 arc-sec. |
| Optical Beacon | ~2 arc-min. to 1 degree |
| Response Time for Adjustment | ~0.5 sec. or less |

## 4.0 LASER TRANSMITTER

The laser transmitter assembly includes the following components:

1) Laser optical cavity

2) Laser power supply

3) Laser cooling system

4) Transmitter electronics

5) Modulator and modulator driver

6) Optics for offset pointing and beam spoiling.

The optics of Item 6 are described in Sections 2.0 and 3.0. Functional characteristics of the transmitter are indicated in Table 4-1.

## 4.1 TRANSMITTER TECHNOLOGY STATUS

A large number of competing techniques presently exist in the area of cavity design and modulation. For the Nd:YAG systems (0.53 and 1.06 microns) attention is concentrated in the following approaches:

1) Mode locked laser operation with intracavity frequency doubling and external modulation. This work is being carried on at McDonnell Douglas under Air Force sponsorship. To date, the problems associated with simultaneous mode locking and frequency doubling have not been completely resolved.

2) Mode locked operation at 1.06 microns, with external modulation. Modulation driver problems (i.e., requirement for high voltage wideband driver) prevent adequate modulation depth at 1 Gb/s. Also, utility of transmitter is contingent upon advances in 1.06 micron detector technology.

3) Intracavity polarization modulation, non-mode locked, at either 1.06 or 0.53 micron wavelength. This work is being performed at TRW Systems and appears to provide significant advantage in reduction of modulation drive voltage. To date, however, 1 Gb/s operation has not been demonstrated.

4) Relative Aperture. The relative aperture selection is constrained by anticipated packaging limitations (favoring low f-numbers) and by practical design and manufacturing limitations (favoring large f-numbers).

Table 4-1. Laser Transmitter Functional Characteristics

| Component/Parameter | Performance Requirement |
|---|---|
| 1. Laser Cavity | |
| Function | To convert electrical power into coherent optical energy. |
| Lasing Mode | Fundamental ($TEM_{oo}$) |
| Mode Locking | The requirement for mode locking for some or all of the transmitter wavelengths has not been determined (See Section 4.2). |
| Optical Output Power: | |
| 0.53μ laser | ~100 milliwatts average power |
| 1.06μ laser | ~1 watt average power |
| 10.6μ laser | ~5 watts average power |
| Efficiency: | |
| 0.53μ laser | ~0.1 percent |
| 1.06μ laser | ~1 percent |
| 10.6μ laser | ~5 percent |
| 2. Laser Cooling System | |
| Function | To maintain suitable operating temperature for the laser cavity components. |
| Cooling Method | Conductive, no liquids allowed if possible (many future applications will require cooling in a vacuum environment, where fluid containment is impractical). |
| Head Load | ~200 watts |
| Laser Head Operating Temp. | To Be Determined |
| 3. Modulation | |
| Function | To provide high data rate modulation of the transmitter optical energy. |
| Type (A or D) | Digital |
| Data Rate: | |
| $CO_2$ System | ~200 Mb/s |
| Nd:YAG Systems | ~1 Gb/s |
| Technique | TBD. Candidate techniques include polarization modulation, intensity modulation, frequency modulation, pulse position modulation, phase modulation, and FM subcarrier technique. |
| Extinction Ratio | ~20 dB |
| Power Allocation: | |
| $CO_2$ System | ~80 watts |
| Nd:YAG Systems | ~10 watts |
| Format | To Be Determined |
| 4. Laser Power Supply | |
| Function | To convert and regulate raw spacecraft power in a fashion suitable for pumping the laser. |
| Requirements | To Be Determined |
| 5. Transmitter Electronics | |
| Functions | Multiplexing, A/D conversion, formatting. |
| Data Rate | See Item 3 above |
| Detailed Requirements | To Be Determined |

The optical filter requirements for the communication receiver based upon an analysis of bit error rates vs. background level. A bit error rate of $10^{-6}$ was assumed for this analysis. In the case of the $CO_2$ system, background radiance can be rejected by means of an optical heterodyne receiver, greatly relaxing the spectral filter requirements.

The spectral filters for the trackers are necessary in order to operate near the theoretical quantum sensitivity limits with minimum beacon power. If more beacon power were available, the filter bandwidth could be relaxed. This may be particularly appropriate for the coarse acquisition sensor, where the beam diameter may be typically 1/10 that of the collection aperture and, therefore, entrance angles of 5 degrees may be necessary (reduction of beam diameter multiplies the field angles of the entrance beam). Filters are not presently available with acceptance angles of $\pm 5$ degrees and spectral widths of the order of 1 $\text{Å}$.

The requirement for viewing and camera optics is based mainly upon the need to observe and record the background conditions during various experimental procedures. These optics may also be useful in evaluating the performance of tracking acquisition equipment. Further study is needed to determine more specific applications and requirements for the equipment.

## 4.2 OPTICS TECHNOLOGY STATUS

All of the optics described in Section 3.0 are within the state of the art with existing technology. However, considerable engineering and design effort will be necessary to develop a flightworthy system. The most problematic components are the spectral filters, particularly for the relatively wide angle acquisition sensor discussed in Section 4.1. A review of optical component technology status is presented in Reference 1.

## 5.0 LASER RECEIVER

The laser receiver consists of the photodetector(s), receiver optics, and receiver electronics. Preliminary guidelines for the functional characteristics of the laser receiver are summarized in Table 5-1.

## 5.1 RECEIVER COMPONENT TECHNOLOGY STATUS

Detector development is required primarily for the 1.06 micron system, since satisfactory detectors are presently available for the other two wavelengths. The two alternatives at this time are avalanche photodiode detectors or crossed-field photomultiplier tubes (PMT's) with new, higher quantum efficiency photocathodes. The latter detectors appear to offer the greatest promise, although those built to date require bell-jar operation and do not have adequate lifetime.

Receiver electronics operating at 300 Mb/s are presently available. A significant amount of development is anticipated in extending the bandwidth to 1 Gb/s. However, this development is presently being funded by WPAFB/AFAL, and it is anticipated that a 1 Gb/s breadboard system will be developed by mid-1972.

No developmental requirements are anticipated for the receiver optics.

The $CO_2$ communication receiver is dominated by the problems of Doppler shift for the LEO to synchronous satellite link. If a stable frequency local oscillator were used in the heterodyne receiver, Doppler shifts would cause variations in the IF frequency on the order of 10 GHz. Since such variations cannot be tolerated in the system, a variable frequency local oscillator is required. A $CO_2$ local oscillator exhibiting the required tuning range has not yet been developed.

Table 5-1. Laser Receiver Functional Characteristics

| Component/Parameter | Performance Requirement | | |
|---|---|---|---|
| 1. Photodetector(s) | | | |
| Function | To convert received optical power into electrical signals. | | |
| Detector Characteristics: | 10.6μ* | 1.06μ** | 0.53μ** |
| Type | HgCdTe | C.F. PMT | C.F. PMT |
| Quantum Efficiency | ~20% | ~2% | ~20% |
| Internal Gain | None | $\sim 10^5$ | $\sim 10^6$ |
| Frequency Response | 500 Mb/s | >1 Gb/s | >1 Gb/s |
| Operating Temperature | $\sim 100^{\circ}K$ | Ambient | Ambient |
| Gating | No | TBD | TBD |
| 2. Receiver Optics | | | |
| Function | To direct received optical energy onto photodetector(s), including polarization analyzers if appropriate. | | |
| Detailed Requirements | TBD | | |
| 3. Receiver Electronics | | | |
| Function | Video amplification, bit synchronization, demultiplexing, and D/A conversion. | | |
| Data Rate | Up to 1 Gb/s | | |
| Interface Requirements | TBD | | |
| 4. $CO_2$ System Local Oscillator | | | |
| Output Power | 50 mw | | |
| Input Power | TBD | | |
| Frequency Control | ±10 GHz (goal) | | |
| Nominal IF Frequency | 400 MHz | | |

* Optical heterodyne detection system
**Direct detection system

## 6.0 LASER BEACON

The laser beacon serves as a light source to facilitate acquisition and/or tracking from a distant communication terminal. The need for a laser beacon distinct from the communication laser transmitter has not been conclusively established at the present time. Final resolution of this requirement is dependent upon analysis of the following parameters:

1) Initial pointing uncertainties

2) Laser transmitter power and wavelength

3) Allowable acquisition time

4) Tracking system collection area and sensitivity.

Current estimates of the above parameter values indicate that a pulsed beacon probably will be required for acquisition only. Following lock-on, the laser transmitter will serve as the tracking source. Table 6-1 presents a preliminary outline of suggested beacon performance characteristics.

## 6.1 BEACON TECHNOLOGY STATUS

The technology for the beacon specified in Table 6-1 is well within the present state of the art. It is possible that optical damage of the frequency doubling crystal may be a significant problem. In this event, it may be best to operate the beacon at 1.06 microns (not doubled), yielding approximately five times higher power output than the suggested 0.53 micron system. This should provide more than adequate energy for tracking acquisition, assuming conventional S-1 photocathode photomultiplier detectors.

If it should prove necessary to operate the beacon during fine tracking operations (perhaps for the $CO_2$ transponder system), then the recommended beacon pulse rate may be too low to provide the required tracking accuracy. Further, the low pulse rate specified precludes the use of the beacon as a command link data transmitter. An attractive alternative for overcoming these problems is the use of a continuously pumped, repetitively Q-switched laser beacon, operating at approximately 10 KHz repetition rate.

Table 6-1. Laser Beacon Functional Characteristics

| Parameter | Performance Requirement |
|---|---|
| Beacon Type | Q-switched laser, multimode cavity |
| Wavelength | 0.53$\mu$ (preferred) |
| Primary Function | Tracking acquisition |
| Operation Period | Used only during acquisition |
| Rep. Rate | ~5 pps |
| Energy/pulse | ~20 mj at 0.53$\mu$ |
| Pulsewidth | ~20 msec |
| Pump Method | Flash pump |
| Power Consumption | ~100 watts |
| Coding Technique | Pulse position modulation |
| Beamwidth | Variable, $1^{o}$ to 1 arc minute |
| Lifetime | $10^{6}$ flashes or greater (represents approximately 10,000 acquisition maneuvers) |

## 7.0 REFERENCES


1. McIntyre, Charles, Peters, William N., Chi, Changhwi, and Wischina, Herbert F., "Optical Components and Technology in Laser Space Communications Systems," Proceedings of the IEEE, October 1970.

2. Frew, A. M., Kirby, D. K., and Wheeler, P. C. of TRW Systems and Huber, T. C. of NASA/GSFC, "An Integrated System for Precision Attitude Determination and Control," AIAA 1971 Guidance, Control and Flight Mechanics Conference.

3. "SPARS, Space Precision Attitude Reference System," Lockheed/Honeywell/Control Data Papers for the Symposium on Attitude Determination, 30 September 1979.

4. Kraemer, Arthur R., GTE Sylvania, "Acquisition and Angle Tracking of Laser Communication Links," 1971 Wescon Technical Papers, Session 6, presented August 1971.

5. TRW Proposal No. 20088, "Space Data Relay Subsystem-Laser Communications Preliminary Subsystem Design," March 1971.

# EXPERIMENT 10

# ELF/VLF IONOSPHERIC RADIATION

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# 10. ELF/VLF IONOSPHERIC RADIATION

## 10.1 EXPERIMENT CLASSIFICATION

This experiment is categorized as applied research. Potential growth through a developmental phase and into operational testing is envisioned.

## 10.2 EXPERIMENT OBJECTIVES

The experiment is intended to resolve certain significant theoretical uncertainties regarding ELF/VLF propagation from within the ionospheric plasma to earth. Such questions include:

- Antenna impedance
- Radiation efficiency
- Antenna optimization
- Plasma non-linearity effects
- Coupling loss from ionosphere to earth cavity
- Anisotropic directivity effects
- Latitude dependence
- Source height
- Ionization density dependence.

The ability of antennas to radiate effectively within this plasma has not been established. Various models of the ionosphere have been synthesized to predict propagation effects.

Meanwhile these low frequencies have been used in point-to-point communications for years, especially for over-the-horizon and for earth and seawater penetrating communications. The Navy, in particular, is vitally interested in improving these communication techniques. Communications via an orbiting spacecraft would offer even greater capability and flexibility to users of this portion of the spectrum. A greater knowledge of the radiation and propagation phenomena will facilitate more accurate prediction of communication performance at these low frequencies. Experimental data will be useful for proposed long range command and control links to submarines and ships and to hardened missile sites.

If communication proves feasible, satellite transmission could allow emergency and other direct broadcast to extremely simple, low cost, crystal receivers.

Specific objectives of the experiment are:

a) Establish mechanical feasibility of deploying a long wire antenna from an orbiting vehicle. Determine the maximum length that can be extended.

b) Measure input impedance and efficiency, both in free space and in the ionospheric plasma, at frequencies from 20 kHz to several Hz, if possible.

c) Establish propagation behavior through this ionospheric media under varying diurnal and seasonal conditions.

d) Correlate electron and air density measurements impedance and efficiency data.

e) Evaluate alternative antenna concepts such as a vehicle-generated plasma, isotope or conductive particle trails, very large loops or dipoles, ferrite rod devices (loopstick), and ferrite arrays, also antenna structures deployed between two space vehicles rather than merely extended from one.

f) Evaluate the characteristics of various conductors including the following specific tradeoffs:

- Tape, strip, and tube versus round wire
- Stranded and woven materials versus solid
- Reinforced conductors versus simple
- Conductivity versus strength
- Efficiency, bandwidth, and impedance versus thickness.

g) Provide valuable data on the potential space use of the U.S. Navy Omega VLF navigation system.

h) Consider additional measurements that can be accomplished using the long wire as a sensor (e.g., resistance change as an indicator of incident solar flux, noise, etc.).

## 10.3 DISCIPLINE BACKGROUND AND STATUS

Two phenomena affect the coupling and propagation of ELF/VLF energy into and through the ionosphere from an antenna immersed in

this medium. The first of these is the geomagnetic field, which, depending upon the ion density and altitude, can control both the antenna coupling and direction of propagation. The precise nature and magnitude of this effect is not known and should be explored. A measurement of the amplitude and orientation of the geomagnetic field is thus a necessary part of any experiment involving ELF/VLF antenna and propagation measurements.

The second important parameter affecting antenna performance and ionospheric propagation is the local electron density. The electron density of the ionosphere will affect the resonant length of the antenna and its impedance characteristics. In fact, the local electron-ion field becomes part of the antenna as a voltage is induced over its length, and tends to reduce the required length to achieve resonance and radiation. The electron density will vary significantly during the day, seasonally, and during the various phases of sunspot activity. Therefore, the electron density should be measured and correlated with antenna-propagation-related data. Ancillary supporting instrumentation must be provided to obtain these data.

## 10.4 EXPERIMENT DESCRIPTION

A sketch of the conceptual experiment configuration is illustrated in Figure 10-1. The orbiting laboratory transmits signals to and/or receives signals from cooperative stations on earth. The cooperating stations may be of two types: one or more ground-based systems already in existence, and a sea laboratory. A functional block diagram of the equipment configuration aboard the Comm/Nav laboratory is shown in Figure 10-2. Three sets of equipment for measuring necessary parameters are shown: the antenna and accompanying transmitting, adjusting and measurement devices; a magnetometer for measuring the orientation of the earth's magnetic field; and a Langmuir probe for measuring the local electron density.

The experiment would be conducted as follows:

The astronaut would remove the package containing the antenna and its deployment mechanism. This device, weighing approximately 30 pounds, would be of the type manufactured by De Havilland or

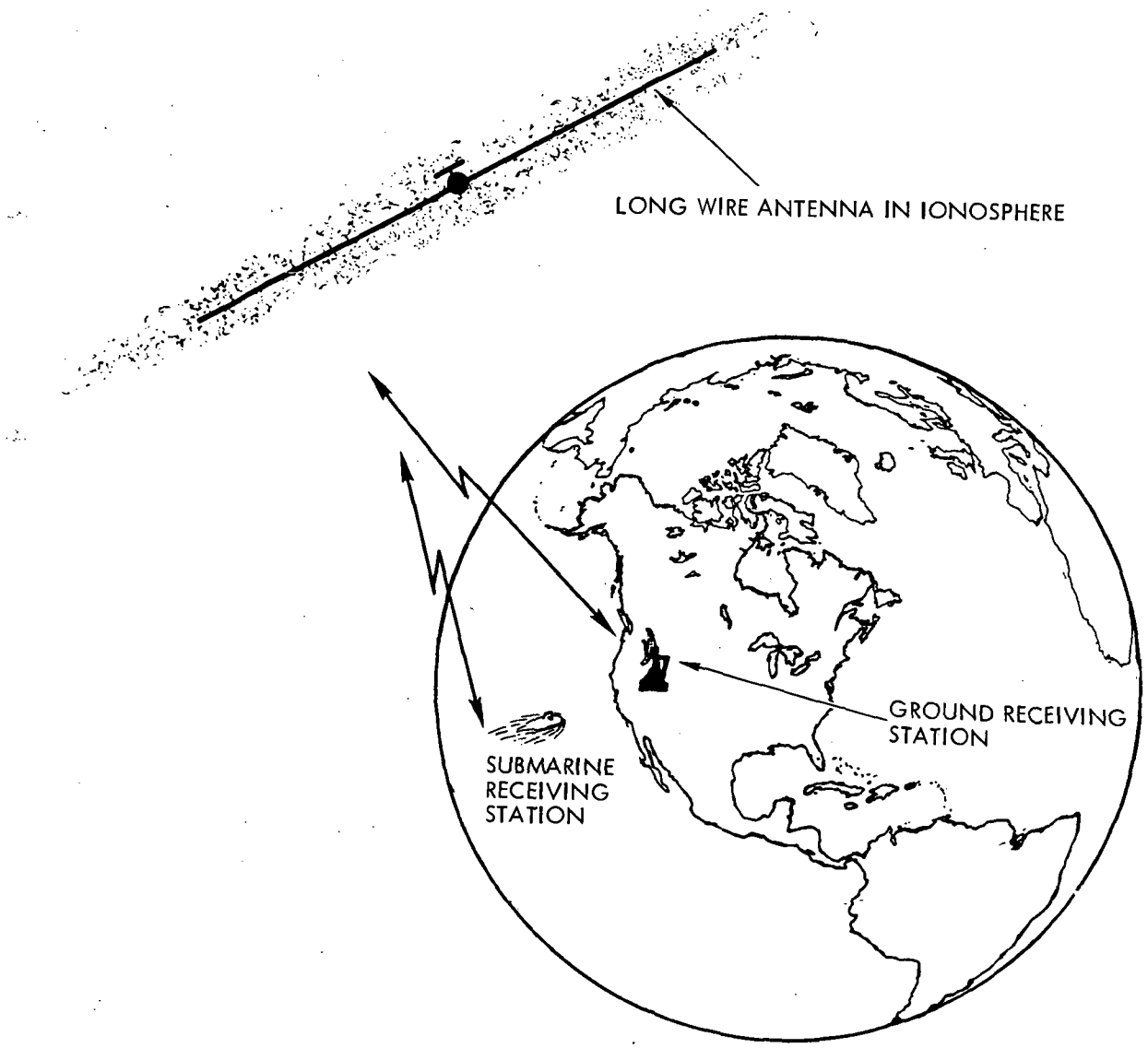


Figure 10-1. ELF/VLF Ionospheric Radiation Experiment Conceptual Sketch

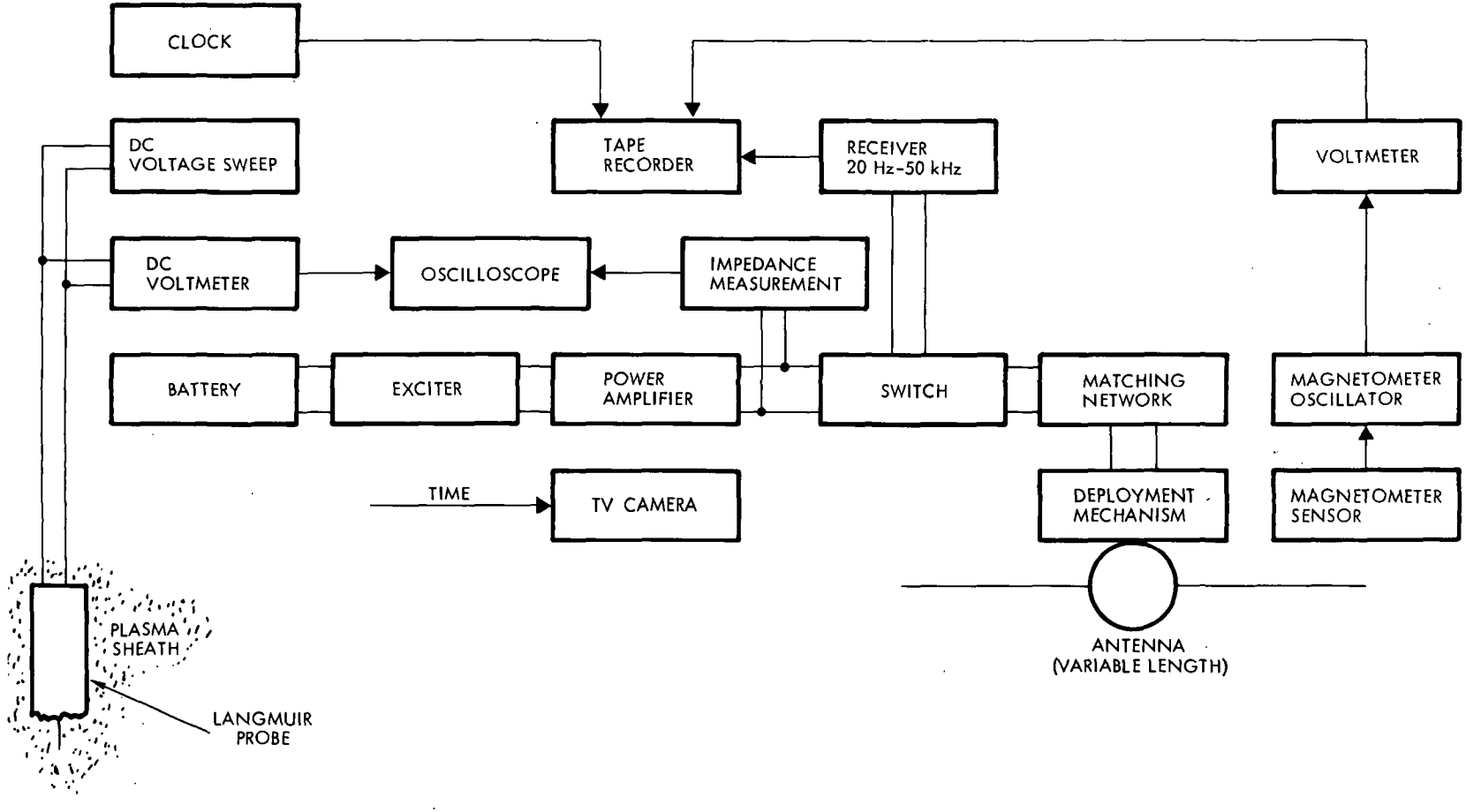


Figure 10-2. ELF/VLF Experiment – Functional Block Diagram

Fairchild-Hiller as shown in Figure 10-3. Feed cables would be previously connected. He would attach the deployable antenna to a telescoping or scissors-like boom and extend the boom away from the spacecraft, observing the cable and boom until they reached final extension. The astronaut would next begin deployment of the tubular antenna by a remote switch, observing the deployment. Motion pictures of the deployment would be taken by the second astronaut. The antenna would be extended to its full length.

The exciter and transmitter would be activated at low power (approximately 10 watts) at a prescribed frequency. The astronaut would observe the impedance match and adjust inductive and/or capacitive reactance to achieve a satisfactory match. Electron density and magnetic field data would be recorded continuously. Verification of signal reception by participating earth stations will be coordinated via normal Shuttle communication channels.

Also, any antenna impedance changes would be recorded. Assuming no signals were intercepted, the power would gradually be increased until a signal from the spacecraft was identified. The output power would be increased to maximum and for several orbits cooperative ground terminals would record signal level profiles versus time. Submerged submarines and/or a sea laboratory would cooperate to the extent of attempting to receive the same signals. The spacecraft would be reoriented to achieve maximum signal reception by the ground station(s), and the above data recorded in a similar fashion. If significant impedance mismatches were to occur, the astronauts would adjust accordingly. The above experiment would be conducted at several selected frequencies in the band of interest.

Alternatively, or as an adjunct to the previous test, the Comm/Nav laboratory may operate in a receive mode, perhaps in conjunction with the Omega VLF navigation system. The transmitter would now be shut down and the antenna switched to the receiver. The antenna would be retracted if necessary to a prescribed position and the impedance match adjusted to receive the maximum amplitude signal at a specified frequency. This signal would be recorded and correlated with geomagnetic and electron density data for several orbits. The spacecraft may be reoriented

A wide variety of types of metal strip may be used to form the element. The choice of metal depends upon the STEM application. Stainless steel, beryllium copper and titanium have all been used with success. The strength and rigidity of the extended tube can be increased by wrapping a number of tubes inside the main tube. For space applications, antennas have already been manufactured varying in length from 15 inches to 850 feet. The photograph shows the compact size of the 850 ft. antenna unit; Type A21, weight, 16 lbs.

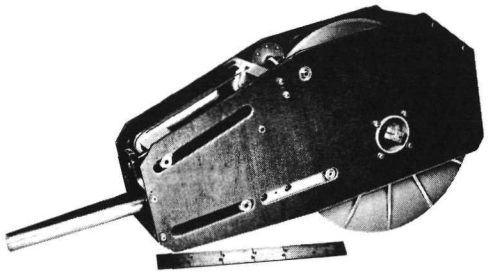

Photo below shows the Libration Damper Boom which also is used on the Radio Astronomy Explorer satellite. Two 315-foot Tubular Extendible Elements emerge from a common reel inside the motorized mechanism.

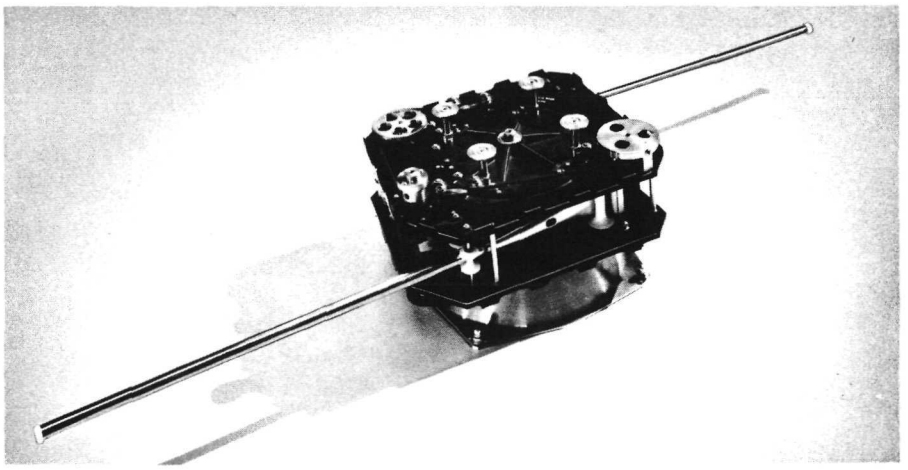

Figure 10-3. Linear Extendable Antennas

to obtain maximum signal response near the ground station. The receive experiment would be conducted at one or more additonal frequencies.

The antenna would be retracted and stored until the vehicle returned to earth. The effects of the space environment applied power on the antenna would be evaluated by materials and processes personnel after the flight.

## 10.5 EXPERIMENT OBSERVATION/MEASUREMENT PROGRAM

The principal measurements to be performed during this experiment include the following:

a) Local electron density. This is essential for the experiment, but is also a fallout which can be used to verify previous data and provide greater insight into the characteristics of the ionosphere.

b) Geomagnetic flux field as a function of location.

c) Angular deviation of the antenna from linear. Any large deviation from a linear dipole would contribute to the cross-polarized field and introduce errors in the magnitude of the signal received by an ideally polarized antenna on the ground. If there is negligible deviation from linear, future extendable antennas of this type could be made smaller and lighter in weight for unmanned satellites.

d) The impedance of the antennas would be measured over the frequency band using standard sweep techniques as a function of voltage and power in the plasma medium. This could possibly develop into another technique for measuring electron density. Comparisons of impedance changes to both the electron density and magnetic field will be made to determine correlation and the degree of impedance predictability for future experiments.

e) Received signal strength as a function of location, orientation, and power input levels. This is one of the primary objectives of the experiment. The effects, if any, of inter-ionospheric ducting, severe refraction, and signal multiple path would be measured.

f) Signal reception. This would establish to some degree the anisotropy of the ionosphere by observing signal reception as a function of time, location, orientations, and frequency.

## 10.6 INTERFACE, SUPPORT, AND PERFORMANCE REQUIREMENTS

### 10.6.1 Operational Requirements

To facilitate selection of polarization and direction of propagation, the spacecraft should be equipped to deploy orthogonally oriented antennas. Alternatively, the host vehicle must reorient, as required, to attain the desired attitude. To determine the effects of varying electron density, the host vehicle should have the capability to change orbits (altitudes 200 to 500 n.mi. desired).

### 10.6.2 Link Power Budget

It is difficult to predict an accurate link power budget for the experiment. As the antenna voltage is increased, some proportion of the energy is used to ionize the medium surrounding the antenna. During many portions of the orbit, high attenutation will occur from the D-layer of the ionosphere (daylight time periods). Since most of the energy which is radiated is postualted to travel along the direction of the earth's magnetic field, it may enter the atmosphere at both poles. Plasma nonlinearities loom as a possible major limitation on the ability to radiate adequate signal. During the early phase of this experiment, a relatively low power transmitter (less than 100 watts) should be adequate.

### 10.6.3 Mounting/Structural Requirements

It is anticipated that a boom, long enough to extend the deployment mechanism some 20 to 30 feet from the spacecraft, may be required. This could be mounted near one of the hatches and either folded or extended by the astronauts.

### 10.6.4 Unique Electrical Power Requirements

Since the operational frequencies of this antenna experiment are quite low (30 Hz to 30 kHz), special shielding may be required to reduce interference with other on-board systems. Communication, measurement, and computer equipment are particularly susceptible.

### 10.6.5 Ground Facility Support Requirements

The support of numerous potential ground-based users in this frequency band should be solicited. It is desirable to acquire representative data samples from many sources and gathered under various operational and propagation conditions.

## 10.7 POTENTIAL ROLE OF MAN

### 10.7.1 Required Functions

The crew experimenters performing this experiment may be required to erect a boom approximately 30 feet long. A deployment scheme similar to that planned for the interferometer experiment boom deployment appears applicable. Subsequently, the experimenters would activate the deployment of the long dipole, simultaneously photographing this action. When a prescribed length has been reached, the deviation from true linear would be observed visually and photographed.

Crew involvement in performing the impedance measurements and tuning/matching procedures is critical to the success in exciting the antenna. Manual adjustment and monitoring of instrumentation are required to effect the desired impedance match. Simultaneous voice communication with participating earth stations will verify receipt of the transmitted signals.

Iterations of this process, including further extension of the antenna, would be made during the mission. On subsequent orbits, attempts to receive earth-generated signals would be made in a similar manner. Man's role will be invaluable in adjusting equipment to changing and unforeseen conditions.

### 10.7.2 Necessary Skills

The experimenters must be acquainted with operation of low frequency RF equipment such as transmitting sources, receivers, impedance measuring devices, and oscilloscopes. A reasonable knowledge of the physics of low frequency propagation in the ionospheric plasma is highly desirable to facilitate interpretations of the real-time results of the experiment during the mission which may influence decisions governing the execution of the remaining portions of the experiment.

## 10.8 EXPERIMENT EVOLUTION

This experiment is considered a candidate for the latter series of the Early Laboratory Sortie Can missions. Further, the scientific and technical community have shown considerable interest in an experiment investigating these phenomena.

The recommended sequence of the experiment would probably evolve from the higher frequencies (1 to 30 kHz) for the early tests, to lower frequencies (300 to 1000 Hz) and finally to the 30 to 300 Hz frequency range. Investigation of each frequency range may be accompanied by higher power levels. Indeed, one might envision an experiment evolving into a search for extra-terrestrial sources, utilizing, of course, an orbit outside of the ionosphere.

## 10.9 SRT REQUIREMENTS

This experiment has unique requirements for deployment of extremely long dipole antenna elements. For example, at a frequency of 10 kHz a wavelength ($\lambda$) is approximately 18 miles! Therefore, each leg of an ideal dipole antenna would be 4-1/2 miles ($\lambda/4$). This requirement exceeds the current capability which approaches 1000 feet. The recommended SRT task includes investigating, developing, and testing suitable devices and techniques for efficiently and reliably deploying extremely long antennas.

Typically the radiation resistance of an antenna comprised of ohmic and radiation resistance components, is dominated by the radiation resistance portion, which is impedance matched to the transmitter to optimize the transmitted power. However, the ohmic loss associated with very long conductors is considerable and techniques must be devised to offset this effect. Utilization of special materials to minimize the ohmic loss is an obvious approach. Designing the antenna to exhibit a relatively large radiation (characteristic) impedance is another method, although it creates a new problem in avoiding corona breakdown associated with the large voltage potentials required to develop the equivalent power. The SRT task is to analyze this problem, examine tradeoff solutions, and verify the recommended approach(es).

Finally, it is recommended that the characteristics of various conductors be evaluated with respect to their suitability as antenna elements. A tradeoff among strength, weight, and resistivity, including testing as required, constitutes the major objective of this suggested SRT task.

In summary, the recommended SRT effort includes evaluating the feasibility and expected performance of the following concepts:

- Long wire antennas (lengths approaching a quarter wavelength
- Ferrite rod antennas and arrays of rods
- Large loop antennas
- Plasma, isotope, or conductive particle trails
- Composite conductors; e.g., foam fiber-reinforced wire, micro-wall
- Review design of existing deployment mechanisms such as the De Havilland "stem"
- Establish design/implementation approach for length of wire up to five miles
- Evaluate the performance of basic materials, including conductivity, density, strength, cost, toxicity, etc.

## 10.10 ACKNOWLEDGEMENTS

### 10.10.1 Related Experiments

The following candidate experiments were used in the preparation of this experiment definition:

| Experiment | Principal Investigator and Association |
|---|---|
| Feasibility of Long Wire Antennas at VLF Frequencies | W. Sisco, TRW Systems |
| ELF Propagation from Within Ionospheric Plasma | J. Mallinckrodt, TRW Systems |

# EXPERIMENT 11

# FIXED MULTIBEAM ANTENNA

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# 11. FIXED MULTIBEAM ANTENNA

## 11.1 EXPERIMENT CLASSIFICATION

The experiments defined herein are classified as developmental in nature.

## 11.2 EXPERIMENT OBJECTIVES

This experiment is representative of the class of experiments designed to demonstrate and evaluate relative performance of competing multiple beam antenna concepts in a space environment. With the ever-increasing requirements for spectrum utilization, the technique of frequency band reuse offers an attractive solution by providing significant increases in capacity.

An approach which appears most promising is the use of multiple narrow beam antennas incorporating polarization diversity. The three most favorable concepts include a lens with multiple feeds, a reflector with multiple feeds, and an antenna array. This point experiment is devoted to a detailed performance evaluation of an antenna configuration comprising a lens with multiple feeds.

## 11.3 DISCIPLINE BACKGROUND AND STATUS

The crowded electromagnetic spectrum demands that alternate techniques be developed to minimize interference and provide for frequency reuse where feasible. This is particularly true where communication satellites are concerned, since limited frequency allocations are available, and spatial diversity is difficult.

While earth-based microwave relay links minimize mutual interference by the use of many very narrow beam antennas pointed in slightly difference directions, the same approach from a satellite-borne microwave relay incurs undue weight, volume, and cost penalities. Ideally, a single antenna, capable of producing several narrow beams from a single aperture would provide a solution to this problem. One simple advance in this direction would be a four-beam antenna, each beam covering a separate time zone of the Continental U.S., as shown in Figure 11-1. Here, alternate frequencies could be used for each time zone, as indicated. The

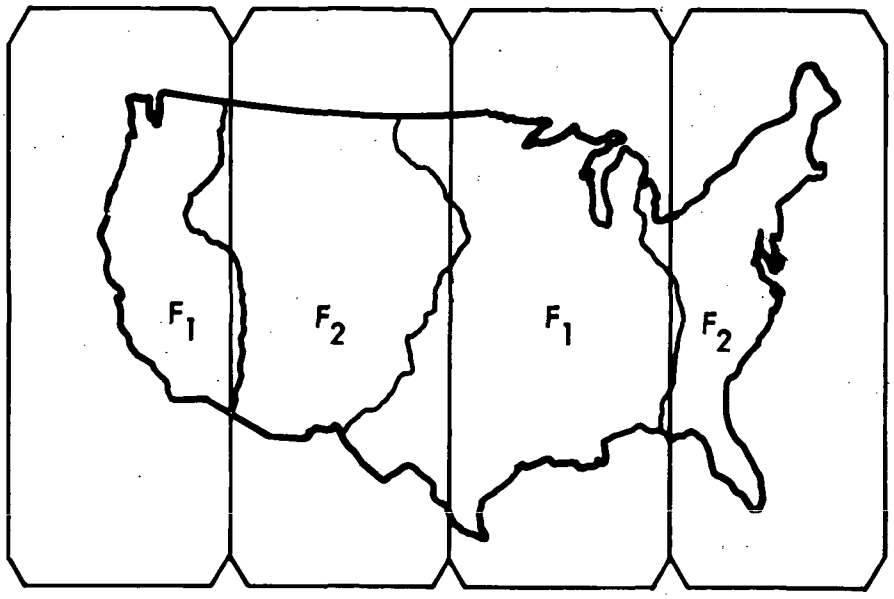


Figure 11-1. Frequency-Diversity Time Zone Coverage

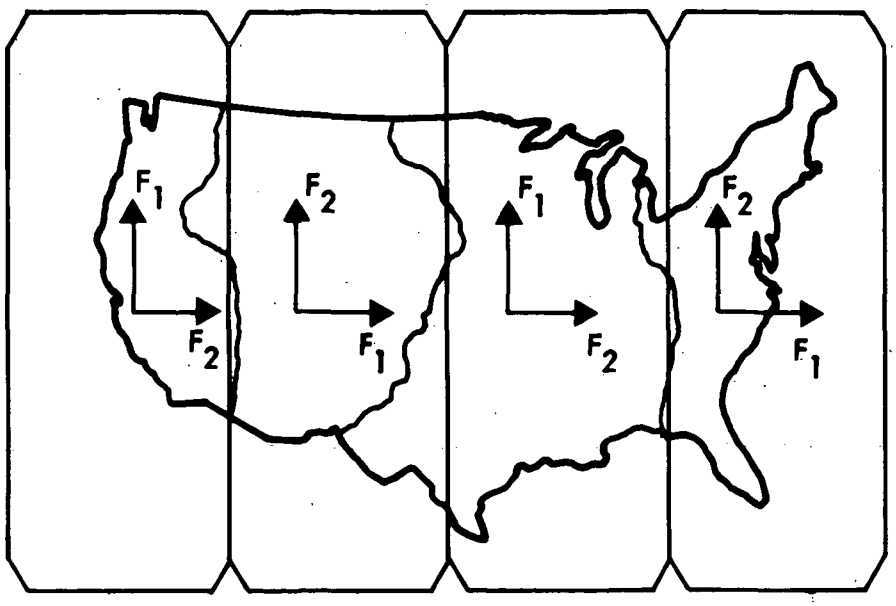


Figure 11-2. Frequency and Polarization Diversity Time Zone Coverage

combination of separate beams and separated frequencies would provide some frequency reuse with sufficient isolation to minimize interference. Another scheme utilizes the properties of polarization isolation in conjunction with spatial and frequency separation. This is illustrated in Figure 11-2. In this example the identical four beams may be radiated, each containing orthogonal linearly polarized components slightly offset in frequency. This configuration effectively doubles the communication capacity for the same frequency utilization. The combination of polarization isolation and frequency separation for a given time zone results in sufficient isolation to provide an interference-free up-or down-link. The adjacent time zone is illuminated by a separate beam from the spacecraft antenna, but offers the opposite combinations of polarization and frequency. Spatial isolation provides an increased degree of non-interference. It is easy to visualize a further division of beams (8, 10, 20, etc.) with accompanying polarization diversity to obtain increased frequency reuse for U.S. or worldwide communications.

## 11.4 EXPERIMENT DESCRIPTION

The first generation of multibeam antennas to be developed will consist of two beams, each beam generating orthogonal polarizations as displayed in Figure 11-2. Conceptually, the antenna is shown in Figure 11-3. The design is an "egg-crate" lens structure wherein two separate focal points are obtained depending upon the direction of arrival of the signal. The metal-plate lens is configured to generate approximately eliptical beams for Continental U.S. time zone coverage from synchronous orbit. The feed subsystem is designed to accept either sense of linear polarization.

It is planned to develop this antenna for operation in the 11 - 14 GHz band. The four time-zone coverage of CONUS requires beamwidths of 2.5 x 3.5 degrees, resulting in approximate gain levels of 33 -34 dBi. At present, it is conceived that the antenna would operate in the receive mode only for the Early Laboratory configuration.

The metal plate lens antenna described previously is a sophisticated design, sensitive to the thermal vacuum environment of real space to an extent not entirely predictable by either theoretical or earth-based

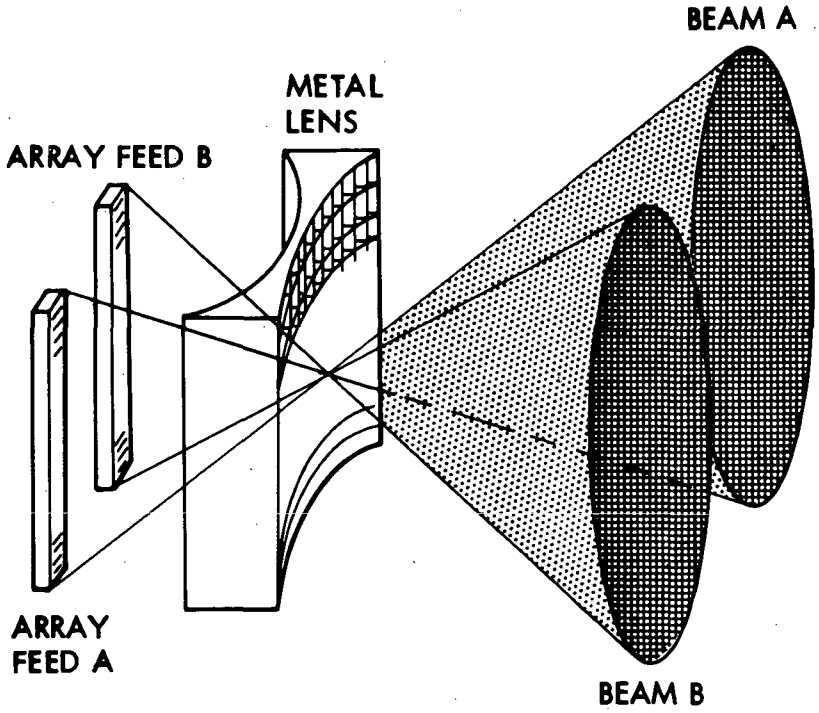


Figure 11-3. Cylindrical Lens Antenna

measurements. Complex sun angles and complete shadowing will cause distortion in the lens as well as the feeds and support structures, resulting in amplitude and phase errors of unknown magnitude. Subsequent beam-shifts, beam cross-coupling and gain degradation can occur. The availability of a space laboratory facilitates the evaluation of the RF performance of this antenna under eal space environmental conditions. Specific objectives, then, will be to obtain the following data as a function of the space environment:

a) Beam-to-beam isolation

b) Polarization isolation

c) Beam shape in E-W and N-S planes

d) Beam pointing errors

e) Relative beam efficiencies (or gain).

The ultimate objective, of course, is to utilize this information in the design of optimum multibeam antennas for satellite communications. A functional block diagram of the experiment configuration is shown in Figure 11-4. The antenna must be pointed toward a cooperative ground station to an accuracy of approximately one-tenth beamwidth or about $\pm 0.25$ degree. Tracking rates will be commensurate with a ground station viewing time of less than 10 minutes, or approximately 1/4 degree per second for an overhead pass using an x-y type mount. An on-board computer, using host vehicle ephemeris data would be employed to point the multibeam antenna, one beam at a time, toward the ground station.

A separate horn antenna, of known polarization purity, will be aligned to one of the polarization vectors of the multibeam antenna and will transmit a narrowband beacon signal to aid the ground station antenna polarization tracking. In this way, polarization tracking by the spacecraft antenna is avoided, and also, the configuration closely simulates the eventual synchronous satellite operational technique.

Following activation of the narrowband polarization beacon, the space-to-ground link is established with a cooperating ground station. The ground station then transmits a CW signal at the center frequency of the spacecraft antenna. From laboratory ephemeris data, the spacecraft antenna is continually pointed at the ground station via open loop computer control. During this initial pass (not more than 10 minutes), the operation of the pointing equipment and reception of signals on one beam would be checked.

As the space vehicle approaches the ground station during the next pass, the computer would direct beam number one toward the ground antenna. The astronauts would begin recording the receive signal power from each beam, adjusting the levels and sensitivities. For each subsequent pass, the remaining beams would be pointed at the ground station and the same data recorded.

Off-axis tests would be conducted during the next phase. These are important, since in actual operation, the antenna must perform over at least the half-power beamwidth of each beam. For a particular beam, offsets from the computer pointed main beam direction would be made to at least the 3 dB points of the antenna in the N-S and E-W directions. The angle offset, signal amplitudes in each orthogonal channel, and channel-

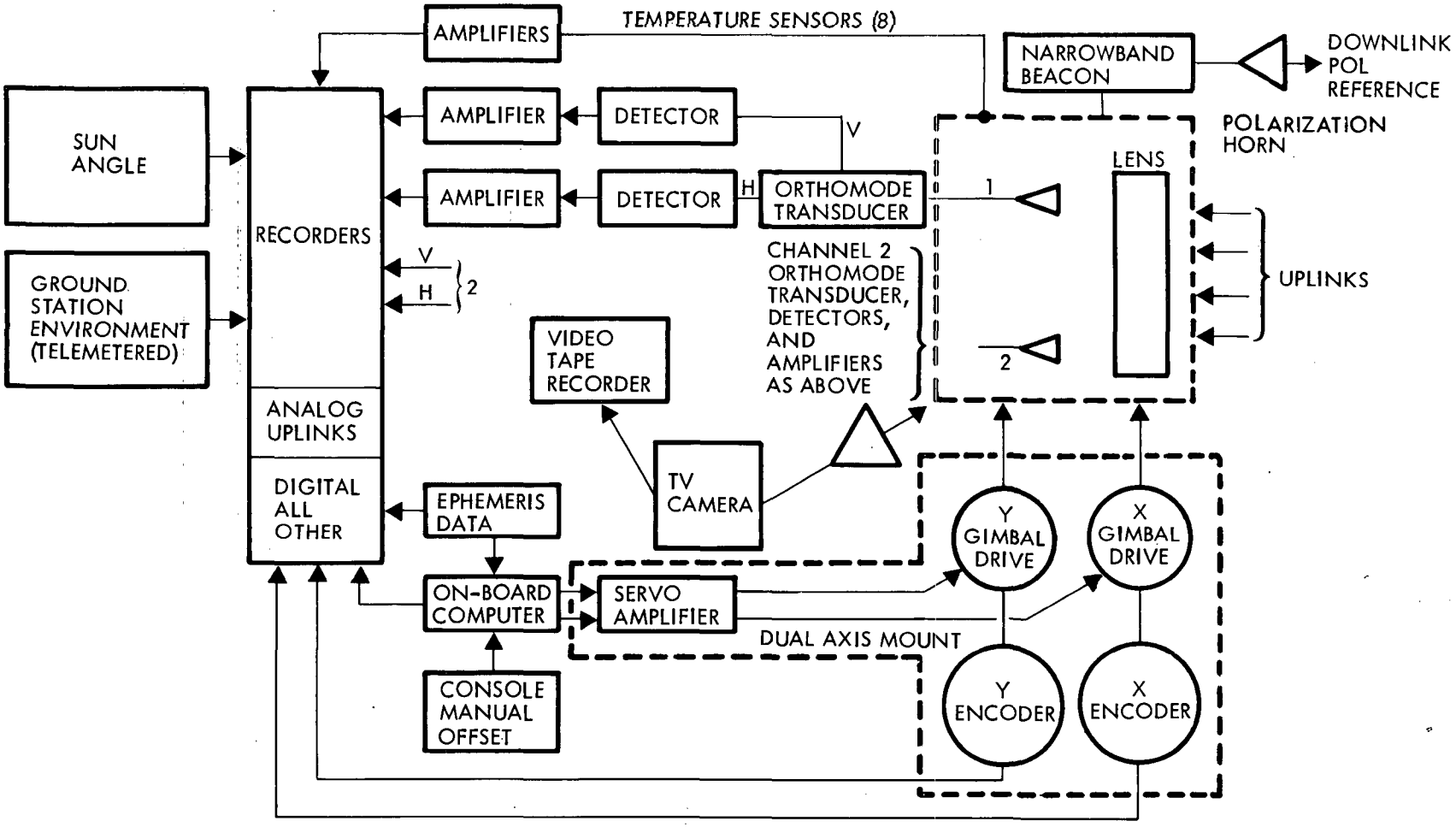


Figure 11-4. Functional Block Diagram — Multibeam Antenna Experiment

to-channel (beam-to-beam) interference levels would be recorded. Antenna physical temperature would also be recorded, while the astronauts would note sun angle and photograph the antenna during various phases of the experiment. Weather data at the ground station would also be recorded. From the above data, beam-to-beam isolation, polarization isolation, beam-pointing errors, relative beam efficiencies, and interference levels can be established.

## 11.5 EXPERIMENT OBSERVATION/MEASUREMENT PROGRAM

The most important measurements are those pertaining to beam and polarization isolation versus antenna surface temperature. The lens antenna is particularly susceptible to this factor, and various sun impingement angles, producing complex temperature gradations across the lens, may induce significant performance variations. The antenna will be extensively instrumented to obtain a detailed temperature profile which may be correlated with photographic data and the electrical performance data measured and recorded during selected CONUS passes.

Relatively simple measurement equipment can be utilized for this experiment. Assuming a 1 kilowatt effective radiated power CW signal emanating from the ground station, signal levels at the laboratory antenna terminals will be -6 dBm on axis to -46 dBm for off-axis measurement of sidelobe interference. Thus, a calibrated crystal detector and DC amplifier provide adequate sensitivity for signal reception. An oscillographic recorder may be used to provide quick-look data; a tape recorder offers a permanent record for post-flight data reduction. The astronaut-experimenter could adjust the sensitivity of the recorders during a given pass. For instance, if the primary beam were pointed at the ground station and no interference was detectable on other beams, the astronaut could switch additional gain into the other channels to obtain a minimum signal level, if present. Since antenna surface temperature variations for a particular pass or series of passes will vary considerably, the crew will adjust amplifier gains accordingly. A temperature profile of the antenna during, after, and prior to electrical performance measurements will be obtained. TV recordings of the antenna position will also be made. Offsets of beam position will be made by the astronauts with accompanying

visual-real time observations and recording of the signal level. Readjustments can be made as necessary.

## 11.6 INTERFACE, SUPPORT AND PERFORMANCE REQUIREMENTS

### 11.6.1 Environmental Requirements

In the Early Laboratory experiments, the antenna-mounted detectors should be temperature-controlled, whereas in later experiments the receivers and transmitters will require thermal protection. In all cases, particular attention must be paid to the design of the drives, gearing, bearings and appropriate lubrication subsystems.

### 11.6.2 Operational Requirements

The operation of the experiment will be semi-automated. The host vehicle must, of course, be oriented in a manner permitting the antenna to be pointed to the ground station throughout the test. Voice links with the cooperating ground station(s) must be effected to coordinate the procedures.

### 11.6.3 Link Power Budget

The experiment for the Early Laboratory is predicated on a receive-only capability at the laboratory. An estimated power budget for this situation, at 14 GHz is given below:

| | |
|---|---|
| Uplink power (1 KW) | 60 dBm |
| Uplink antenna gain (30 foot antenna) | 60 dB |
| Effective radiated power | 138 dBm |
| Space loss (slant range 700 nmi) | -177 dB |
| Power received at Space Lab | -39 dBm |
| Space Lab antenna gain | 32 dB |
| Miscellaneous losses | -1 dB |
| On-axis signal level at detector | -6 dBm |
| Isolation; beam-to-beam | 40 dB |
| Detector sensitivity required | -46 dBm |

### 11.6.4 Special Pointing Requirements

The Early Laboratory half-power beamwidths are proposed to be 2.5 x 3.5 degrees. Pointing accuracies should be approximately 1/10 beamwidth, or 0.25 degree, as referenced to the participating ground station. Growth Laboratory and Total Laboratory antenna pointing requirements will be increasingly stringent, in terms of absolute accuracies.

### 11.6.5 Mounting/Structural Requirements

The antenna should be mounted on a firm structural base on the laboratory. This base must be aligned to an accuracy in the order of $\pm 0.02$ degree to the spacecraft reference system.

### 11.6.6 Electrical Power/Thermal Requirements

A candidate drive system for the antenna is a D.C. torquer operating at 24 volts and consuming slightly less than 100 watts when activated. Thermal protection should be afforded the drive system structure to prevent distortions in pointing.

### 11.6.7 Ground Facility Support Requirements

The cooperating ground station should be capable of providing polarization tracking of the downlink beacon signal with readout accuracies of approximately 0.01 degree. It must be capable of transmitting orthogonally polarized uplink signals with power levels up to 1 KW. It will be required that the ground station crew record polarization angle, uplink power levels, time of acquisition, and local weather conditions. It is anticipated that a single ground station will be capable of supporting experiments for Early, Growth and Total Laboratories.

## 11.7 POTENTIAL ROLE OF MAN

### 11.7.1 Required Functions

Prior to initiating a data collection pass, the host vehicle must be oriented to permit the single axis drive system to position one of the beams to illuminate the cooperating ground station. As data is being acquired, the crew will make gain adjustments in non-used channels to determine signal levels. On later orbits, pointing offsets will be manually introduced to evaluate beam coverage and additional interference effects.

### 11.7.2 Necessary Skills

The experimenters should be knowledgeable in the following areas:

- Antennas and microwaves
- Digital electronics

- Digital and analog recorder operation
- General electronics equipment operation, such as amplifiers, servos, and detectors.

## 11.8 EXPERIMENT EVOLUTION

### 11.8.1 General Considerations

In general, the Growth and Total Laboratory multibeam antennas are more complex versions of the Early Laboratory antennas. The experimental objectives will be similar, with the exception that further performance evaluation will be obtained in the following areas:

a) Transmit-receive isolation

b) Power handling capacity

c) Autotrack capability.

The ability of the astronauts to deploy and assemble the much larger antennas in space will also be demonstrated. With the advent of extended missions and higher orbits in space, the reliability of associated new materials and components will be tested along with accompanying effects upon antenna performance.

Since additional antenna beams, including transmit beams will invariably characterize these antennas, prime attention will be focused on beam polarization/transmit/receive isolations. It is inevitable that transmitted power levels will increase during the 1985-plus time period, and the power handling capacity of the antenna will be tested in space by increasing power levels until (or if) multipactor or corona effects occur within the antenna system. The collimation of a given antenna beam will be measured by comparing it to the autotracking reference beam location.

### 11.8.2 Growth Laboratory

The next generation of multibeam antennas would generally be improved versions or variations of the Early Laboratory antenna incorporating additional capabilities:

a) Very sharp cut-off beams

b) Transmit capabilities

c) A total of eight receive and eight transmit beams would be accommodated on the same antenna.

A similar design is anticipated, but with a considerably larger aperture. It is presently estimated that the antenna aperture will be in the order of 8 - 10 feet wide in the longest dimension, and from 6 - 10 feet in focal length.

For the eight-beam antenna, where E-W time zone coverage will still be maintained, but N-W coverage would be halved, resultant beamwidths would be in the order of 1.7 x 2.5 degrees. However, beam shapes would no longer be Gaussian, but would approximate those shown in Figure 11-5. More than one feed would be required to obtain appropriate shaping, and a simplified indication of the circuitry is shown in Figure 11-6. The dual feed combination shown provides both transmit (TX) and receive (RX) capability at vertical (V) and horizontal (H) polarizations for one spatial beam and employs both phase (P) and amplitude (A) control over the beam.

### 11.8.3 Total Laboratory

It is anticipated that by the year 1990 and beyond, there will be an even greater need to isolate satellite communication systems from one another. Thus, one might envision multibeam coverage of the U.S. by some four to eight beams per time zone depending upon population density. Or further multi-national coverage, such as might be encountered in South America or the larger European countries, is another possibility.

In any case, much larger antennas would be involved--perhaps 30 or 40 feet in diameter. Such antennas would have to be deployable or assembled in space. Since beamwidths of less than one degree are likely, autotracking of a reference ground station would be required on a separate channel. In essence, however, this antenna would be extension of the complexity of the Growth Laboratory antenna, utilizing newly-acquired lightweight materials technology and beamshaping techniques.

Table 11-1 summarizes the significant factors in the evolution of the multiple beam antenna.

## 11.9 SRT REQUIREMENTS

The multiplicity of channels required, especially for Growth Laboratory indications, would suggest that efforts be made to develop solid state, high power integrated amplifier-multiplier-exciter devices.

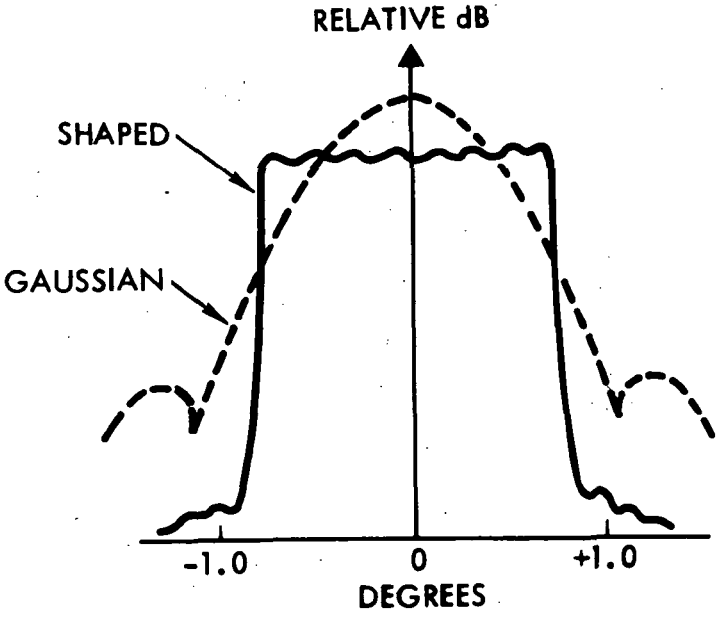


Figure 11-5. Shaped and Gaussian Patterns

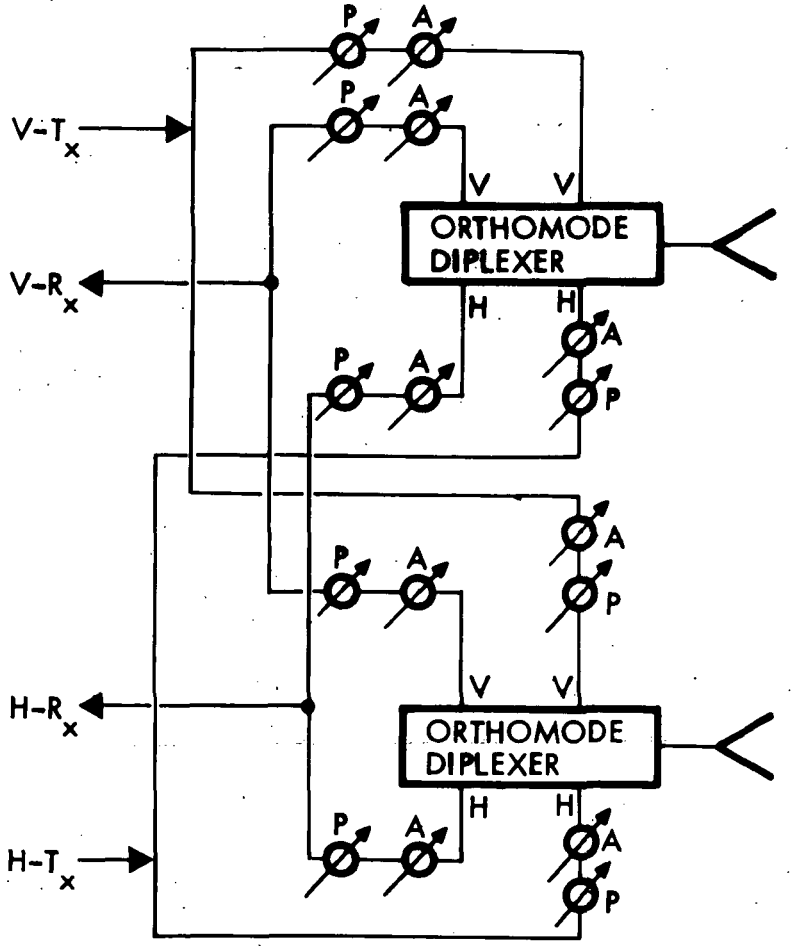


Figure 11-6. Transmit-Receive Dual Polarization Circuitry for Shaped Patterns

Table 11-1. Fixed Multibeam Antenna Evolution

| Time Frame | Antenna Description | Experiments | Comments |
|---|---|---|---|
| Early Lab (1980-85) | Four Beams Total<br>• Two Spatially Separated<br>• Each Dual Polarized<br>Egg-Crate Lens Structure<br>• Aperture: 75" x 25"<br>• Focal Length: 44"<br>• Biax Drives: +70°, X and Y<br>• Weight: 100 pounds<br>• Power: 30 - 40 watts | • Beam Isolation<br>• Polarization Isolation<br>• Beam Shape<br>• Relative Efficiency<br>• Temperature Dependency | • Pointed by Ephemeris Data<br>• Lens/Feed Assembled in Space<br>• Receive Only Experiment<br>• Narrowband Beacon Downlink |
| Growth Lab (1985-1990) | Twenty-Four Beams Total<br>• Eight Frequency Separated<br>• Eight Spacially Separated<br>• Eight Dual Polarized<br>Egg-Crate Lens Structure<br>• Aperture: 8 - 10 ft.<br>• Focal Length: 6 - 8 ft.<br>• Three-Axis Drives<br>• Weight: >100 pounds<br>• Power: >100 watts | • Beam Isolation<br>• Polarization Isolation<br>• Beam Shape<br>• Relative Efficiency<br>• Temperature Dependency<br>• Power Handling Capacity<br>• Receive/Transmit Isolation | • Pointed by Ephemeris Data<br>• Lens/Feed Gimbals Assembled in Space<br>• Transmit and Receive Simultaneously<br>• Shaped Beams |
| Total Lab (1990-?) | Forty-Eight(?) Beams Total<br>• Sixteen Spacially Separated<br>• Sixteen Frequency Separated<br>• Each Above Dual Polarized<br>Structure-Lens ?<br>• Aperture: 30 - 40 ft.<br>• Focal Length: 20 - 30 ft.<br>• Three Axis Drives<br>• Weight: 800 pounds (?)<br>• Power: >1000 watts (?) | • Beam Isolation<br>• Polarization Isolation<br>• Beam Shape<br>• Relative Efficiency<br>• Temperature Dependency<br>• Power Handling Capacity<br>• Receive/Transmit Isolation<br>• Assembly in Space?<br>• Deployment in Space?<br>• Autotrack Accuracy | • Autotrack Pointing<br>• 1° Beamwidths<br>• Shaped Beams |

While several companies are already in the early stages of developing solid state equivalents of the TWTA, future efforts should be devoted to achieving integrated, small size, low weight packages. Virtually the same statements can be made concerning the receiver chain. Here, the need for low noise, solid state parametric amplifiers prevails.

## 11.10 ACKNOWLEDGEMENTS

### 11.10.1 Related Experiments

| Experiment | Principal Investigator and Association |
|---|---|
| Communication Satellite Antenna Research | Goddard Space Flight Center, Research and Technology Operating Plan (RTOP) |
| Frequency Reuse and Multiple Shaped Beam Antennas | V. Galino/W. Imbriale, TRW Systems Group |
| Multiple Feed Reflector Antenna | J. Duncan, TRW Systems Group |
| Multiple Shaped Beam Antenna | J. Duncan/V. Galindo, TRW Systems Group |
| High Gain Multiple Beam Antenna System | J. Duncan, TRW Systems Group |
| Multiple Beam Antenna Configuration | Lipke, ComSat Corporation |
| Phased Array Antenna | R. Krentel, ComSat Corporation |
| Multiple Shaped Beam Antenna | H. Ward, Fairchild-Hiller Corp. |

# EXPERIMENT 12

# LARGE DEPLOYABLE REFLECTORS

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# 12. LARGE DEPLOYABLE REFLECTORS

## 12.1 EXPERIMENT CLASSIFICATION

Developmental/Operational Testing.

## 12.2 EXPERIMENT OBJECTIVES

The objectives of this experiment are to:

a) Evaluate the deployment mechanism of large reflectors in the space environment

b) Measure the mechanical and thermal stability after deployment

c) Measure RF performance characteristics.

Determination of the detailed performance of very large deployable structures in the zero-gravity, space thermal environment is ideally suited to the scope of activities envisioned for the Comm/Nav laboratory program. Specifically, this experiment focuses attention on very large reflectors--up to and possibly exceeding 150 feet in diameter--used primarily as high gain, narrow-beam antennas. Unmanned spacecraft, employing reflectors with ever increasing size are already evolving in satisfaction of requirements for commercial and military communications, direct TV satellite broadcast, and civil systems data usage.

A simple, easily erected narrow-beam antenna providing greatly enhanced directivity and gain at the lower space communication frequencies would be a valuable contribution to the United Stats communication and navigation progress. Among many potential uses it would be applicable to the location and identification of terrestrial sources of RF noise and interference.

## 12.3 DISCIPLINE BACKGROUND AND STATE

Large deployable reflectors, with the attendant high gain and narrow beamwidth, offer many advantages to alleviating the communication link power budget problem and the narrow area coverage required for future communication applications. This is particularly true at the lower frequencies where interference must be minimized and low cost/complexity ground-based users must be satisfied. For example, in the case of direct broadcast TV in the 690 MHz region, large deployable high gain

antennas offer an attractive approach to obtaining the required effective radiated power to permit home TV reception direct from a synchronous satellite. Conceivably large city communications sytems, such as the police departments, could achieve clear UHF communication via satellites employing such antennas. Data communications systems of similar local usage will also benefit from such a system.

From synchronous orbit, antenna beamwidths in the order of one degree or less are required to restrict coverage to reasonable geographical areas--New England, Florida, Southern California are representative examples. At the direct TV broadcast frequencies (690 MHz), antenna diameters in the order of 100 feet would be required, while at the allocated UHF local mobile frequencies below 460 MHz, 150 foot diameter reflectors would be required.

Numerous aerospace companies have conceived of various schemes for deployable parabolic reflectors. Several government and company-funded studies have ensued and a wide variety of deployable parabolic and passive reflectors have been proposed. These concepts range from simple restrained energy "pop-open" quasi-parabolas to complex, slowly deploying, electrically actuated structures.

There are several important characteristics which determine the relative merit of the competing designs for space applications. Among these are the effects upon spacecraft stability, deployment reliability, thermal distortions after deployment, surface accuracy after deployment, and overall RF performance. Implementation of a manned orbiting laboratory will readily permit direct observation and measurement of the above events using candidate antennas in the actual space environments, including the most important effect, the zero gravity condition.

## 12.4 EXPERIMENT DESCRIPTION

Three phases are involved in the performance of this experiment:

- Observation and measurement of the deployment sequence
- Measurement of the stability and condition of the reflector after deployment
- Evaluation of the RF performance of the reflector after deployment.

Several diverse approaches to deploying and evaluating the large reflectors have been considered. The key features of each are discussed in the following paragraphs.

Figure 12-1 illustrates conceptually a simple technique employing an extendable boom with the deployable reflector package attached to the end. Extension of the boom and unfurling the antenna would be controlled from within the pressurized laboratory. Cables interconnecting instrumentation attached to the antenna with monitoring equipment in the laboratory will be routed through or along the boom structure. In order to recover the antenna at the conclusion of the test phase, it must be capable of being refurled or astronaut extra-vehicular activity (EVA) is required to manually accomplish this operation.

Two-axis control of the antenna beam pointing for RF performance tests presents a special problem, the solution to which is not completely defined at this time. A conventional drive mechanism at the laboratory-attach point of the boom may induce an oscillation or "nodding" of the antenna. However, a further investigation of this problem must be conducted to ascertain its acceptability.

An alternate approach involves release of a subsatellite with the reflector package attached to it. During the ensuing deployment sequence empirical data can be obtained on the effects of the reaction forces exerted on the subsatellite. Antenna beam pointing control must be considered if operational performance evaluation is an objective. Gravity gradient stabilization offers an interesting approach for cases where the opposing link source is a cooperating ground station.

A third scheme requires assembling and inflating a metalized mylar reflector in space by means of EVA based on the Shuttle-supported Comm/Nav laboratory. Figure 12-2 is an artist's rendition of the implementation concept. The mylar reflector would consist of two large discs of the same diameter, one of aluminized mylar, and the other plain, welded together around their circumference to form a mylar bag. The reflector would be attached to a large light alloy ring fabricated of multiple identical thin wall arc sections that are assembled in space.

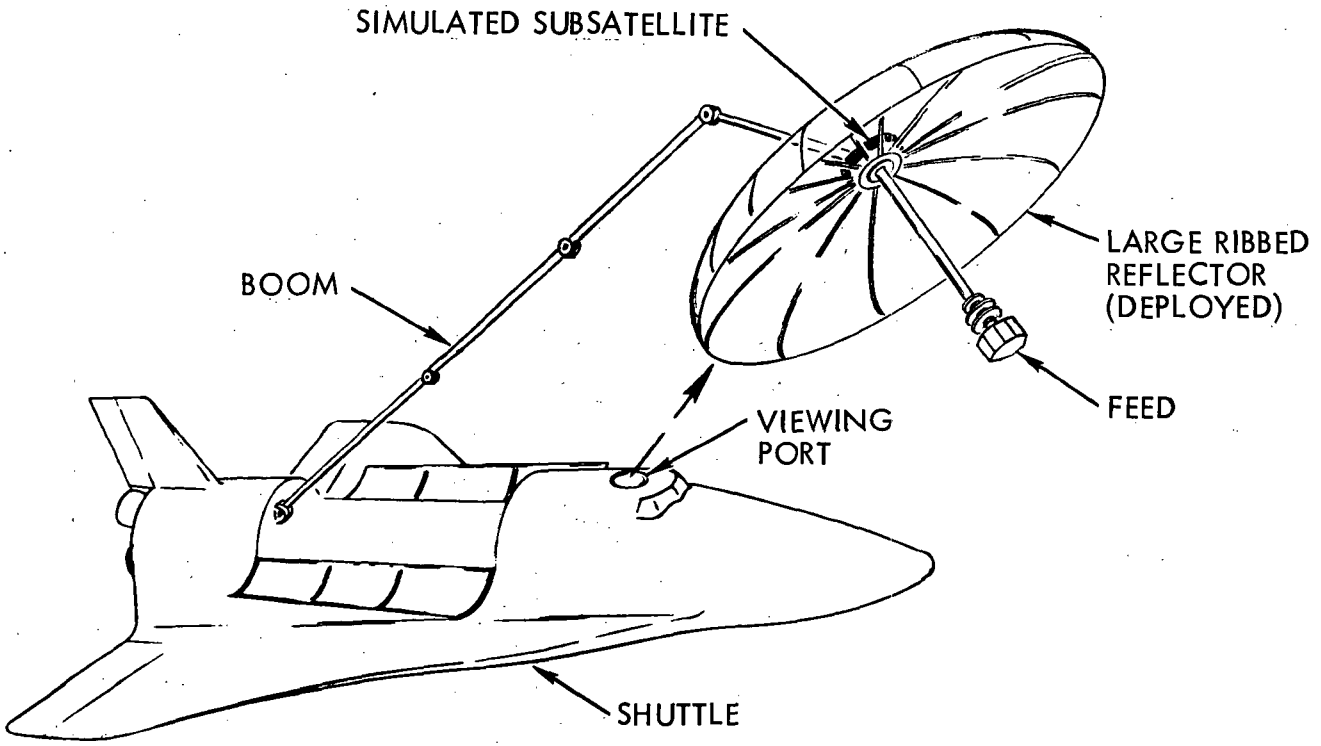


Figure 12-1. Boom-Attached Deployable Reflector

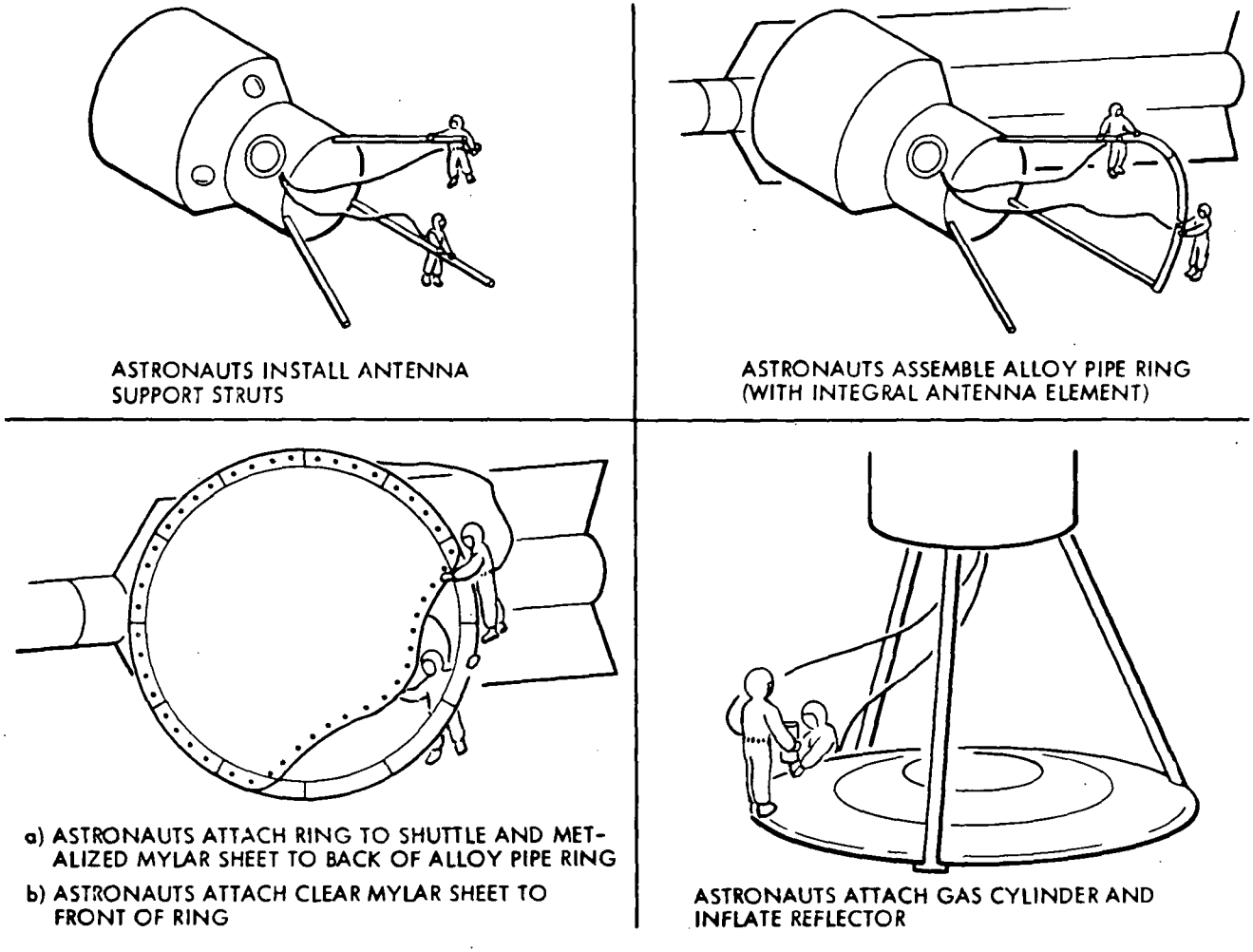


Figure 12-2. Erection Sequence for Large Inflatable Reflector

The mylar bag would be attached to the assembled ring and then slightly inflated using high pressure bottled inert gas. The inflation would separate the two discs and form a double convex shape. The metalized disc would serve as a parabolic reflector, while the plain mylar disc would be transparent. A simple dipole, mounted within the bag during manufacture, would serve as the receiving element.

Three of the ring segments would be provided with mounting lugs to allow the reflector-antenna subsystem to be attached by three light alloy tubes (legs) to either the Shuttle pallet or free-flying module.

The reflector size range of interest for 100 MHz operation is between 50 and 500 feet in diameter. At 100 MHz the skin depth penetration is 0.35 mils, making a mylar reflector entirely feasible from a metalizing standpoint. Pressure control offers prospect for variable focus.

In each of the techniques discussed above, the succession of deployment events would be recorded on film using high speed photography. The experimenters' visual observations would also be recorded on magnetic tape. Accelerometers will sense the forces generated at critical points of the structure and particularly at the subsatellite interface. For several orbits, the aperture or parabolic shape of the reflector would be photographed with cameras having various degrees of resolution. During this activity, incident sun angles and reflector surface temperatures would be recorded simultaneously. Figure 12-3 depicts the functional interconnection of instrumentation to make these measurements.

The final step in the experiment would be measurement of the RF performance of the antenna in the operational environment. Ideally, a broadband feed would be employed to obtain relative gain and pattern measurements as a function of frequency. This data will be correlated with thermal distortion measurements to provide a measure of the deviation of the reflector surface from the ideal precision paraboloid.

## 12.5 EXPERIMENT OBSERVATION/MEASUREMENT PROGRAM

Figure 12-3 identifies the essential elements required to evaluate the deployment process:

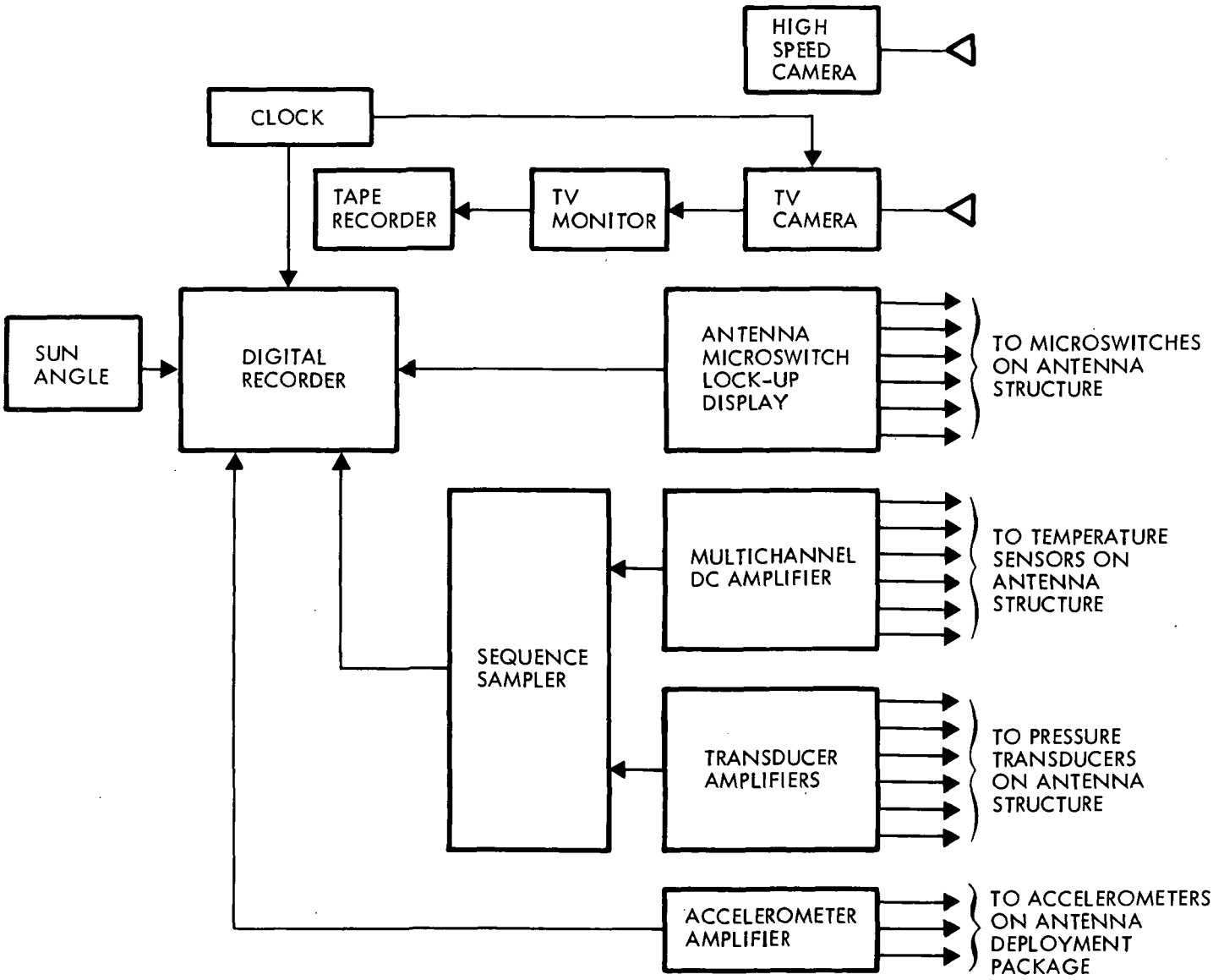


Figure 12-3. Instrumentation Configuration — Antenna Deployment Monitoring

- A high speed camera
- Accelerometers on antenna structure
- TV camera, monitor and recorder
- Pressure transducers
- Microswitch actuations of deployment sequence

One astronaut-experimenter controls the high speed camera while the other operates the TV camera and optimizes the picture quality, both noting their subjective observations. Antenna-mounted transducers would automatically record the forces generated on various parts of the structure during deployment, while the sequential actuation of deployment would be time-recorded via microswitches on the antenna. Accelerometers sense the forces generated during deployment upon a simulated satellite.

Following deployment, the temperature and pressure sensor outputs would continue to be recorded concurrently with measurements of incident sun angle on the reflector. The TV camera would make periodic visual recordings, actuated by the clock.

Three sources are potential candidates which can be used to determine the RF performance of the antennas:

a) Cooperative ground stations

b) One or more synchronous satellites emitting signals in the frequency range of operation of the antennas

c) Known stellar radio sources such as Cassiopeia A, Taurus A, Cygnus A, and Virgo A.

The first of these requires modest slew rates and produces relatively short periods of data collection. The accelerations associated with pointing such a large, lightweight antenna may cause distortions not realistically simulating any expected application for this antenna.

The second approach permits the experimenters to obtain data for approximately one-half orbit, or about 45 minutes using a single satellite as a source. It is anticipated that an increasing number of synchronous satellites will be available in the projected operational time period for the Comm/Nav laboratory (1980-1990) which can provide suitable trans-

missions over the frequency bands of interest. Moreover, the ground station terminals associated with these synchronous satellites can serve as references for the laboratory measurements. Figure 12-4 is a pictorial sketch of this configuration.

The third technique involves exo-atmospheric radio astronomy procedures and, therefore, the antenna could be employed for additional experiments specifically associated with radio astronomy (not now planned in the NASA research investigations). The practicality of the method is evidenced by the simplicity of equipment involved and the fact that it is widely used to calibrate large ground antennas. The prime limitation of this technique is system sensitivity. Consequently, measurement of sidelobes below 20 - 25 dB is unlikely.

Future systems utilizing narrow shaped-beam antennas will require suppressed sidelobes since this represents potential interference to adjacent areas of the earth. On the basis of this preliminary assessment, RF performance using synchronous satellites appears the most promising. Figure 12-5 illustrates the supporting equipment required in the pressurized laboratory.

The antenna (boom-mounted) is pointed at the satellite from tape-generated ephemeris data and receives signals via a conventional tunable receiver. Simultaneously, an earth station also monitors the satellite emission. The amplitude of the received signal on-board the space laboratory is recorded for on-axis conditions and compared with the predicted amplitude as well as the ground station received signal data.

Antenna pattern data would be generated by offsetting the antenna boresight and recording the received signal level until the receiver reached threshold. It is estimated that at 400 MHz, receiver sensitivities of approximately -117 dBm will be adequate. (Reference power budget in Section 12.6.)

## 12.6 INTERFACE, SUPPORT AND PERFORMANCE REQUIREMENTS

### 12.6.1 Operational Requirements

Implementation of this experiment will most probably require a brief EVA by the astronaut experimenter(s) to perform some portions of the deployment and/or furling sequence. Following deployment,

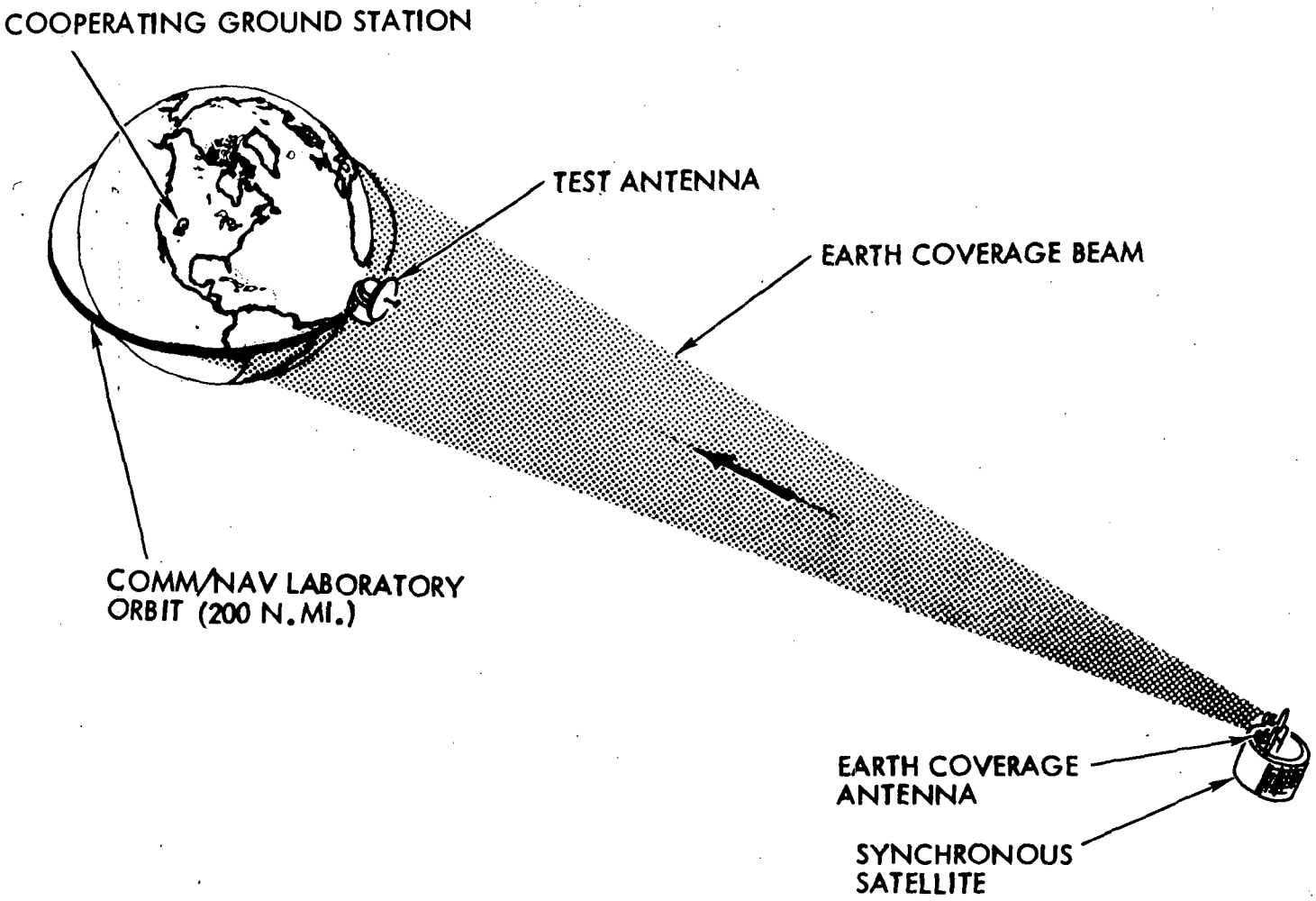


Figure 12-4. RF Performance Evaluation Using Cooperative Synchronous Satellite

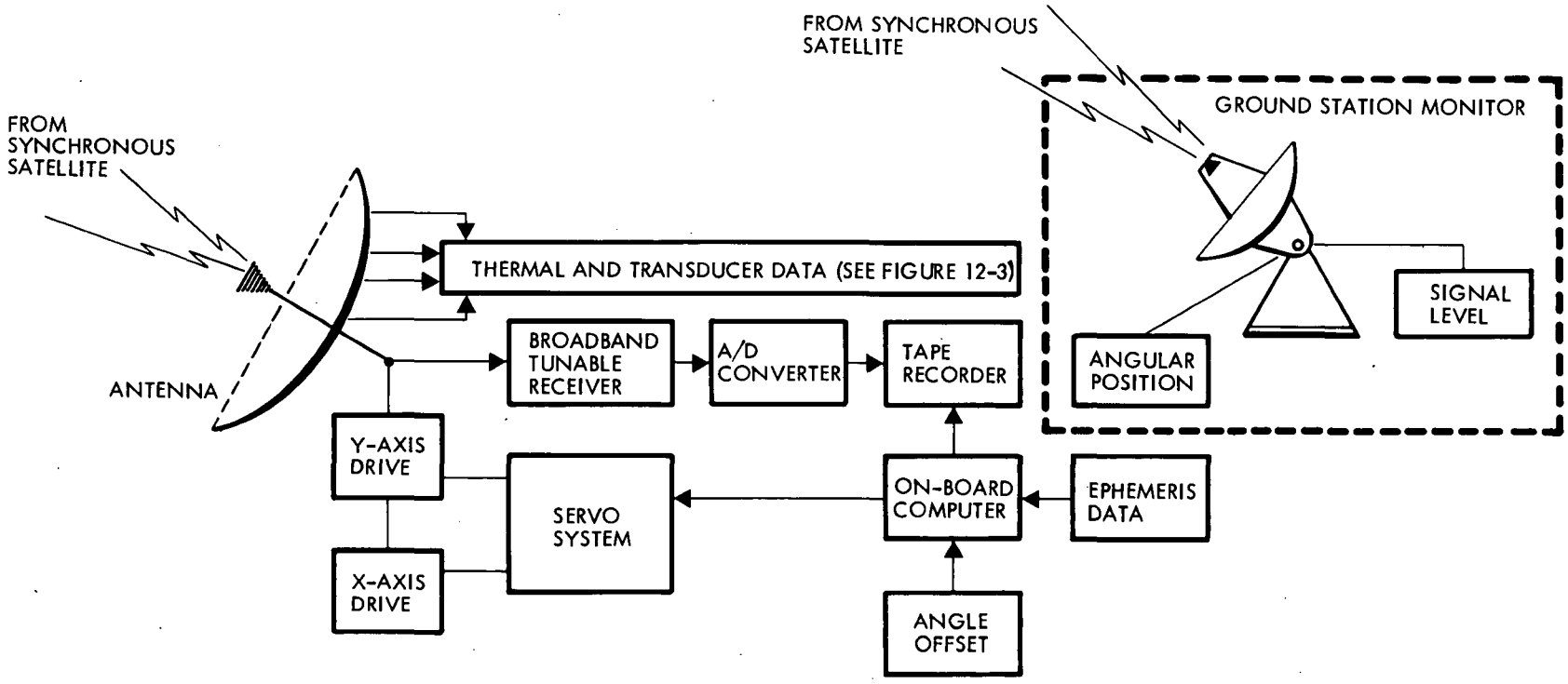


Figure 12-5. Supporting Equipment Configuration – RF Performance Evaluation

reorientation of the laboratory will be required to aid pointing of the antenna at a desired source. It may also be desired to permit exposure of the antenna to a wide range of incident sun angles.

Participating cooperating ground stations will be required to monitor the synchronous satellite transmissions to provide a reference for comparative performance evaluations with the data collected by the Comm/Nav laboratory.

### 12.6.2 Power Budget

An estimated power budget for measurement of the reflector gain and pattern data is given below, assuming an earth coverage antenna from synchronous altitude operating at 400 MHz.

| | |
|---|---|
| Frequency: 400 MHz | |
| Synchronous Satellite Power Output (10 W) | 40 dBm |
| Synchronous Satellite Antenna Gain (Edge of earth) | 13 dBi |
| Coupling Losses | - 1 |
| Effective Radiated Power | 52 dBm |
| Space Loss (23, 000 n. mi.) | -177 dB |
| Received Power at Space Station | -125 dBm |
| Space Station Antenna Gain (100 ft. antenna) | 38 dBi |
| Power Available at Receiver Terminal | - 87 dBm |
| Capability to Measure Sidelobe 30 dB Down | - 30 |
| Required Receiver Sensitivity | -117 dBm |

### 12.6.3 Special Pointing Requirements

The beamwidth of a UHF antenna in the order of 100 - 150 feet in diameter will be less than two degrees and less than one degree at the TV broadcast frequency. Therefore, the antenna should be capable of being positioned to an accuracy of 0.1 degree, or 1/10 of a beamwidth.

## 12.7 POTENTIAL ROLE OF MAN

### 12.7.1 Required Functions

The experimenters must perform the following functions:

- Operate TV camera
- Actuate boom deployment
- Position boom
- Actuate antenna deployment

- Monitor displays
- Position antenna
- Operate receiver.

12.7.2 Necessary Skills

The following skills or areas of knowledge are considered necessary for this experiment:

- Knowledge of general purpose electronic instrumentation
- Acquaintance with deployment techniques and mechanization
- High speed camera operation.

## 12.8 EXPERIMENT EVOLUTION

The complexity of deploying and pointing the large structures involved in this experiment and the requirements for EVA suggest that these experiments be deferred to the Growth Laboratory phase, although earlier tests are certainly possible. The evolution of the experiments should progress from small, simple antenna structures, perhaps without RF capability, to larger more complex structures with operational RF capabilities. Another candidate for consideration (not previously discussed) is the deployment of a large (≈100 foot square) passive reflector, re-radiating energy to the ground when the reflector is illuminated by ground stations.

## 12.9 SRT REQUIREMENTS

The proposed experiment is devoted to a space demonstration and evaluating the performance of candidate reflector designs. To support this experiment, the completion of the following SR&T activities is required:

a) Large diameter reflector development

b) Tethering and safety aspects of EVA assembly

c) Improved measurement techniques for assembled reflectors.

The reflector development activities will include materials research, constructional methods evaluation and development, reflector design, fabrication and testing.

Deployment of the antenna may involve EVA; therefore, it will be necessary to study and establish design constraints that will minimize the possibility of "losing" system components during an assembly process in space.

Another aspect of the same study must be consideration of astronaut safety needs during EVA. For example, if retaining lines are used for each structural item, an astronaut's life line could become tangled with these other lines, or the structure. A second SR&T task, therefore, involves establishing safe methods of material control for EVA.

The third area will treat the problem of evaluating the electrical performance of the assembled antenna. Very large antennas used at high frequencies have narrow beamwidths which complicates the measurement activities. If a conventional laboratory-to-ground communication link is used for the evaluation, one has to provide a tracking mount. Without this pointing capability, the dwell time at a given ground station is very short and infrequent. Alternatives are to measure the antenna characteristics using a fixed remote transmitter, extended on long tripod legs in front of the dish. Fresnel (near-field) measurements could be obtained in this manner, which could be converted to the conventional Fraunhofer (far-field) patterns.

Optical methods of measuring the deviation of reflector surfaces from the design contour have been developed and appear potentially feasible for space use. The dish is illuminated with a coherent light source at the focus. The reflected wavefront is allowed to interfere with a direct wave from the source, in the plane of a photographic film. The interference pattern between these two monochromatic waves sets up a spatial intensity pattern on the film which can be directly related to reflector distortions.

A television camera might be substituted for the regular film plate cameras used in a terrestrial environment, allowing the time history of distortion, as a function of such variables as solar illumination angle to be accumulated on magnetic tape for future detailed analysis.

## 12.10 ACKNOWLEDGEMENTS

### 12.10.1 Related Experiments

The following suggested experiments were considered in the preparation of this experiment definition:

| Experiment | Principal Investigator and Association |
|---|---|
| Signal Relay Systems Using Large Space Arrays | J. Yates, MITRE Corp. |
| Ku-Band Unfurlable Antenna | Radiation Systems |

### 12.10.2 References


1. Preliminary Edition of Reference Earth Orbital Research and Applications Investigations (Blue Book), vol. V, Communications/Navigation, NASA, 15 January 1971.

2. 1969 Company IR&D on Expandable Truss Antennas, TRW Systems Group Document No. 99994-6050-R0-00, 31 December 1969.

3. Large Erectable Antenna for Space Applications, General Dynamics Report GDC-DCL-69-003, Final Report, 30 December 1969.

4. R. L. Scrafford, "Proposal for Air-Inflated Antenna Study," TRW Systems Memo 7260.5-11, 13 December 1960.

# EXPERIMENT 13

# NARROWBEAM TRACKING EXPERIMENT

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# 13. NARROWBEAM TRACKING EXPERIMENT

## 13.1 EXPERIMENT CLASSIFICATION

The proposed activities are a combination of engineering development and operational testing to demonstrate feasibility.

## 13.2 EXPERIMENT OBJECTIVES

The primary objectives for this experiment are:

- By comparative evaluation, to select the most promising candidate method
- To combine the best mixture of concepts and hardware to form a space compatible design
- To perform evaluation tests in space to validate the operational characteristics and identity potential improvements.

The immediate application for the results of this experiment is in data relay space communication links between various space vehicles and the proposed Data Relay Satellite (DRS).

The concept of data relay, described in the Communication Relay experiment (Section 6.0), assumes the use of two spacecraft in geostationary (synchronous) orbit. These two satellites are used to track a variety of NASA satellites and space vehicles in lower-altitude orbits to relay commands from the ground to "user" satellites and, in turn, relay their measurement and other data back to earth. These communication services are now performed by NASA's global network of terrestrial stations, but this can only accommodate relatively low data rates. Current data gathering satellites use simple, low power telemetry equipment to communicate directly with the terrestrial ground stations, from altitudes of a few hundred miles. In the data relay concept, the user satellites will be communicating with the tracking relay spacecraft over distances of more than 20,000 miles, because of its synchronous orbit.

Vital to the solution of communicating over the significantly greater distance is the capability to achieve the mutual pointing accuracy required by the data relay and user satellites. Transmission of data rates in excess of 1 megabit/second are expected to employ Ku-band frequencies

(13.4 - 15.35 GHz). Link power budget considerations dictate selection of antenna apertures which will exhibit beam widths ranging from 0.1 to 0.5 degree. The time-dependent geometry variation, illustrated in Figure 13-1, coupled with the narrow antenna beamwidths necessitates inclusion of some provision for pointing the antenna.

In addition to the potential scientific and commercial interest, numerous military applications depend on the successful implementation of this concept. Space-to-space links will operate in the 60 GHz region, the oxygen absorption band, so that the considerable atmospheric attenuation provides high interference isolation from terrestrial sources and thereby minimizes the possibility of detection by hostile earth-based stations.

## 13.3 DISCIPLINE BACKGROUND AND STATUS

A number of aerospace companies are experimenting with millimeter antenna tracking systems for space applications. At least three technological disciplines are concerned: the antenna/microwave field, the active controls and drive motors field, and the materials and processes field. Dominant among these is the antenna/microwave area which demands feed subsystems capable of achieving and maintaining tracking and collimation, controls and motors which respond accurately to error signals, and antenna surfaces which are essentially distortion-free under the space environments.

An example of state-of-the-art technology in these disciplines is illustrated by a TRW-developed 9-ft diameter Cassegrain antenna system designed to operate at 60 GHz. This antenna employs low coefficient of expansion graphite-reinforced fiber as the basic structural material. The resultant reflector exhibits surface tolerances of 0.003 inch RMS. Recent gain and autotracking tests demonstrated that excellent performance was achieved with a five-horn tracking feed. However, the thermal environment likely to be encountered in space cannot be adequately simulated and evaluated, especially at 60 GHz where atmospheric conditions which influence the test results are variable and difficult to control. Moreover, the tracking dynamics under the same conditions and over wide angular coverage cannot be tested realistically. The Comm/Nav laboratory offers an ideal test bed to support the design and development test verification effort.

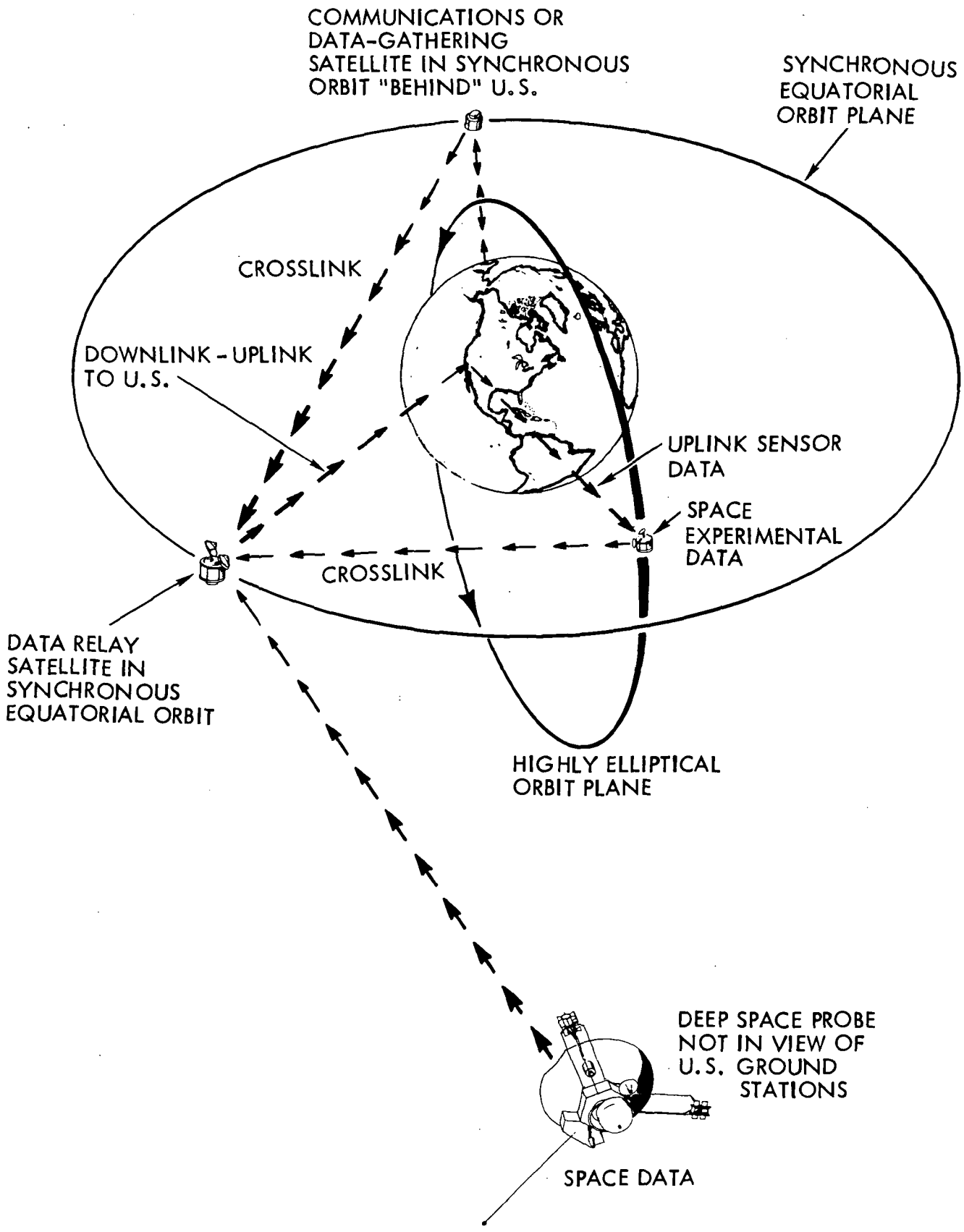


Figure 13-1. Data Relay Satellite Applications

## 13.4 EXPERIMENT DESCRIPTION

### 13.4.1 Choice of Antenna

At this time it is not clear whether the link operating frequencies for the proposed experiment will be in the 13.25 - 15.35 GHz or the 60 GHz range. Although the intent of the experiment can be demonstrated at either frequency, the actual choice will have a significant effect on the experiment design and results. The lower frequency does not provide the oxygen absorption isolation from earth originated RFI and makes it more difficult to realize a 0.5 degree beamwidth to fully test the narrow beam performane. For the purposes of this description it has been assumed that both frequencies will be used, the 13.25 - 15.35 GHz range for the earlier experiments and the 60 GHz range for later experiments. In either case, the same reflector and mount can be employed. The feed systems, receivers and transmitters would be interchanged as necessary.

Various applications of Data Relay Satellites were shown in Figure 13-1. Figure 13-2 illustrates the type of geometry encountered with a low-orbiting space laboratory in communicating with a cooperating geo-synchronous satellite. An earth coverage radiation pattern is assumed, so that the Comm/Nav laboratory will have slightly more than one-half an orbit to conduct experiments. The space lab antenna must, therefore, rotate at least 180 degrees, in one plane to maintain continuous coverage from point A to point B, and to provide maximum flexibility in accommodating various orbital elements, and probably 180 degrees in the orthogonal plane.

A preliminary power budget indicates that at 60 GHz an antenna gain of 63 dBi will be required, resulting in an antenna diameter of approximately 10 feet and half-power beamwidths of slightly greater than 0.10 degree. At 13.25 GHz, the gain from this antenna would approach 50 dB with a beamwidth in the order of 0.5 degree. In order to minimize circuit loss and maximize antenna efficiency, a Cassegrain antenna is the optimum choice. The antenna can use either non-linear illumination to provide a shaped geometry, or the feed subsystem can be designed to achieve uniform illumination and thereby otpimize aperture efficiency. It is envisioned that more than one set of tracking feeds would be employed to evaluate the relative performance of these approaches or some

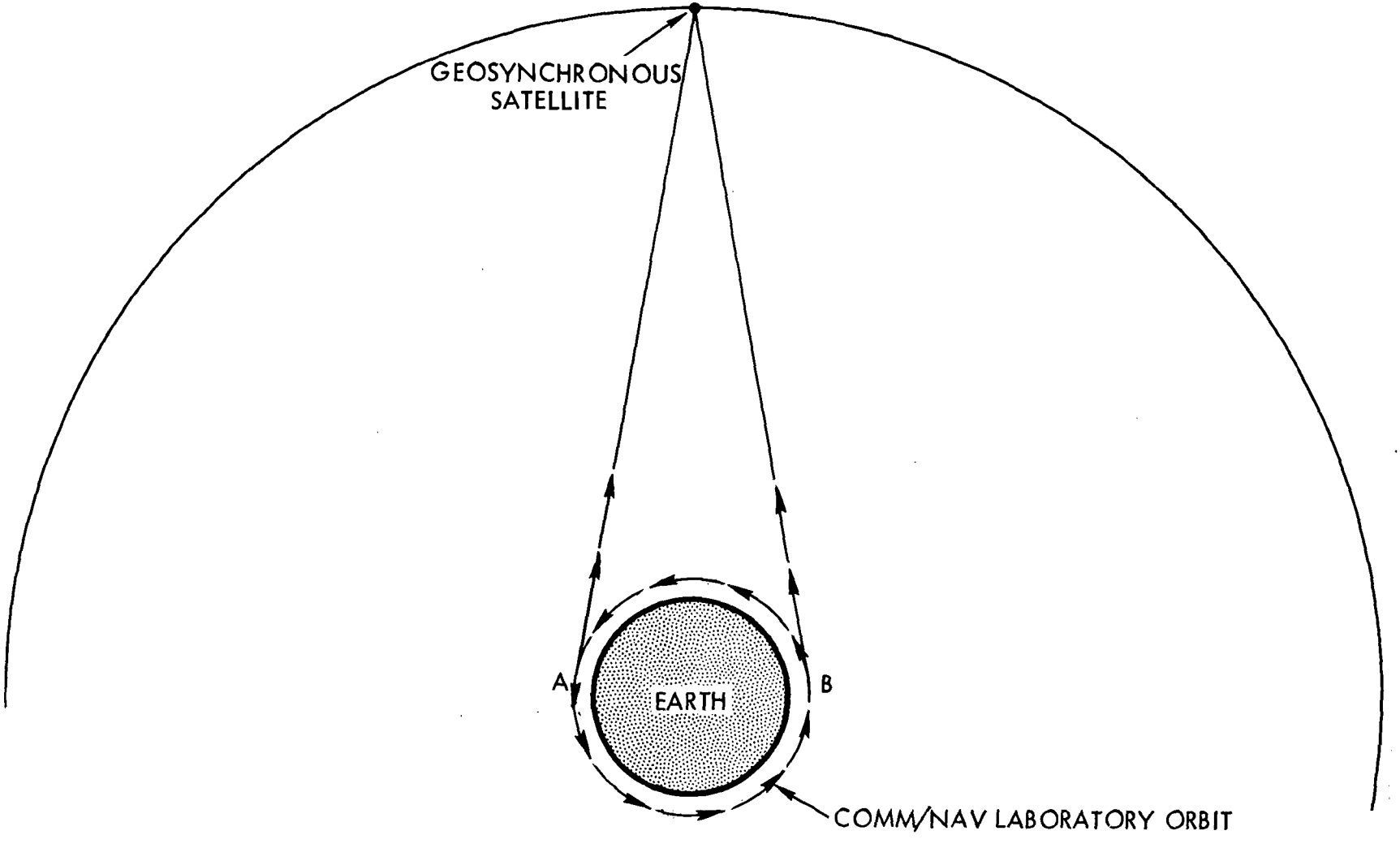


Figure 13-2. Geometry of Space Lab Tracking Geocentric Satellite

combinations for at least one frequency band. Multihorn, multimode, lens or other (as yet undeveloped) feed subsystems are candidates.

### 13.4.2 Equipment Requirements

The test antenna subsystem must permit both an evaluation of its tracking, performance, and the resulting wideband data collection ability of the complete system. Figure 13-3 is a functional block diagram of the subsystem necessary to perform these functions. As indicated by the dashed line, much of the equipment is mounted directly on the antenna, or, at least, in close proximity of it. This is necessary to minimize the number of cables, that must be run to the pressurized interior of the spacecraft, and enhances cable flexibility and reliability. The pedestal or mount, indicated only by the drive motors in the diagram would be an improved version of existing two-axis tracking assemblies used for classified space reflectors, combined with the latest refinements used in the much heavier and more complex design used at ground stations.

### 13.4.3 Experiment Procedure

Prior to launch, the pedestal would be in a horizontal position attached to the space laboratory floor by a hinge, while the antenna and its associated equipment would be stored nearby. In space, the astronauts would unlatch the pedestal, erect it into the vertical position, and lock it in place. The antenna would then be placed on the mount and also locked in place. Coaxial and control cables leading to the pressurized cabin would be connected. Finally, some initial operational tests would be conducted, such as antenna positioning via manual and computer modes, transmitter functioning, and receiver chain operation.

The next step would include acquisition of the geostationery satellite using the computer mode of operation and tracking through one or more half-orbits. Deliberate manual offsets could be made and re-acquisition performed. After this initial familiarization and successful operation of the system, subsequent orbits would be devoted to conducting formalized tests to accumulate statistically valid data on the DRS link pointing errors.

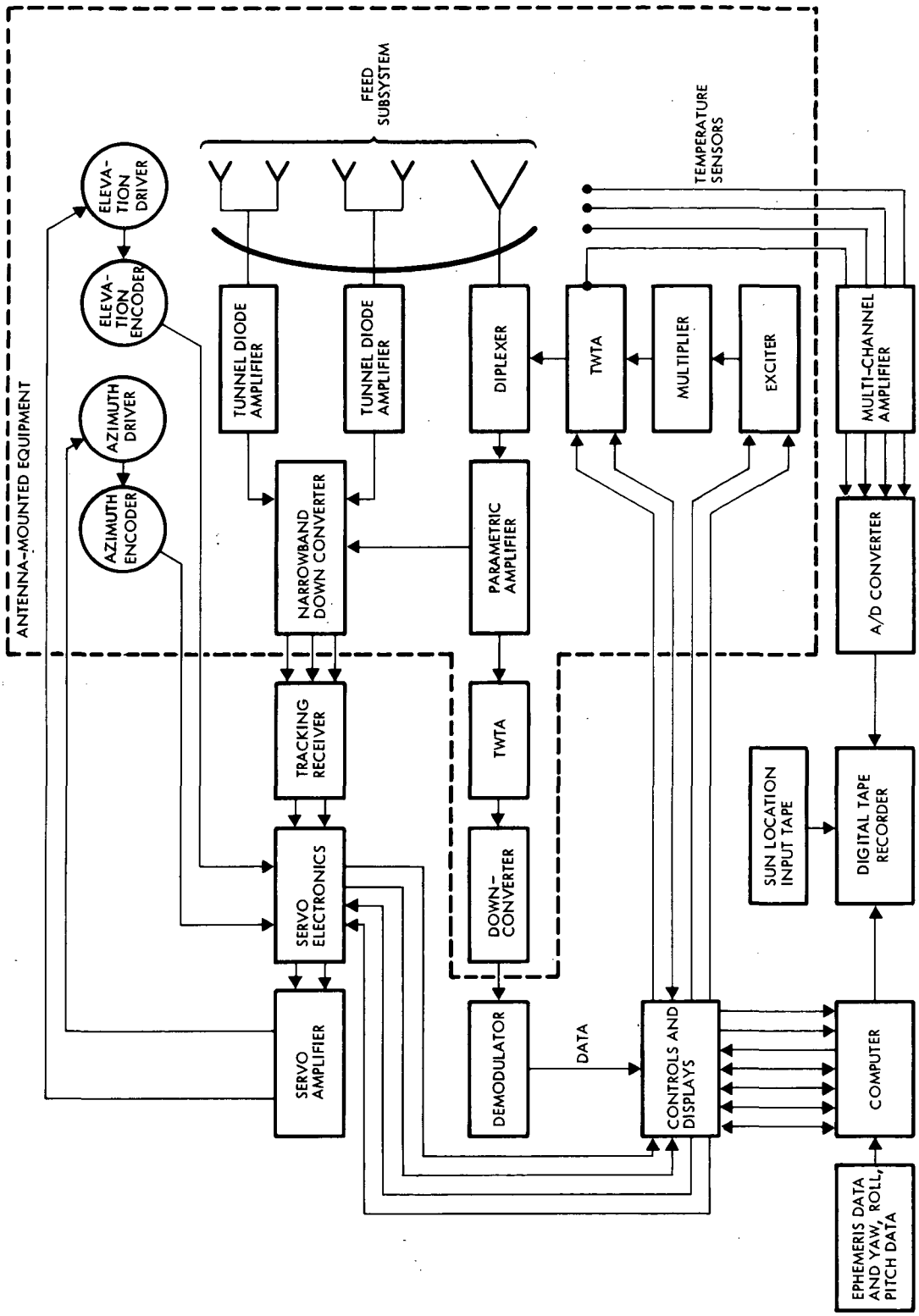


Figure 13-3. Functional Block Diagram – Narrow Beam Tracking Experiment

## 13.5 EXPERIMENT OBSERVATION/MEASUREMENT PROGRAM

Measurements to be made during this experiment include the following:

1) Acquisition time
2) Tracking jitter
3) Receive and transmit beam collimation
4) Bit error rate
5) Sensitivity limitations (receiver)
6) Temperature of antenna and other equipment
7) Atmospheric and multipath effects
8) Effect of sun angle on tracking and data rate performance.

The acquisition time will be measured as follows:

1) The astronaut/experimenter will initiate a computer-aided pointing mode to direct the antenna at the geo-synchronous satellite based on predicted estimates of the position of the two terminals.
2) The autotrack mode will be selected, initiating an antenna scan sequence.
3) The limits of antenna scan and verification of stable lock-on will be recorded as a function of time.

Tracking jitter will be continuously recorded via the encoder outputs through the computer and into the digital tape recorder.

Receive and transmit beam collimation will be measured as follows:

1) The experimenter will "dial in" small (digital) offsets in elevation and azimuth to the extent that the autotrack mode is not lost.
2) The receive signal level will be recorded on the digital recorder together with manual offset angles.
3) Changes in transmit signal levels will be recorded on the ground in time synchronization with the experiment.

The bit error rate will be measured automatically and recorded on the digital recorder during various data rate tests from the ground station.

Autotrack limitations will be measured by reducing the gain of the tunnel diode amplifiers or downconverters from the control console. Since the cooperating satellite is a transponder device, receiver sensitivity will be measured by reducing the transmitter power until the phase lock loop loses lock.

The temperature of various portions of the antenna and other critical equipment such as the transmitter, parametric amplifier and tunnel diode amplifier will be continuously monitored to correlate with time, event, and ephemeris data.

As the Comm/Nav laboratory approaches points near the limb of the earth, the effects of the earth's atmosphere and reflections from the earth itself will degrade communication and tracking capabilities. At the onset of this condition, the experimenter may employ compensatory techniques including increases in the transmitted power.

The effect of the sun on antenna performance is two fold: First, the thermal heating induces antenna distortions which produce consequent gain and boresight errors; secondly, when the sun is positioned it produces significantly higher noise temperature and results in appreciably reduced sensitivity. Therefore, the sun-laboratory-antenna boresight angle is an important parameter which must be calculated from the laboratory ephemerides and the antenna pointing data to permit correlation with the system performance data.

## 13.6 INTERFACE, SUPPORT AND PERFORMANCE REQUIREMENTS

### 13.6.1 Environmental Requirements

The equipment located on the antenna and pedestal must be capable of operating in the anticipated space environment. The pedestal itself will require particular attention to lubricants, drive motor heat dissipation, and thermal protection. Heat dissipation techniques will have to be applied to the majority of electronic units installed on the antenna.

### 13.6.2 Operational Requirements

The primary operational requirement is that the host vehicle be oriented in a manner permitting the antenna to maintain track of the geosynchronous satellite during the period when experiments are conducted.

13.6.3 Link Power Budget

a) For operation at 60 GHz:

| | | |
|---|---|---|
| Thermal noise in 1 MHz bandwidth, 300°K (KTB) | -144 dBw | |
| Receiver threshold for NF = 14 dB | -130 dBw | |
| Desired SNR for DPSK and BER $\approx 10^{-5}$ | 9.5 dB | |
| Minimum acceptable signal power | | -121.5 dBw |
| Losses and gains: | | |
| • Space loss, 26K mi. | -221 dB | |
| • Laboratory antenna gain, 9 ft dia. | 63 dB | |
| • DRS 4 ft antenna gain (3 dB earth-edge) | 51 dB | |
| • System margin for degradation | -6 dB | |
| Total (Loss) | -113 dB | |
| Minimum Laboratory Transmitter Power Needed = | | -8.5 dBw |

Suggested Transmitter Power = 0.2 Watts (-7 dBw)

b) For operation at 15.25 GHz:

| | | |
|---|---|---|
| Thermal noise in 1 MHz bandwidth, 300°K (KTB) | -144 dBw | |
| Receiver threshold for NF 10 dB | -134 dBw | |
| Desired SNR for DPSK, and BER $\approx 10^{-5}$ | 9.5 dB | |
| Minimum acceptable signal power | | -124.5 dBw |
| Losses and gains: | | |
| • Space loss, 26K mi. | 209 dB | |
| • Laboratory antenna gain, 9 ft dia. | 50 dB | |
| • DRS, 4 ft antenna gain (3 dB edge of earth) | 43 dB | |
| • System margin for degradation | -6 dB | |
| Total (Loss) | -122 dB | |
| Minimum Laboratory Transmitter Power Needed = | | -2.5 dBw |

Suggested Transmitter Power = 0.5 Watts (-3 dBw)

The assumptions used concerning the characteristics of the DRS are taken from Reference 1; however, it should be noted that the plans described therein do not provide for any 60 GHz capability, although the potential performance of such a link is examined. The impact of this is to place the burden of requesting any necessary 60 GHz capability in the DRS on the Comm/Nav program.

### 13.6.4 Special Pointing Requirements

As mentioned previously, the antenna must be pointed toward the cooperating spacecraft using ephemeris data via a computer. The accuracy to which the antenna must be pointed from a known reference system is approximately $\pm 0.05$ degree. This is beyond the presently planned stability of the Shuttle host vehicle and will entail a supplementary stable platform.

### 13.6.5 Mounting/Structural Requirements

The pedestal must be aligned to an accuracy of $\pm 0.01$ degree relative to the laboratory axes in order to meet pointing requirements and to accurately reflect the data being gathered. Structural requirements in relation to the launch environment and tracking dynamics must be carefully analyzed and cannot be stated at this time.

### 13.6.6 Unique Electric Power/Thermal Requirements

It may be desirable to use direct drive DC motors in the pedestal. These would be operational for at least one half the orbit period and use approximately 40 watts in each axis from a 24-volt supply. In the event that thermal dissipation is a problem, thermal covering of the pedestal will very likely be required to prevent distortion.

## 13.7 POTENTIAL ROLE OF MAN

### 13.7.1 Required Functions

The astronaut-crew will be required to erect the pedestal, attach the antenna to the pedestal, connect the cabling, and physically rotate the pedestal axis to assure that no damage has been incurred during launch. Following this procedure, man will perform the following functions:

- Operate antenna in manual mode
- Turn on and monitor transmit and receive subsystems
- Initiate acquisition sequence
- Introduce manual offsets
- Re-initiate acquisition

- Change amplifier gains
- Conduct bit error rate tests
- Observe and record equipment operation.

13.7.2 Necessary Skills

Crew skills involve a general familiarity with the following disciplines:

- Microwave systems
- Servo electronics
- Computer programming and operation
- Digital recording techniques.

13.8 EXPERIMENT EVOLUTION

13.8.1 Early Laboratory (1980 - 1985)

If the 13.25 - 15.35 GHz band is first available for experiments during this period, but not the 60 GHz band, it is recommended that an existing 9 - 10 ft diameter antenna be employed for this experiment. However, if an antenna development program is approved, the reflector would be fabricated to tolerances capable of maintaining low phase error loss at 60 GHz and be used for these experiments at a later date.

13.8.2 Growth/Total Laboratory

It is anticipated that even higher frequencies will be used for data relay satellites (up to 150 GHz) in future applications. Assuming that higher power outputs become available, antennas in the 10 ft diameter category will still be applicable to this experiment. Improved surface tolerance (perhaps to 0.001 inch RMS) should also become available. Thus, it is reasonable to look forward to this combination of technology in the period 1985 to 1990 and beyond. Since beamwidths of 0.05 degree would be anticipated, commensurate advances in pointing and tracking accuracies will be encountered.

13.9 SRT REQUIREMENTS

Among the new technology development necessary to support this experiment are:

1) Low noise (<6 dB NF) solid state parametric amplifiers

2) Reliable, crystal controlled higher power transmitter sources for 60 GHz

3) High efficiency feed subsystems

4) Temperature invariant structural materials.

## 13.10 ACKNOWLEDGEMENTS

### 13.10.1 Related Experiments

The following experiment was used in the derivation of the candidate narrow beam tracking experiment defined herein:

| Experiment | Principal Investigator and Association |
|---|---|
| Low Side Lobe Millimeter Wavelength Antenna | J. Duncan, TRW |

### 13.10.2 References


1. "GSFC Mark-I Tracking and Data-Relay Satellite (TDRS) System Concept," Phase A Study, Final Report, vol. 1, GSFC, November-1969. (expected noise temperatures pp 6-58, proposed operating frequencies, pp 6-66).

2. "Orbiting Data Relay Network," RCA, Contract NASW 1447, March-1967.

3. "Synchronous Communications and Tracking Relay System Feasibility Study," Hughes Aircraft Company, Contract NAS8-21071, May-1967).

4. "Study of a Low Altitude Satellite, Using a DRS," Hughes Aircraft Company, Contract NAS5-11602, January 1969.

# EXPERIMENT 14

# RANGE AND RANGE RATE NAVIGATION

# AND

# SURVEILLANCE TECHNIQUES

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# 14. RANGE AND RANGE RATE NAVIGATION AND SURVEILLANCE TECHNIQUES

## 14.1 EXPERIMENT CLASSIFICATION

This is a set of applied technology experiments to demonstrate the operation and performance of space-to-earth range and range rate radio links using equipment and techniques suitable for operational satellite navigation or surveillance systems. The experiments will provide a direct comparison of candidate signal structures and signal processing techniques.

## 14.2 EXPERIMENT OBJECTIVES

The objective of this group of experiments is to demonstrate the operation and quantify the performance of L-band radio range and range rate signaling and measuring techniques between space and earth terminals for future terrestrial navigation, surveillance and search/rescue systems. The experiments are to provide general information and specific systems design data in the following areas:

a) Attainable range and range rate accuracy and resolution

b) One- and two-way link configurations

c) Range and range rate modulations

d) Multiple access modulations

e) Multipath and ionospheric propagation effects

f) Performance and complexity of terrestrial and space equipment

g) Location computation techniques (software)

h) Clock stability requirements

This information and data will provide a means of designing cost effective future operational satellite navigation, surveillance and search/rescue systems.

## 14.3 DISCIPLINE BACKGROUND AND STATUS

A variety of multi-satellite systems, at synchronous and subsynchronous attitudes, have been proposed and studied by NASA, Department of Transportation, and Department of Defense to provide continuous precision regional and global navigation, surveillance, and search/rescue

to aviation and marine users. Each proposed system is optimized for a specific application. The most significant design parameter, common to all the proposed systems, is cost. The total system cost includes the satellite subsystem, the supporting ground stations and the user costs consisting of equipment and its installation and maintenance. The use of a satellite system is generally justified by its ability to serve a large geographic area. If this area contains many users, the total cost of the user equipment alone may exceed the combined costs of the satellite and ground subsystem. The choice of a system design may, therefore, be based on the use of simple low cost user equipment instead of a minimum cost satellite subsystem.

Alternatively, if only regional coverage is required with a restricted number of users, a system design which minimizes the satellite and ground subsystem costs may be optimum. The optimum RF link configurations, signal structures, and equipment for the regional and global system will usually be different.

The RF link configurations can be divided into the four basic configurations as illustrated by Figures 14-1 through 14-4, where the operational satellite is simulated by the Comm/Nav Laboratory. The associated system applications (navigation or surveillance) for each link configuration is indicated on each figure. For the link configurations shown by Figures 14-1 and 14-4, the terrestrial terminal makes the range measurement. If the satellite positions are known, terrestrial navigation is possible by multilateration measurements. Conversely, satellite position measurements (surveillance) can be made by a ground station at a known location. With the link configurations illustrated in Figures 14-2 and 14-3, the range measurements are made at the satellite or a ground station if a data relay satellite is used. (The relay link to a ground station is not shown in Figures 14-2 and 14-3).

With multilateration range measurements, these two link configurations can be used for aircraft surveillance or spacecraft navigation relative to a ground station. The choice between a one- or two-way link is dictated by the specific application and costs. For example, if a two-way voice or data communication capability is also required, it may be cost effective to use a two-way ranging link. In search and rescue systems, only

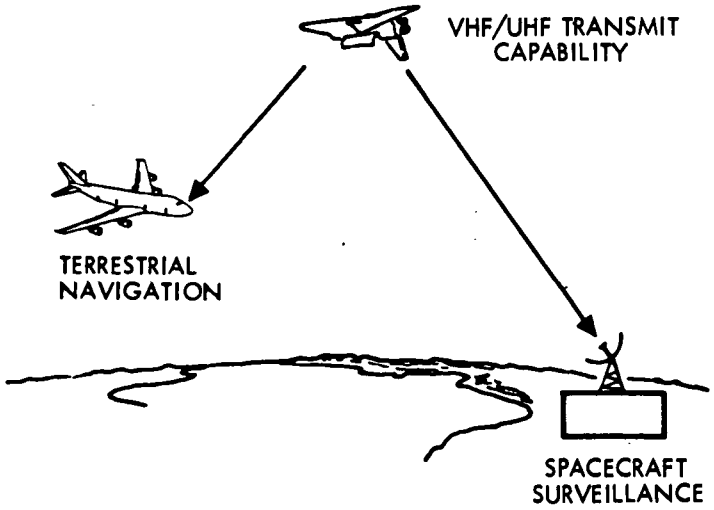


Figure 14-1. Downlink Configuration

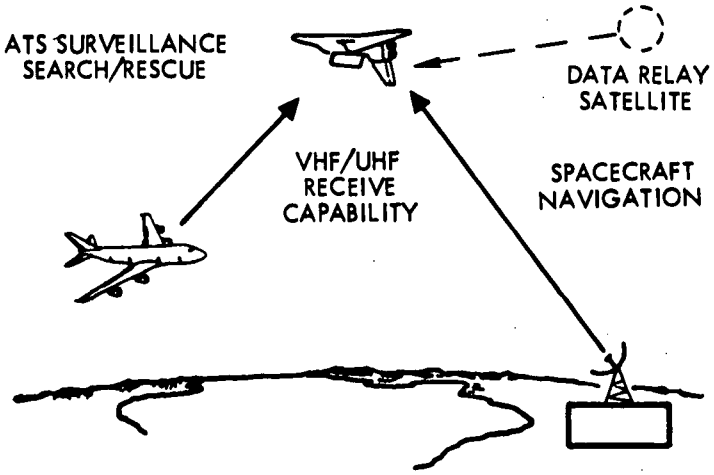


Figure 14-2. Uplink Configuration

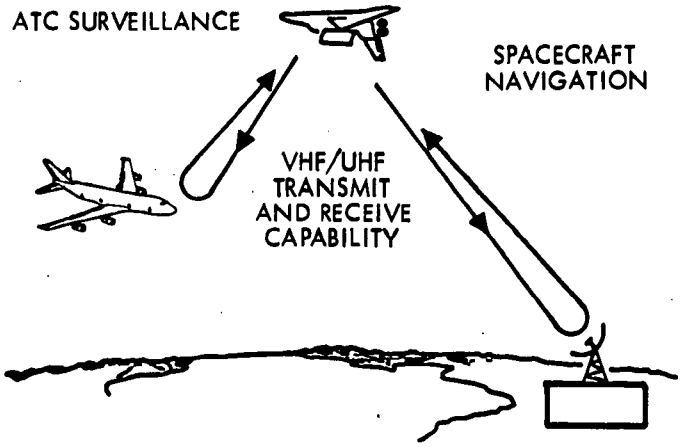


Figure 14-3. Down/Uplink Configuration

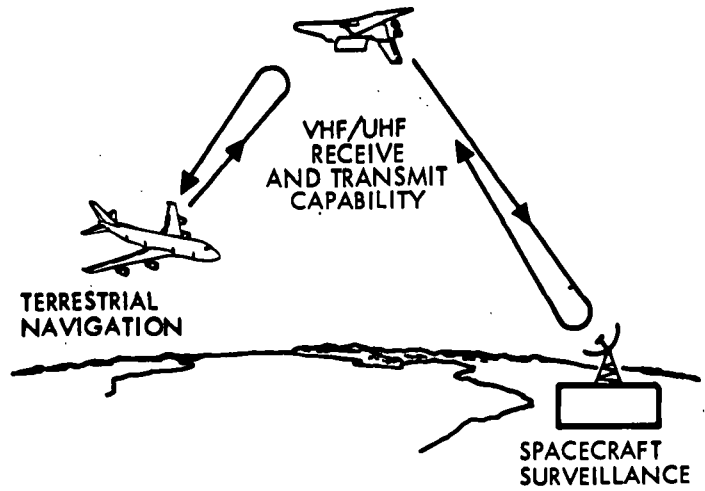


Figure 14-4. Up/Downlink Configuration

terrestrial transmitters are used, which requires the link configuration of Figure 14-2.

The Comm/Nav Laboratory provides an effective means of making comparative evaluations of these different link configurations for specific system applications. The total Comm/Nav Laboratory will be configured to accommodate all four basic link configurations described above.

## 14.4 EXPERIMENT DESCRIPTION

Candidate range and range rate systems using one and two-way link configurations, as illustrated in Figure 14-1, will be tested. The one-way link configurations require a transmitting or receiving terminal, whereas the two-way link configurations require terminals with simultaneous transmitting and receiving capabilities. The Comm/Nav Laboratory will be configured with the following representative types of equipment for the different link configurations:

a) Frequency-diplexed transmit/receive earth-coverage antenna

b) Preamplifier and down-converter

c) Coherent carrier tracking receiver

d) Range and range rate measurement equipment

e) Up-converter and transmitter (variable power)

f) Modulator

g) Range signal generator

h) Reference clock

With the exception of the antenna, the terrestrial terminals require essentially the same types of equipments to participate in the different link configuration tests. The terrestrial terminal antennas must be compatible with the vehicle antenna and can vary from narrow to wide (omni) beamwidths.

The functional terminal (ground station or Comm/Nav Laboratory) configurations are shown in Figure 14-5 through 14-8 for the different link configurations. The two-way link configurations provide real-time single fix range and range rate measurements using a common terminal

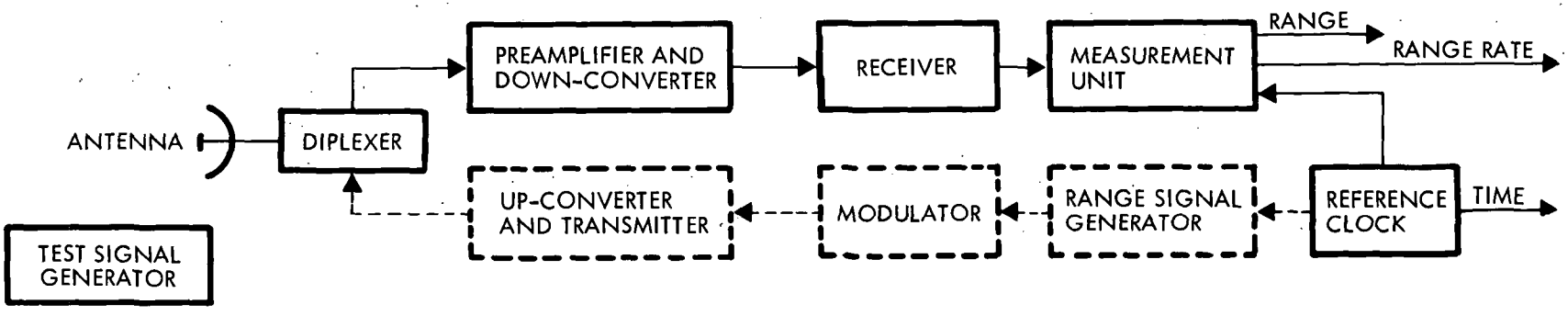


Figure 14-5. Receive-Only Configuration



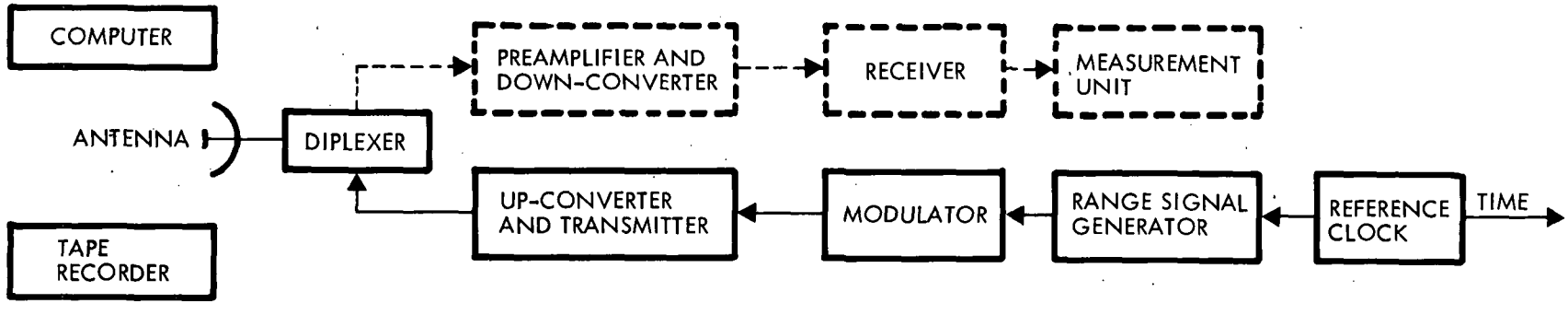


Figure 14-6. Transmit-Only Configuration

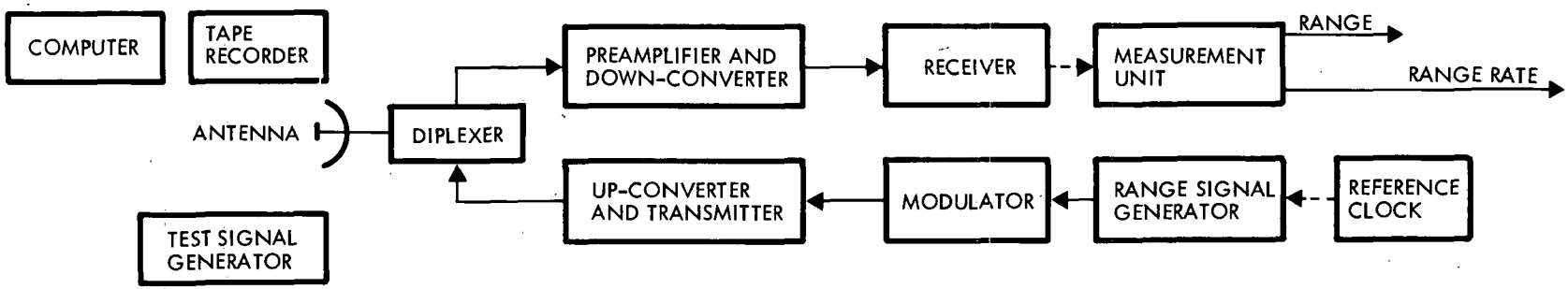


Figure 14-7. Transmit/Receive Configuration



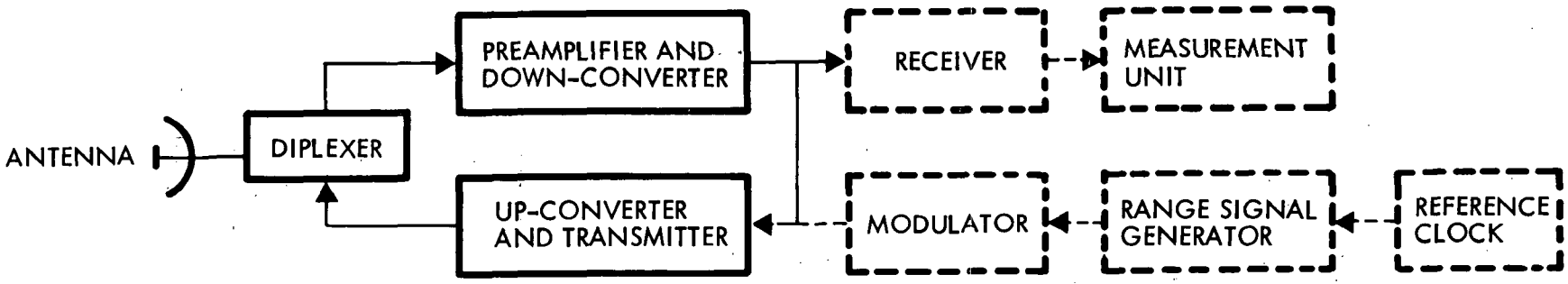


Figure 14-8. Repeater Configuration

clock. The one-way link configurations use two independent clocks and provide only relative range and range rate measurements. The actual range and range rate must be computed using sequential multilateration techniques to estimate the unknown clock parameters.

The data processing and reduction function requires a general purpose computer at the final receiving terminal. A computational capability is required by the terrestrial users in link configurations depicted in Figures 14-1 and 14-4. For the link configurations illustrated in Figures 14-2 and 14-3, the uplink signals would normally be relayed to a central ground data processing center in an operational system. However, to simplify the Comm/Nav Laboratory equipment requirements, this additional real-time data downlink will not be used. Instead, the on-board Comm/Nav Laboratory general purpose computer will be used to perform the navigation computations. This choice allows the Comm/Nav Laboratory to directly monitor the measurement results and observe the effects of hardware and software parameter variations. The processed measurement data will be stored on magnetic tape for further ground analysis. In addition, the processed data can be transmitted to the ground in near-real time, by a data telemetry link if desired.

Postulating a Comm/Nav Laboratory orbit altitude of 200 n. mi., a mutual visibility period of approximately six minutes occurs 3 to 5 times each day for a participating terrestrial station and the Laboratory. This limits the range and range rate data that can be obtained with any given user. However, a sequence of measurements for five minutes is sufficient for data smoothing and accurate user position and velocity determinations. A mix of airborne, shipborne, and landbased users, distributed over a wide geographical area, is recommended to observe the effects of representative multipath, ionospheric and weather conditions. The participation of multiple users will also allow different multiple access modulation techniques to be demonstrated and evaluated.

A variety of signal formats for different types of satellite ranging applications has been proposed and studied. The Comm/Nav Laboratory has been configured to accommodate the majority of baseband range signal processing and generation techniques. Accommodation of different types of ranging signals is accomplished by substituting the range signal generator

and measurement unit equipment. Different modulators and receivers can also be used for the PN, FM, or AM signal transmission and reception techniques.

A representative ranging signal for a time-division multiple-access terrestrial navigation system, depicted by Figure 14-1, is the BINOR (BInary Optimum Ranging) signal. The use and equipment implementation for BINOR has been studied by TRW for NASA/ERC. The BINOR signal is a binary, octavely-related multitone ranging signal with coherent PSK carrier modulation and demodulation. This signal structure is representative of a wide class of candidate binary coherent modulation techniques suitable for satellite navigation and surveillance systems. This type of ranging signal will, therefore, be used in defining the baseline link power budget and the Comm/Nav Laboratory equipment requirements.

Tests involving other classes of ranging signals, such as noncoherent signal processing techniques may necessitate use of different transmitting and receiving equipment in addition to different signal generation and measurement equipment. Generally, these functional equipment changes can be most easily accomplished by equipment substitutions.

## 14.5 EXPERIMENT OBSERVATION/MEASUREMENT PROGRAM

The basic parameters to be measured for the four link configurations discussed in Section 14.3 are listed in Table 14-1. Each entry indicates the origin of each measurement. These measurements should be continuous during each contact with participating terrestrial terminal(s). Fixed ground terminals at known locations will be used for calibration. The inflight computed navigation and surveillance position data for each test will be compared with independent ground system position measurements to obtain accuracy and resolution estimates.

The range and range rate measurement errors resulting from thermal noise will be minimized to allow the propagation and equipment-induced errors to be observed. Range and range rate measurement noise errors of 5 ft rms and 1 fps rms, respectively, have been adopted for the baseline design. Table 14-2 shows that a signal-to-noise ratio of 40 dB is required to meet these measurement accuracies with a signal bandwidth of 1 MHz, a range rate measurement time of 1 millisecond, and a signal carrier frequency of 1570 MHz. The power budget for the link between

## Table 14-1. Range and Range Rate Measurement Parameters

| Measurement Parameters | Link Configuration | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | One-Way Link | | | | Two-Way Link | | | |
| | C/N to T/T | | T/T to C/N | | C/N to T/T to C/N | | T/T to C/N to T/T | |
| | Range | Range Rate | Range | Range Rate | Range | Range Rate | Range | Range Rate |
| Experiment Measurements | | | | | | | | |
| 1. Time of Transmission | C/N | | T/T | | C/N | | T/T | |
| 2. Time of Arrival | T/T | | C/N | | C/N | | T/T | |
| 3. Transmitted Carrier Frequency | | C/N | | T/T | | C/N | | T/T |
| 4. Received Carrier Frequency | | T/T | | C/N | | C/N | | T/T |
| 5. Time of Measurement | | T/T | | C/N | | C/N | | T/T |
| 6. Transmitted Signal Strength | C/N | C/N | T/T | T/T | C/N | C/N | T/T | T/T |
| 7. Received Signal Strength | T/T | T/T | C/N | C/N | C/N | C/N | T/T | T/T |
| 8. System Noise Temperature | T/T | T/T | C/N | C/N | C/N | C/N | T/T | T/T |
| Supporting Measurements | | | | | | | | |
| 1. C/N Orbit Parameters | G/S | G/S | G/S | G/S | G/S | G/S | G/S | G/S |
| 2. Terrestrial Terminal Location | G/S | G/S | G/S | G/S | G/S | G/S | G/S | G/S |
| 3. Propagation Conditions | G/S | G/S | G/S | G/S | G/S | G/S | G/S | G/S |

Measurement Location:

C/N Communication/Navigation Laboratory

T/T Participating Terrestrial Terminal (e.g., aircraft, ship, etc.)

G/S Ground Support System (e.g., tracking, meteorological, etc.)

Table 14-2. Range and Range Rate Experiment Power Budget

| | |
|---|---|
| **Range Measurement** | |
| Range measurement noise error | $\sigma_R$ = 5 ft, rms |
| Signal bandwidth | B = 1 MHz |
| Required SNR (Note 1) | 40 dB |
| **Range Rate Measurement** | |
| Range rate measurement noise error | $\sigma_{\dot{R}}$ = 1 fps, rms |
| Measurement time | $T_m$ = 1 ms |
| Carrier frequency | 1570 MHz |
| Required SNR (Note 2) | 40 dB |
| **Up or Downlink Power Budget** | |
| Required SNR | 40 dB |
| Measurement noise bandwidth (10 Hz) | 10 dB-Hz |
| Required $C/N_o$ | 50 dB-Hz |
| Receiver noise figure | 5 dB |
| $KT_o$ | -204 dBw/Hz |
| Required received power | -149 dBw |
| Receiving circuit losses | -2 dB |
| Receiving antenna gain | 3 dB |
| Space loss (700 n. mi. @ 1570 MHz) (Note 3) | -159 dB |
| Required transmitter ERP | 9 dBw |
| Transmitter antenna gain | 3 dB |
| Transmitting circuit losses | -2 dB |
| Required transmitter power | 8 dB |
| Available transmitter power (50 watts) | 17 dB |
| Margin | 9 dB |

Notes

(1) $SNR = \left(\frac{C}{2B\sigma_R}\right)^2$ C = speed of light

(2) $SNR = \left(\frac{C}{2\pi f_o T_m \sigma_{\dot{R}}^{\circ}}\right)^2$

(3) Maximum slant range is approximately 700 n. mi. at a cross track displacement of 6 degrees and an elevation angle of 10 degrees.

the Comm/Nav Laboratory and a terrestrial terminal is also tabulated. This link power budget applies to either the up or downlink configurations. The 50 watt transmitter power provides a 9 dB link margin for the selected 40 dB baseline measurement signal-to-noise ratios. A 9 dB margin should provide sufficient flexibility in the selection of signal formats and processing techniques without requiring an increase in transmitter power.

The Comm/Nav Laboratory data measurement requirements consisting of data type, precision, dynamic range, measurement rate and data bit rate are listed in Table 14-3. The right hand column summarizes the data bits cumulated during a 5 minute data collection pass over a participating terrestrial terminal. This data tabulation represents the maximum Comm/Nav Laboratory requirements corresponding to the experimental link configurations shown by Figure 14-2 or Figure 14-3. With link configurations represented in Figures 14-1 or 14-4, the terrestrial terminal position and velocity data is not required at the Comm/Nav Laboratory since the terrestrial terminal must perform the navigation computation knowing the Comm/Nav Laboratory position and velocity. This computation can be made in real time by the user, or it can be done at a central ground processing center by recording the user measurement data.

All measured and computed data in the Comm/Nav Laboratory will be stored for post-flight analysis. The receiver, transmitter and computed navigation data will be displayed for inflight performance monitoring by the astronaut-experimenters.

## 14.6 INTERFACE, SUPPORT AND PERFORMANCE REQUIREMENTS

The range and range rate experiments require a complex of participating terrestrial terminals to receive, transmit or transpond the ranging signal, depending on the link configuration selected. It is anticipated that the Total Comm/Nav Laboratory will be configured to operate with any of the four link configurations. Therefore, a corresponding set of terrestrial terminal equipment must ultimately be available for each link configuration. A combination of fixed and mobile terrestrial equipment should be used. The use of fixed equipment, at known sites, can be used to calibrate the range and range rate measuring equipment and establish precision performance baselines. The use of mobile equipment

## Table 14-3. Comm/Nav Laboratory Measurement Data Requirements

| Data Type | | Precision | Dynamic Range | Data Bits | Measurement Rate | Data Bit Rate | Data for 5 Min. Pass |
|---|---|---|---|---|---|---|---|
| Time of Arrival or Transmissions | | 1 Nanosecond | 24 Hrs | 37 | 10/sec | 370 bps | 111 K Bits |
| Received or Transmitted Frequency | | 0.1 Hz (~0.064 fps) | 100 kHz (~$6.4 \times 10^4$ fps) | 20 | 10/sec | 200 bps | 60 K Bits |
| Comm/Nav Laboratory Position and Velocity | X | 1 ft | 400 n. mi. | 22 | 10/sec | 220 bps | 66 K Bits |
| | Y | 1 ft | 400 n. mi. | 22 | 10/sec | 220 bps | 66 K Bits |
| | Z | 1 ft | 400 n. mi. | 22 | 10/sec | 220 bps | 66 K Bits |
| | $\dot{X}$ | 0.1 fps | $5 \times 10^4$ fps | 16 | 10/sec | 160 bps | 48 K Bits |
| | $\dot{Y}$ | 0.1 fps | $5 \times 10^4$ fps | 16 | 10/sec | 160 bps | 48 K Bits |
| | $\dot{Z}$ | 0.1 fps | $5 \times 10^4$ fps | 16 | 10/sec | 160 bps | 48 K Bits |
| | | | | 114 | | 1140 bps | 342 K Bits |
| Terrestrial Terminal Position and Velocity (10 Terminals) | X | 1 ft | 400 n. mi. | 22 | 100/sec | 2200 bps | 660 K Bits |
| | Y | 1 ft | 400 n. mi. | 22 | 100/sec | 2200 bps | 660 K Bits |
| | Z | 1 ft | 400 n. mi. | 22 | 100/sec | 2200 bps | 660 K Bits |
| | $\dot{X}$ | 0.1 fps | $5 \times 10^4$ fps | 16 | 100/sec | 1600 bps | 480 K Bits |
| | $\dot{Y}$ | 0.1 fps | $5 \times 10^4$ fps | 16 | 100/sec | 1600 bps | 480 K Bits |
| | $\dot{Z}$ | 0.1 fps | $5 \times 10^4$ fps | 16 | 100/sec | 1600 bps | 480 K Bits |
| | | | | 114 | | 11400 bps | 3.42 Bits |
| Receiver | | | | | | | |
| Sensitivity | | 1 dB | 16 | 4 | 1 pass each | 0 | |
| Lock Status | | - | - | 2 | 10/sec | 20 bps | 6 K Bits |
| Signal Strength | | 1 dB | 32 dB | 5 | 10/sec | 50 bps | 15 K Bits |
| | | | | 7 | | 70 bps | 21 K Bits |
| Transmitter | | 1 dB | 16 | 4 | 10/sec | 40 bps | 12 K Bits |
| TOTAL | | | | | | | 3795 K Bits |

or aircraft, ship and vehicles will provide user navigation and surveillance performance data under typical user environmental conditions.

The position and velocity of each terrestrial terminal must be independently known as a function of time to an accuracy of about 10 ft and 0.1 fps (one sigma) respectively to adequately demonstrate the link and equipment measurement performance. The Comm/Nav Laboratory position and velocity must also be known to an equivalent accuracy. This information can be obtained by an independent tracking system such as MSFN to establish the Laboratory orbit parameters and the orbit perturbations.

## 14.7 POTENTIAL ROLE OF MAN

The signal reception and measurement instrumentation will be tested and calibrated prior to each data collection pass by substituting an RF test signal at the antenna input interface. The crew will vary the test signal power and frequency to simulate the anticipated received signal power levels and Doppler frequency shifts. The transmission equipment will also be tested and calibrated prior to a data collection pass. Under these test conditions the operator can observe and calibrate the following equipment parameters:

- Receiver signal acquisition threshold level
- Receiver acquisition probability and time versus signal strength
- Receiver lock status indicators
- Received signal strength indicators
- Transmitted signal strength indicators
- Range and range rate measurement unit.

During a collection pass, the operation of the signal reception, transmission and measurement equipment has been automated to obtain a rapid sequence of measurements. The operator participation in the data collection phase of the experiment is limited to performance monitoring.

After a data collection pass, the Comm/Nav Laboratory operator can recall from the computer selected raw and calculated position and velocity estimates to verify the overall equipment performance. The time

required for this post-pass data review and evaluation may vary from a few minutes to an hour, depending on the authenticity and consistency of the data. If the data is acceptable, the operator can command it to be permanently stored for detailed post-flight ground analysis. If the data is erratic or exceeds expected limits, the operator can retest the equipment to isolate malfunctions and make the necessary adjustments or repairs as required.

## 14.8 EXPERIMENT EVOLUTION

There are four basic link configurations that comprise the total scope of the experiment defined herein. The experiment description addresses all four link configurations; however, it may be desirable to implement the experiment in evolutionary stages starting with the simplest equipment configurations. The following chronological ordering of equipment configurations for the Comm/Nav Laboratory provides a logical growth sequence:

| Comm/Nav Laboratory Equipment Configuration (Reference Figures 14-5 to 14-8) | Link Configurations (Reference Figures 14-1 to 14-4) |
|---|---|
| Repeater | Up/Downlink |
| Transmit Only | Downlink |
| Receive Only | Uplink |
| Transmit/Receive | Down/Uplink |

The repeater configuration requires a minimum of Comm/Nav Laboratory equipment and would be used for the Early Laboratory missions. For the Growth Laboratory, either the transmit or receive only configurations can be used with a modest increase in laboratory equipment. The Total Laboratory can accommodate all of the above equipment configurations and provide maximum experimentation flexibility. It may also be advantageous to combine the range and range rate experiment with the interferometric navigation experiment in the Total Laboratory to provide a comparison demonstration of specific navigation and surveillance system concepts.

## 14.9 SRT REQUIREMENTS

The Comm/Nav Laboratory and the terrestrial instrumentation and equipment for the above range and range rate experiment can be implemented using current technology and known equipment designs. No support research and technology program is required to conduct this group of experiments.

Special purpose signal generation and processing/measurement equipment may, however, have to be developed to demonstrate specific types of ranging signal designs not identifiable at this time. This effort can be time phased with the evolutionary growth of the Comm/Nav Laboratory as needed or desired with little or no impact on the laboratory equipment volume or prime power allocations. The use of the Comm/Nav Laboratory to evaluate different candidate signal modulations, signal processing equipment and data processing software is consistent with the proposed baseline range and range rate experiment link and equipment configurations.

## 14.10 ACKNOWLEDGEMENT

The following three navigation and surveillance system demonstration experiments were submitted for the Comm/Nav Laboratory. These proposed experiments were used in formulating the generic types of range and range rate link configurations for this experiment group.

| Experiment | Principal Investigator and Association |
|---|---|
| 1. Position Location and Aircraft Communications | Charles R. Laughlin, Goddard Space Flight Center |
| 2. Surveillance and Search and Rescue Systems Demonstrations | Blue Book, Vol. V, 15 Jan 1971, No. 3 |
| 3. Satellite Navigation Techniques for Terrestrial Users | Blue Book, Vol. V, 15 Jan 1971, No. 4 |

EXPERIMENT 15

# RADIO INTERFEROMETRIC NAVIGATION AND SURVEILLANCE TECHNIQUES

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# 15. RADIO INTERFEROMETRIC NAVIGATION AND SURVEILLANCE TECHNIQUES

## 15.1 EXPERIMENT CLASSIFICATION

This is an applied technology experiment directed toward demonstrating the operational performance of typical spaceborne interferometers suitable for terrestrial navigation and surveillance for air traffic control (ATC) systems. The mechanical design and construction of long stable antenna booms (approximately 32 feet) will require a development and testing (SRT) effort prior to integration in the Comm/Nav Laboratory. The antennas and the signal processing equipment can be mechanized with present hardware technology.

## 15.2 EXPERIMENT OBJECTIVES

The primary objective of this experiment is to demonstrate the line-of-sight measurement accuracy of a long baseline spacecraft receiving interferometer. The experiment will demonstrate the interferometer calibration procedure using four calibration ground transmitter stations and the interferometer boom attitude stability under actual spacecraft dynamic conditions.

The computational software required for the calibration and measurement error calculations will also be demonstrated using the on-board general purpose Comm/Nav Laboratory computer. In summary, the experiment objectives are to obtain quantitative and qualitative data for the following items:

a) Obtainable directional angle accuracy and resolution

b) Mechanical stability of long baseline antenna configurations

c) Calibration procedures

d) Performance of electrical phase angle measurement instrumentations

e) Ionospheric effects

f) Multipath effects

g) Position location computation techniques (software).

## 15.3 DISCIPLINE AND STATUS

Previous NASA studies have shown that the use of satellite radio interferometers with and without a user-to-satellite ranging measurement is one of the principal candidate techniques for future navigation or surveillance systems. The use of two orthogonal line-of-sight angle measurements from a single satellite to an aircraft, and knowledge of the aircraft altitude is sufficient to locate the aircraft. The need for each aircraft to measure its own altitude can be eliminated by also measuring the satellite to aircraft range. The use of a range measurement improves the overall precision of the position determination. Either technique, however, requires the use of long baseline interferometers, with an ambiguity resolution capability, to obtain precision angle measurements using practical transmitter power levels and electrical phase measurement equipment.

Both transmitting and receiving satellite interferometer configurations have been proposed for operational systems. Transmitting interferometers are generally used in navigation systems while receiving interferometers are used in surveillance systems. In addition, the transmitting or receiving interferometer can be implemented using either a one-way or a two-way link with a transponder. These four basic link configurations are illustrated in Figure 15-1 with the Comm/Nav Laboratory representing the operational satellite. The choice of configuration for a specific system is dictated by the operational requirements. For a terrestrial navigation system, the user requires knowledge of his position and, therefore, the configuration shown by Figures 15-2 or 15-3 with a transmitting interferometer would be used. For an ATC surveillance system, the air traffic control system requires knowledge of the aircraft position. This would require a receiving satellite interferometer using either a one- or two-way link, as shown by Figures 15-1 and 15-4. The surveillance position signal or data is normally relayed by the satellite to a central ground station in an operational system. This relay link is not shown. The choice between a one- or two-way link is influenced by the need for ranging and/or communications links in addition to line-of-sight measurement and hardware cost and complexity considerations.

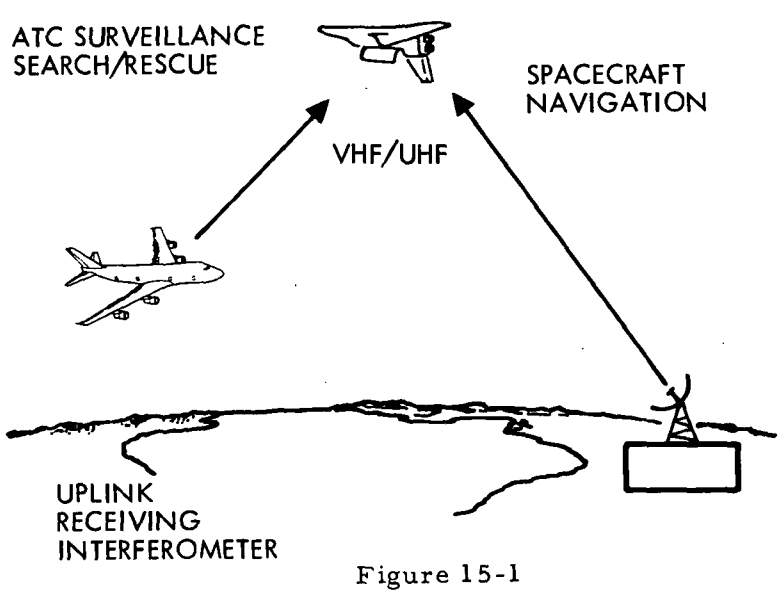


Figure 15-1

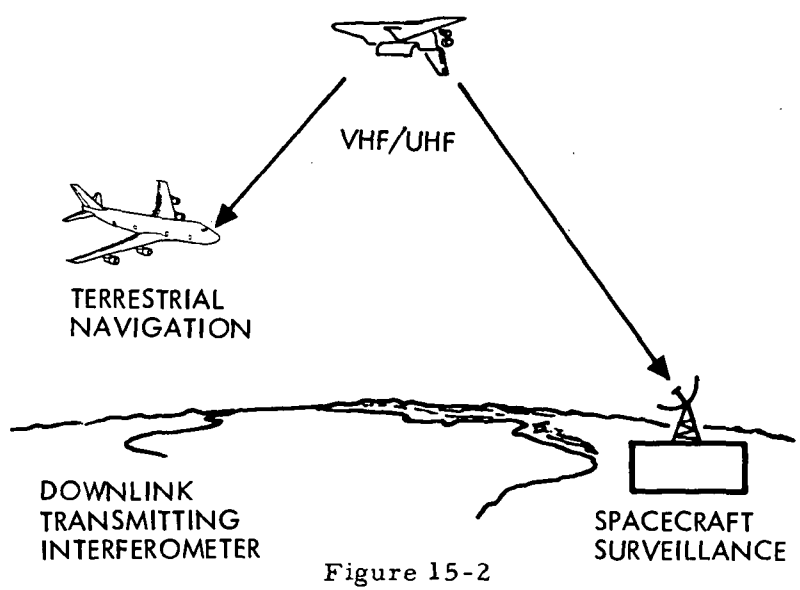


Figure 15-2

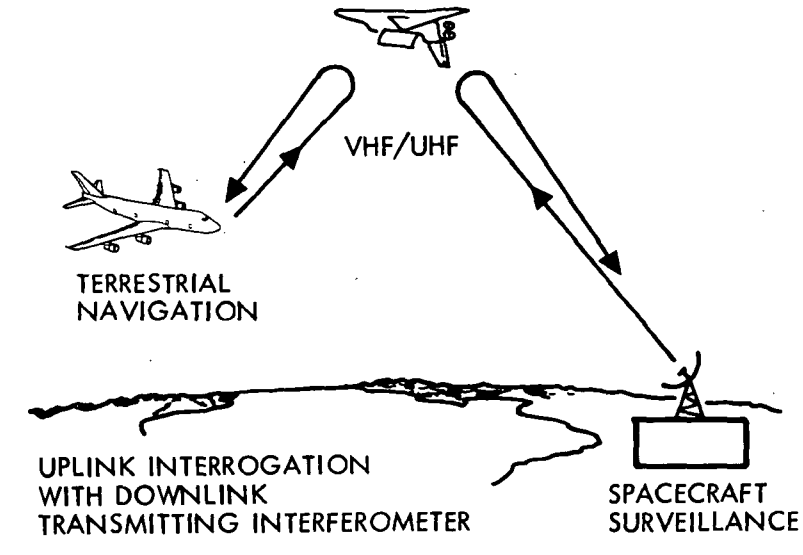


Figure 15-3

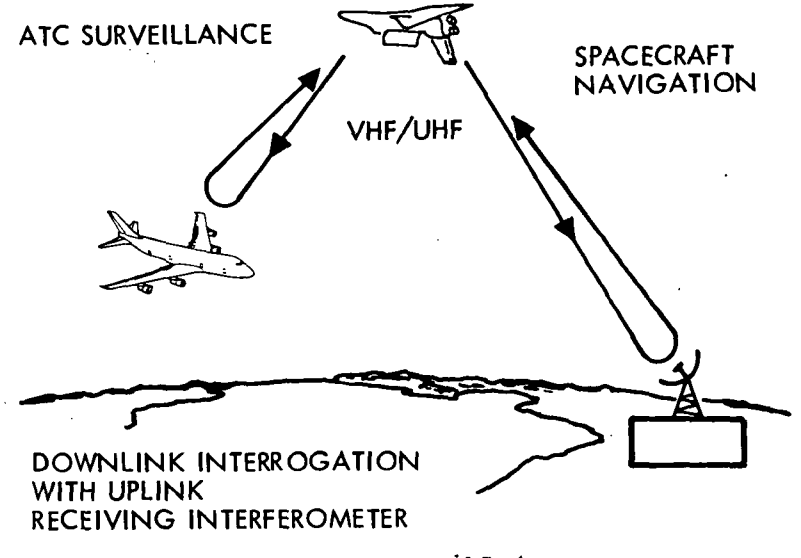


Figure 15-4

Figures 15-1 through 15-4. Spaceborne Interferometer Experiment Link Configurations

The need for a satellite-borne interferometer antenna subsystem is common to either configuration. Since it is not possible to precisely stabilize the interferometer baselines, a calibration process is required for either a transmitting or receiving interferometer. The accuracy with which the interferometer can be calibrated determines its ultimate utility for a navigation or surveillance system and is, therefore, a major objective of this experiment.

## 15.4 EXPERIMENT DESCRIPTION

The choice of the link configuration for the Early Comm/Nav Laboratory is primarily dictated by operational convenience and equipment simplicity. The Comm/Nav Laboratory equipment required for the four link configurations is functionally illustrated by Figures 15-5 to 15-8. The two-way link configurations require both transmitting and receiving equipment on-board the Comm/Nav Laboratory as shown by Figures 15-7 and 15-8. This added complexity is not required to evaluate the basic performance of the interferometer. The configuration choice for the initial experiment will, therefore, be limited to the receiving configuration (Figure 15-5).

A 200 n. mi. circular orbit limits the visibility period at a single ground station or closely grouped complex of stations to about 15 minutes a day. The use of additional ground station complexes situated on different types of land terrain and near water would increase the time utilization of the experiment and would provide experimental data under a variety of multipath and propagation conditions. If additional ground stations are used, their complexity should be minimized. This dictates the use of a receiving satellite interferometer with simple carrier wave (CW) ground station transmitters and satellite-borne measurement equipment.

Ideally, the ground transmission signals should be received simultaneously at the satellite to obtain an instantaneous calibration of the interferometer baseline parameters. This, however, would require multiple satellite measurement equipment. Alternatively, the satellite radio frequency (RF) and measurement equipment can be time-shared among the ground station signals. The need for time sharing the ground station transmissions and a common timing reference, can be avoided by frequency division multiplexing and ground station transmissions. This

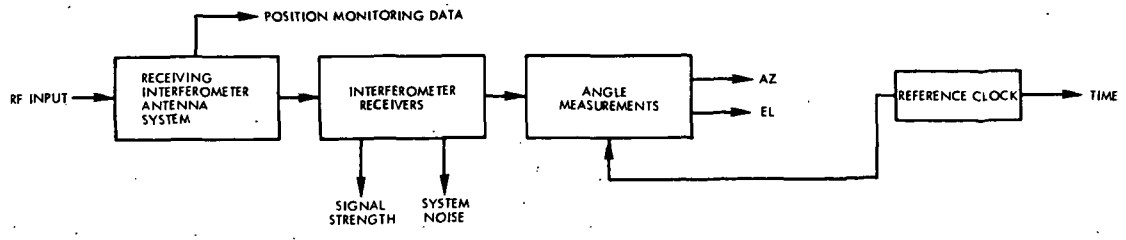


Figure 15-5. Receiving Interferometer Configuration

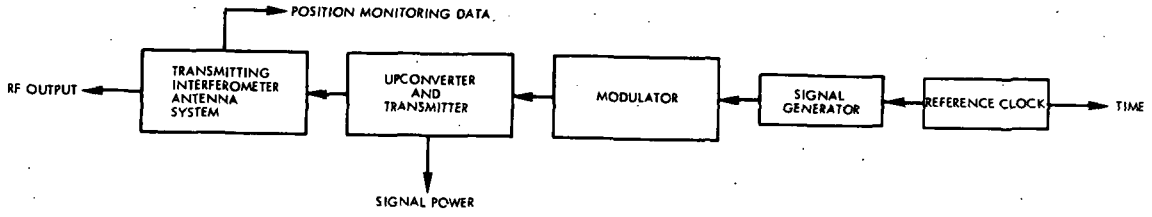


Figure 15-6. Transmitting Interferometer Configuration

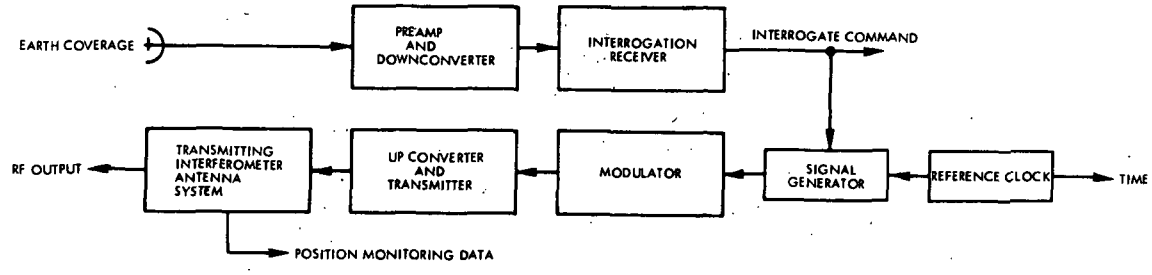


Figure 15-7. Interrogated Transmitting Interferometer

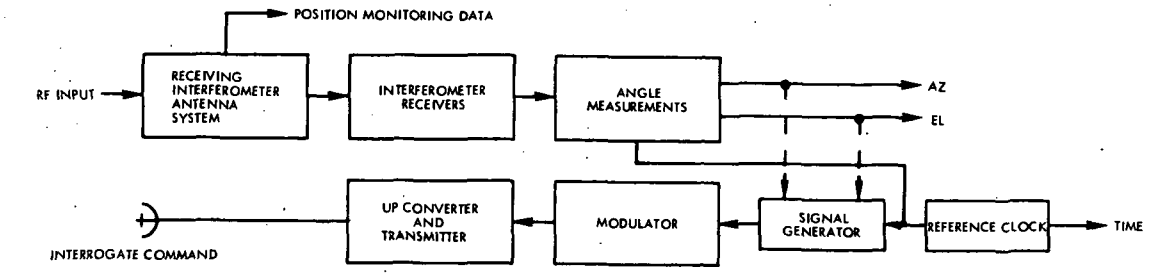


Figure 15-8. Interrogated Receiving Interferometer

approach requires a rapidly tunable satellite interferometer receiver; however, this added complexity is justified to provide flexibility in selecting the dwell time on each ground station signal.

A minimum of five ground transmitters is required for each ground complex. Four ground stations are required to calibrate the interferometer. The fifth ground station is used to simulate an aircraft, and its angular position will be measured with the calibrated satellite interferometer.

The time required to measure the five ground station signals must be short compared to the expected attitude angle rates of the satellite. Typically the attitude rates for an attitude stabilized satellite are less than 0.01 deg/sec or 175 $\mu$rad. This corresponds to a subsatellite position error of 2.12 feet for a 200 n. mi. satellite altitude, which is acceptable for this experiment.

For a single baseline interferometer, the measured electrical phase angle is:

$$\phi = \frac{2\pi D}{\lambda} \cos\theta + 2\pi m + \Phi + N \qquad (1)$$

where $\phi$ = differential phase angle between the signals intercepted by the two interferometer antennas

$D$ = distance between the two antenna phase centers (i. e., baseline length)

$\lambda$ = signal carrier wavelength

$\theta$ = angle between the baseline and the line-of-sight

$m$ = measurement phase ambiguity integer

$\Phi$ = measurement bias error

$N$ = measurement noise error

The line of sight ambiguity angle, $\Delta\phi_m$, for large values of $D/\lambda$, is approximately

$$\Delta\phi_m \approx m\left(\frac{\lambda}{D}\right) \quad \text{for} \quad \left(\frac{D}{\lambda}\right) >> 1 \qquad (2)$$

Proposed operational interferometer systems use baselines of approximately 100 wavelengths ($D/\lambda \approx 100$) to obtain the required precision;

consequently $\Delta\theta_m \approx 0.01$ m radians. In operational synchronous altitudes interferometer satellite systems, this line-of-sight ambiguity corresponds to approximately a 220 n. mi. position ambiguity at the subsatellite point. This ambiguity can be resolved by using either two baseline lengths or two carrier frequencies. For the proposed Sortie Can mission, the Shuttle altitude is about 200 n. mi. with a resultant position ambiguity of about 2 n. mi. The objective of the proposed interferometer experiment is to demonstrate the attainable line-of-sight accuracy employing ground stations at known locations. Since the ground stations and the satellite location will be known to within 50 ft., a dual length baseline or dual frequency technique to resolve ambiguities is not required for the Early Laboratory experiment. This greatly simplifies the supporting experiment equipment. In addition, a one dimensional baseline interferometer is adequate for the Early Laboratory configuration to demonstrate calibration and measurement accuracies. A two-orthogonal baseline system can, however, be implemented using three booms configured as a star (120 degree separations). This additional boom and receiver channel is therefore justified for the Growth and Total Laboratory configurations.

With reference to Figure 15-9, the direction cosine ($\cos\theta$) from an x-axis oriented interferometer baseline to a ground station, using an earth centered coordinate is,

$$\cos\theta = \frac{1}{R}(x_1 - x_s)\cos\psi\cos\gamma + (y_1 - y_s)\cos\psi\sin\gamma + (z_1 - z_s)\sin\psi \quad (3)$$

where $(x_1, y_1, z_1)$ = the ground station location

$(x_s, y_s, z_s)$ = the satellite location

$(\psi, \gamma)$ = angular directions of the interferometer baseline relative to the x-axis.

$$R = \sqrt{(x_1 - x_s)^2 + (y_1 - y_s)^2 + (z_1 - z_s)^2} = \text{slant range from the ground station to the satellite.}$$

The interferometer baseline orientation ($\psi$ and $\gamma$) is not precisely known due to satellite attitude errors and boom bending or oscillation. A 45.5 $\mu$rad error in $\psi$, for example, causes a 1 n. mi. position error at the sub-point of a synchronous altitude satellite, and a 54.6 ft position

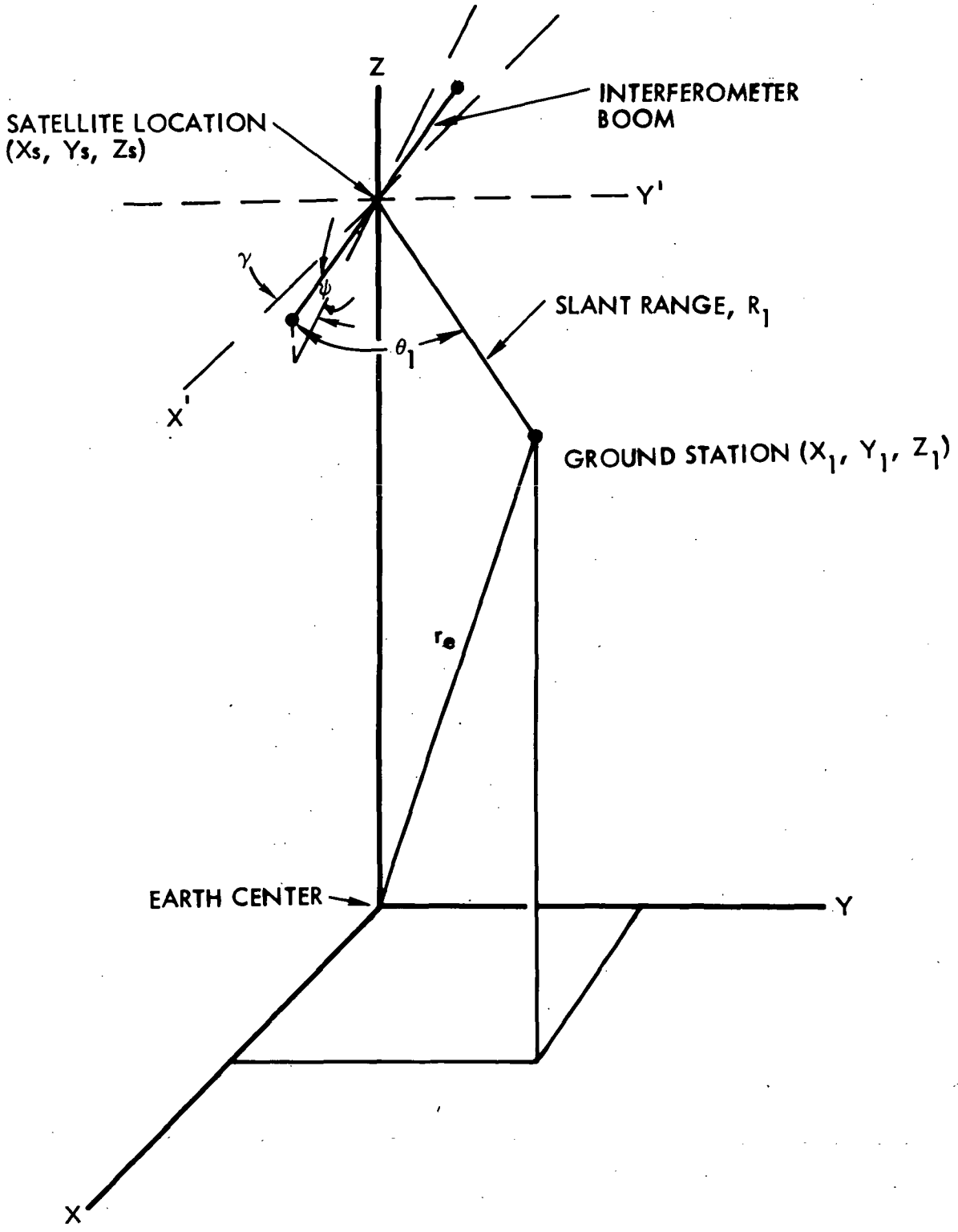


Figure 15-9. Coordinates for an X-Axis Oriented Interferometer

error for the 200 n. mi. altitude Communication/Navigation Laboratory.

For a practical interferometer satellite, boom orientation accuracy is limited to approximately 0.1 degree (1.75 milliradians). Consequently, to demonstrate the performance of synchronous satellite interferometers, the experiment interferometer orientation must be calibrated by measuring the line-of-sight angles to a complex of ground stations at locations known to be better than 54.6 ft. These ground stations can also be used to determine the baseline length and the phase measurement bias errors. The phase measurement bias error is relatively constant with time; however, the baseline orientation and length change relatively rapidly with time as a function of the boom and satellite attitude dynamics. The calibration process must, therefore, be essentially continuous during each pass.

For a 200 n. mi. altitude orbiting vehicle, the ground station visibility period (for $10^{\circ}$ minimum elevation angle) is limited to 6 minutes for a zenith pass, and decreases to zero for a ground station cross-range location 688 n. mi from the satellite ground track. Initial signal acquisition and multiple calibrations and measurements require a visibility time of about 5 minutes. This restricts the ground station cross track offset to about 36 n. mi.

Since there are four independent interferometer parameters ($\psi$, $\gamma$, D, $\Phi$) that must be calibrated for each baseline, four independent ground station calibration measurements must be made for each baseline, assuming that the baseline errors for a two-orthogonal baseline system are independent. This is a reasonable assumption since the boom dynamics may be considered uncorrelated. The same set of four ground stations, however, can be used for both baselines of a two-orthogonal baseline interferometer system. The four ground stations should be separated as far as possible from each other and the satellite ground track. This dictates a 72 n. mi. square configuration of four ground calibration stations to obtain a mutual visibility time of about 5 minutes. This configuration is illustrated by Figure 5-10. The fifth ground station is used to simulate an unknown station (or aircraft) whose line-of-sight direction from the laboratory is to be determined by interferometric measurements.

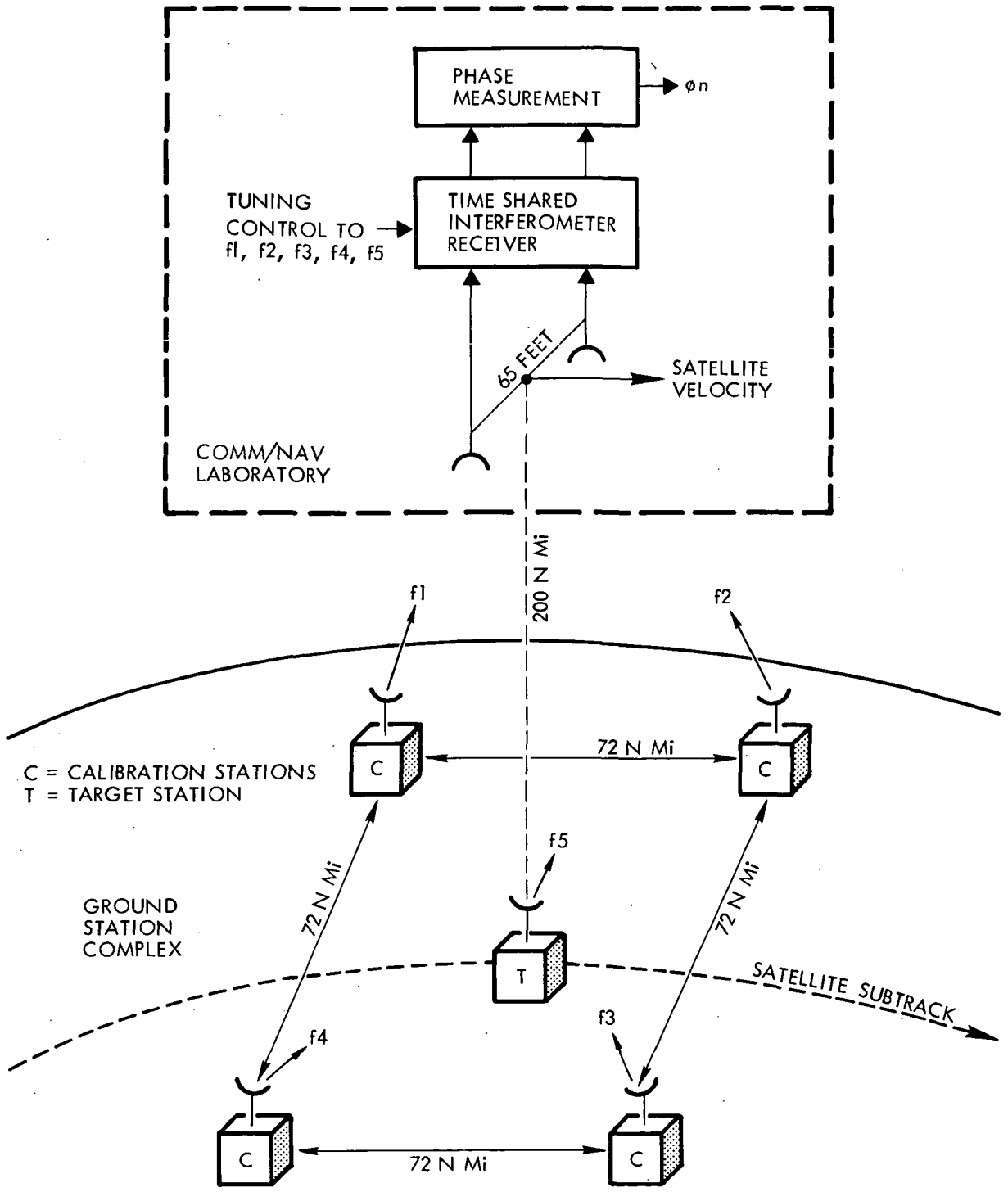


Figure 15-10. Single Baseline Interferometer Experiment Configuration

A functional block diagram of the proposed signal processing and measuring equipment for a single baseline interferometer is shown in Figure 15-11. The two phase lock receivers independently track the phases of the received interferometer antenna signals. A common frequency reference is used for both receivers to maintain phase coherence. The relative phase of loop VCO signals from each receiver is measured by the digital phase meter to provide a direct measure of the relative received signal phases. The measured electrical phase difference is used to calculate the line-of-sight angle to the ground station. The digital phase meter is enabled when both receivers have acquired the signal. The monitored signals are recorded and used to estimate the confidence of the measurements and predict the measurement variance. The test signal generator provides a means of testing and calibrating the receivers and digital phase meter prior to a data acquisition pass over the ground stations.

## 15.5 EXPERIMENT OBSERVATION/MEASUREMENT PROGRAM

For simplicity, the Early Laboratory Sortie Can missions will be configured with a single baseline interferometer. This provides one line-of-sight direction measurement to an unknown ground station. This, however, is adequate to demonstrate the combined calibration and measurement accuracy of a satellite-borne interferometer. By combining equations (1) and (3), the observed electrical phase angle of the $n^{th}$ ground station signal for small interferometer baseline orientation angle errors is,

$$\phi_n = \frac{2\pi}{\lambda_n}\left[D\cos\theta_{nx} + D\gamma\,\mathrm{Cos}\,\theta_{ny} + D\psi\,\mathrm{Cos}\,\theta_{nz}\right] + \Phi + N \qquad (4)$$

where

$$\mathrm{Cos}\,\theta_{nx} = \frac{x_n - x_s}{R_n} \qquad (5)$$

$$\mathrm{Cos}\,\theta_{ny} = \frac{y_n - y_s}{R_n} \qquad (6)$$

$$\mathrm{Cos}\,\theta_{nz} = \frac{z_n - z_s}{R_n} \qquad (7)$$

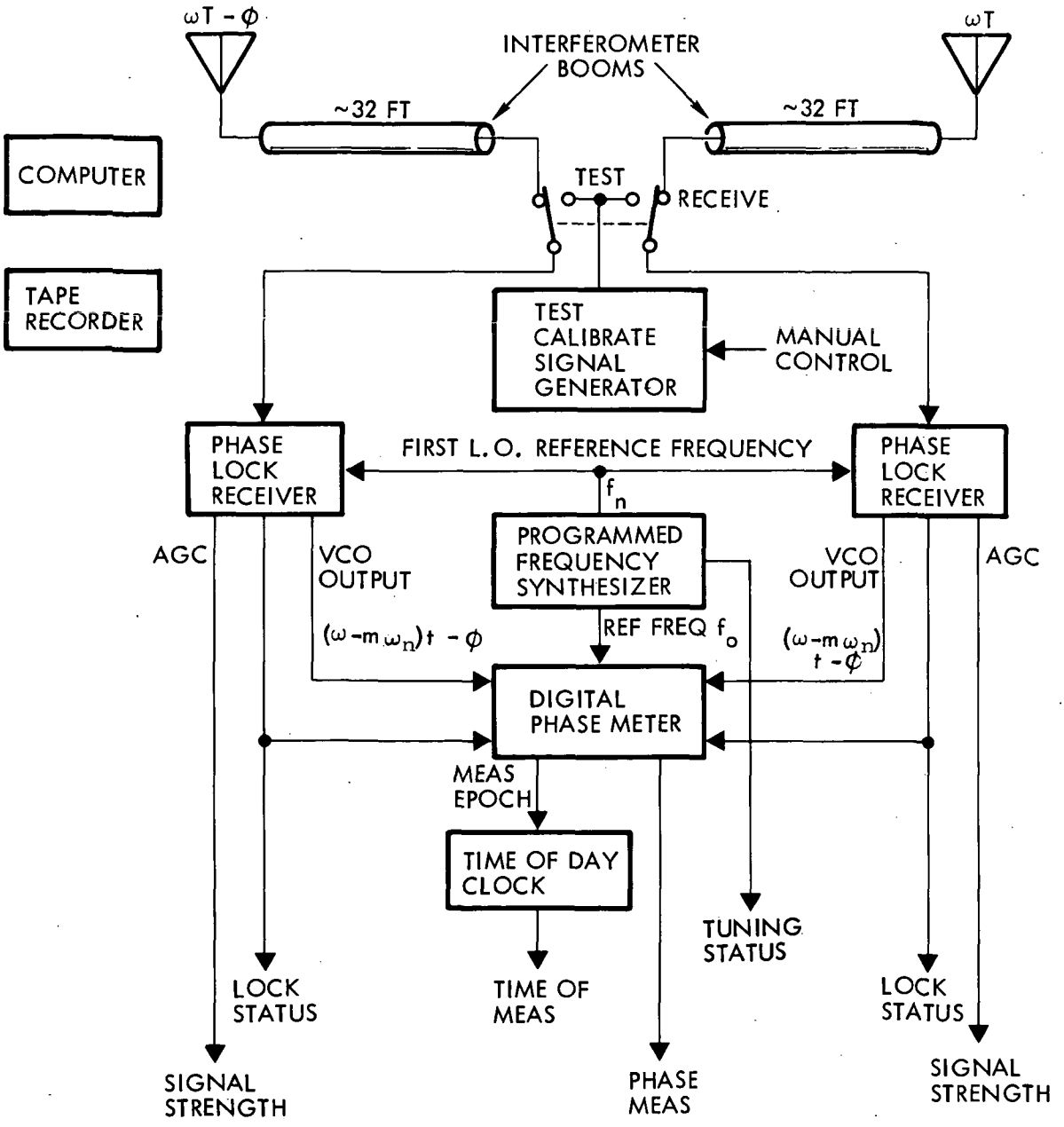


Figure 15-11. Comm/Nav Laboratory
Single Baseline Interferometer Equipment Configuration

The calibration process requires four independent observations to estimate the interferometer parameters D, $\gamma$, $\psi$, $\Phi$. Using Matrix notations these unknowns can be experessed as

$$G = P^{-1}M \tag{8}$$

where $P^{-1}$ is the inverse of P, and

$$G = \begin{bmatrix} D' \\ (\gamma D)' \\ (\psi D)' \\ \Phi' \end{bmatrix} \tag{9}$$

$$P = 2\pi \begin{bmatrix} \frac{\text{Cos } \hat{\theta}_{1x}}{\hat{\lambda}_1} & \frac{\text{Cos } \hat{\theta}'_{1y}}{\hat{\lambda}_1} & \frac{\text{Cos } \hat{\theta}_{1z}}{\hat{\lambda}_1} & (2\pi)^{-1} \\ \frac{\text{Cos } \hat{\theta}_{2x}}{\hat{\lambda}_2} & \frac{\text{Cos } \hat{\theta}_{2y}}{\lambda_2} & \frac{\text{Cos } \hat{\theta}_{2z}}{\hat{\lambda}_2} & (2\pi)^{-1} \\ \frac{\text{Cos } \hat{\theta}_{3x}}{\hat{\lambda}_3} & \frac{\text{Cos } \hat{\theta}_{3y}}{\hat{\lambda}_3} & \frac{\text{Cos } \hat{\theta}_{3z}}{\lambda_3} & (2\pi)^{-1} \\ \frac{\text{Cos } \hat{\theta}_{4x}}{\hat{\lambda}_4} & \frac{\text{Cos } \hat{\theta}_{4y}}{\hat{\lambda}_4} & \frac{\text{Cos } \hat{\theta}_{4z}}{\hat{\lambda}_4} & (2\pi)^{-1} \end{bmatrix} \tag{10}$$

$$M = \begin{bmatrix} \phi 1 \\ \phi 2 \\ \phi 3 \\ \phi 4 \end{bmatrix} \tag{11}$$

The "hatted" parameters denote estimated values, and the "primed" parameters denote calculated values. After the elements of G are estimated, the line-of-sight angle to the fifth ground station (simulated unknown) can be estimated. The calculated line-of-sight direction to the fifth ground station is obtained from equation (4) with n = 5.

$$\theta'_{5x} = \text{Cos}^{-1}\left[\frac{\hat{\lambda}_5}{2\pi D'}(\phi_5 - \Phi') - \gamma' \text{Cos } \hat{\theta}_{5y} - \psi' \text{Cos } \hat{\theta}_{5z}\right] \tag{12}$$

The calculated line-of-sight angle, $\theta'_{5x}$, to the fifth ground station should closely agree to the estimated line-of-sight angle $\hat{\theta}_{5x}$. The difference between the calculated and estimated line-of-sight angles is a measure of the interferometer accuracy, defined as,

$$\delta\theta_{5x} = \theta'_{5x} - \hat{\theta}_{5x} \tag{13}$$

Since both $\theta'_{5x}$ and $\hat{\theta}_{5x}$ are approximately equal and close to $\pi/2$ radians, the difference of the arc cosines can be approximated as

$$\delta\theta_{5x} \cong \frac{\hat{\lambda}5}{2\pi D'} (\varphi_5 - \Phi') - \text{Cos } \hat{\theta}_{5x} - \gamma' \text{ Cos } \hat{\theta}_{5x} - \psi' \text{ Cos } \hat{\theta}_{5x} \tag{14}$$

In matrix notation, the calculated line-of-sight error is

$$\delta\theta_{5x} \cong \frac{\hat{\lambda}5}{2\pi D'} [\varphi_5 - J\ G] \tag{15}$$

where

$$J = \left[\frac{\text{Cos } \hat{\theta}_{5x}}{\hat{\lambda}_5} \cdot \frac{\text{Cos } \hat{\theta}_{5y}}{\hat{\lambda}_5} \cdot \frac{\text{Cos } \hat{\theta}_{5z}}{\hat{\lambda}_5} (2\pi)^{-1}\right] \tag{16}$$

Substituting equation (8) into (15) gives

$$\delta\theta_{5x} \cong \left(\frac{\hat{\lambda}5}{2\pi}\right) \frac{\varphi 5 - JP^{-1} M}{Q\ P^{-1} M} \tag{17}$$

where

$$Q = 1000 \tag{18}$$

Equation (17) will be implemented on-board the Communication/Navigation Laboratory using a general purpose computer to provide real time measurement results. This enables the operator to monitor the interferometer performance following each pass over a ground station complex. Figure 15-12 shows the data flow and processing implementation to calibrate the interferometer (G-matrix) and compute the measured line-of-sight error to the fifth test ground station. The input and output data buffering operations and the indicated computational steps are performed by the general purpose computer. The input and output data parameters and their associated data rates are listed in Tables 15-1 and 15-2, respectively. The data display and permanent data storage requirements are summarized in Table 15-3.

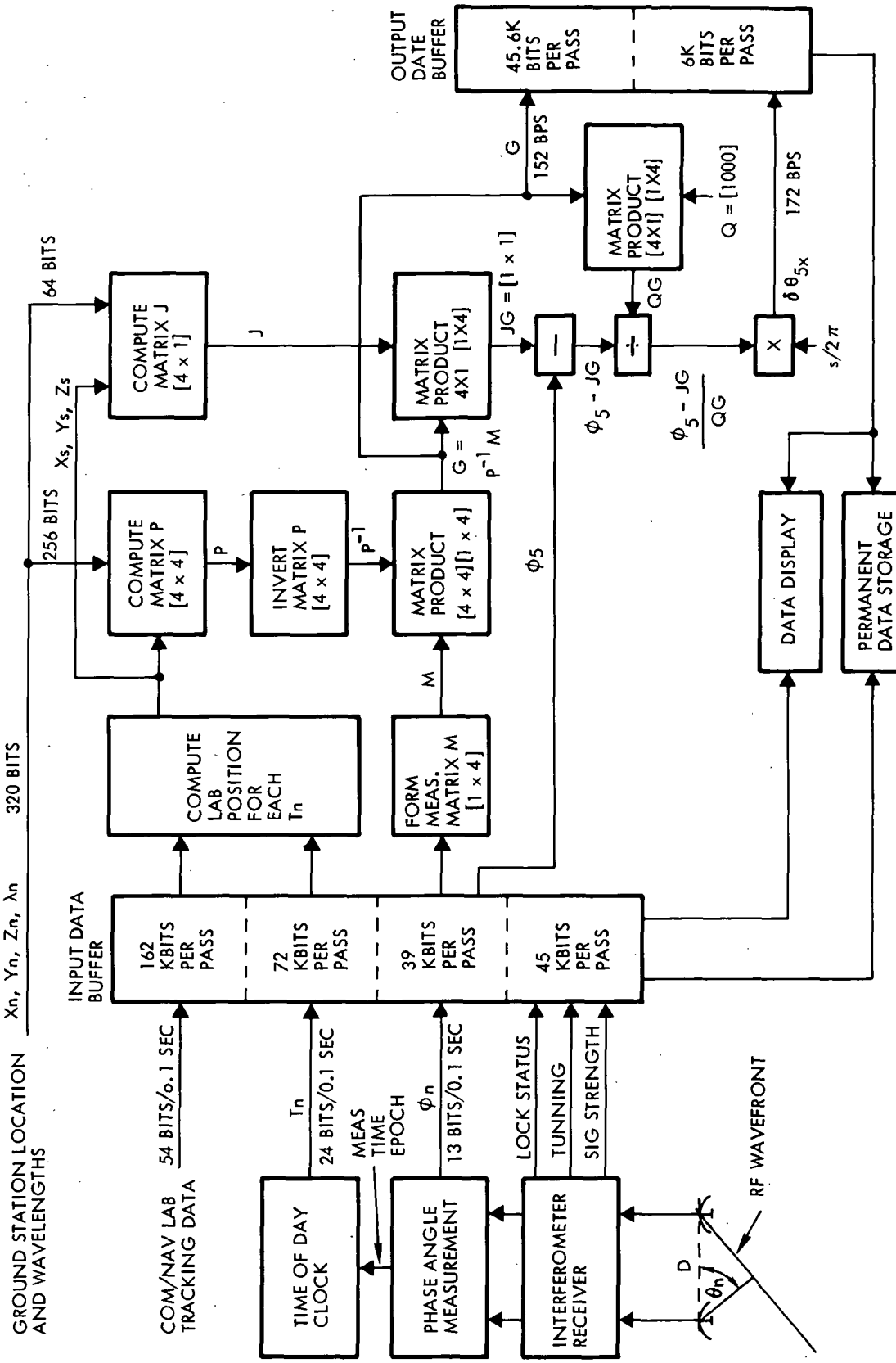


Figure 15-12. Data Flow and Processing Diagram

Table 15-1. Input Data Requirements

| Parameter | Precision | Dynamic Range | Data Bits | Measurement Rate | Input Data Rate | Total Input Data Per 5 Min. (300 sec.) Pass |
|---|---|---|---|---|---|---|
| Ground Station Locations | | | | | | |
| $x_n$ | 10 ft | 400 n. mi. | 18 each | Once | - | - |
| $y_n$ | 10 ft | 400 n. mi. | 18 each | Once | - | - |
| $z_n$ | 10 ft | 400 n. mi. | 18 each | Once | - | - |
| $\lambda_n$ | $6.5 \times 10^{-8}$ ft | $4.22 \times 10^{-2}$ ft | 20 each | Once | - | - |
| | | | 74 each | Once | - | - |
| | | | 320 (5 stations) | Once | - | - |
| Comm/Nav Location | | | | | | |
| $x_s(T_n)$ | 10 ft | 400 n. mi. | 18 | 10/sec | 0.18 Kbps | 54 KBits |
| $y_s(T_n)$ | 10 ft | 400 n. mi. | 18 | 10/sec | 0.18 Kbps | 54 KBits |
| $z_s(T_n)$ | 10 ft | 400 n. mi. | 18 | 10/sec | 0.18 Kbps | 54 KBits |
| | | | 54 | | 0.54 Kbps | 162 KBits |
| Time of Day, $T_n$ | 0.01 sec | 24 hrs | 24 | 10/sec | 0.24 Kbps | 72 KBits |
| Phase Angle, $\phi_n$ | $10^{-3}$ rad | 6.28 rad | 13 | 10/sec | 0.13 Kbps | 39 KBits |
| Interferometer Receiver | | | | | | |
| Lock Status | - | - | 2 | 10/sec | 20 Bps | 6 KBits |
| Rec. Tuning State | - | - | 3 | 10/sec | 30 Bps | 9 KBits |
| Signal Strength (Two) | 1 dB | 32 dB | 10 | 10/sec | 100 Bps | 30 KBits |
| | | | 15 | | 0.15 Kbps | 45 KBits |
| TOTALS | | | | | 1.06 Kbps | 318 KBits |

Table 15-2. Computed Output Data

| Parameter | Precision | Dynamic Range | Data Bits | Computation Rate | Output Data Rate | Total Output Data Per 5 min. (300 Sec.) Pass |
|---|---|---|---|---|---|---|
| G-Matrix | | | | | | |
| D | $10^{-3}$ in | 1 in | 10 | 2/sec | 20 Bps | 6 KBits |
| $D\gamma$ | $10^{-9}$ in | $10^{-3}$ in | 30 | 2/sec | 60 Bps | 18 KBits |
| $D\psi$ | $10^{-9}$ in | $10^{-3}$ in | 30 | 2/sec | 60 Bps | 18 KBits |
| $\Phi$ | $10^{-4}$ rad | $2 \times 10^{-2}$ rad | 8 | 2/sec | 16 Bps | 4.8 KBits |
| | | | 76 | | 152 Bps | 45.6 KBits |
| Line of Sight Angle Error, $\delta\theta$ | $10^{-6}$ rad | $10^{-3}$ rad | 10 | 2/sec | 20 Bps | 6 KBits |
| TOTALS | | | | | 172 Bps | 51.6 KBits |

Table 15-3. Data Display and Permanent Storage for Each Pass

| Parameters | Storage | Display |
|---|---|---|
| Comm/Nav Location | 162.0 KBits | |
| Time of Day | 72.0 KBits | |
| Phase Angle | 39.0 KBits | |
| Inteferometer Rec. | 45.0 KBits | 45.0 KBits |
| G-Matrix | 45.6 KBits | 45.6 KBits |
| L.O.S. Angle Error | 6.0 KBits | 6.0 KBits |
| Total Bits per pass | 369.6 KBits | 96.6 KBits |
| Passes per day | 3* | - |
| Total Bits per day | 1.1098 MBits | - |
| Sortie Mission days | 14 | - |
| Total Bits per Sortie Mission | 15.5372 MBits | - |

* for each ground station complex

## 15.6 INTERFACE, SUPPORT AND PERFORMANCE REQUIREMENTS

The candidate interferometer experiment requires at least one complex of five ground transmitter stations as illustrated by Figure 15-10. The location of each ground station must be known to about 10 ft. (one sigma) to evaluate accuracy of the interferometer system. A single ground station complex affords approximately 15 minutes of data acquisition per day for an orbiting vehicle at 200 n. mi. altitude. It is, therefore, desirable to use additional ground complexes at different longitudes to increase the total data base. Ideally, the sites for the additional ground station complexes should be selected to provide representative land and water multipath conditions.

Each ground station transmitter should have an available power of at least 50 watts at L-band (1569.75 to 1570.25 MHz) to provide 7 dB signal-to-noise margin. A power budget for the ground station-Comm/Nav Laboratory link is shown in Table 15-4.

The Comm/Nav Laboratory position must also be accurately known as a function of time to measure the interferometer accuracy. A position accuracy of about 10 ft (one sigma) is required. The laboratory position or orbit must be measured by an independent tracking system such as MSFN. The data must be supplied to the Laboratory via a real-time data link while the laboratory is passing over each ground station complex. An accurate Laboratory position fix is required for each phase angle measurement. The times at which the phase measurements are made will not necessarily coincide with the times at which the laboratory position measurements are made. Consequently the laboratory position will have to be computed by interpolation of the position data. This computational step is indicated in Figure 15-12.

## 15.7 POTENTIAL ROLE OF MAN

An extra-vehicular activity (EVA) capability for the Early Laboratory is not anticipated; consequently the deployment of the interferometer booms will have to be automated. The role of man for this phase of the experiment is, therefore, shifted to control and observation of the boom deployment processes and subsequent observation of their in-flight dynamics. Malfunctions in boom deployment or abnormal dynamic

Table 15-4. Interferometer Experiment Power Budget

| | |
|---|---|
| Estimated phase noise, $\sigma_\phi$ | 7.07 m rad rms, nominal |
| Required phase lock loop SNR (Note 1) | 40 dB |
| Phase lock loop bandwidth (10 Hz) | 10 dB-Hz |
| Required $C/N_o$ | 50 dB-Hz |
| Receiver noise figure | 5 dB |
| $KT_o$ | -204 dBw/Hz |
| Required receiver power | -149 dBw |
| Interferometer antenna losses | 2 dB |
| Interferometer antenna gain | 3 dB |
| Space loss (700 n. mi. @ 1570 MHz) (Note 2) | 159 dB |
| Required ground station ERP | 9 dBw |
| Ground station antenna gain | 0 dB |
| Ground station RF losses | 1 dB |
| Required ground station transmitter power | 10 dBw |
| Available ground station transmitter power (50 watts) | 17 dBw |
| Margin | 7 dB |

Notes:

1) $SNR = \frac{1}{2\sigma_\phi^2}$

$\sigma_\phi$ = phase noise

2) Maximum slant range is approximately 700 n. mi. to a ground station at a cross track displacement of 36 n. mi. and an elevation angle of 10 degree.

behavior of the extended booms should be photographed with a motion picture camera.

Prior to a data collection pass, the crew will test the laboratory interferometer instrumentation located in the Sortie Can module by substituting a test signal for the received antenna signals (Reference Figure 15-11). This test signal will be varied in power and frequency to simulate the anticipated received ground transmitter signals. Under the test conditions the crew will observe the following items for each ground station frequency:

a) Receiver signal acquisition thresholds (each receiver)

b) Receiver acquisition probability and time versus signal level (each receiver)

c) Phase measurement accuracy versus signal level (each receiver)

d) Verify receiver lock status indicators (each receiver)

e) Calibrate signal strength indicators (each receiver).

During a data collection pass, the receiver control and phase measurements have been automated to facilitate a rapid sequence of measurements. Rapid measurements are required to minimize the Laboratory and boom attitude changes during the calibration and measurement cycle. Consequently, the crew will not participate in the data collection phase of the experiment.

After the data collection pass, the crew will recall from the computer memory selected raw data and calculated line-of-sight error data and display it to check its credibility. The time required for a post pass data evaluation may vary from a few minutes up to an hour depending on the authenticity and consistency of the data. If the data is erratic or outside of the expected tolerance limits, the operator may instigate fault isolation procedures or he may choose to abort the experiment. If the collected data is acceptable, the operator will command permanent storage of the data for post flight analysis. It may be advantageous to send the data to the ground to permit ground based principal investigators to analyze the results and direct configuration/objective modifications which will optimize the remainder of the experiment operations.

## 15.8 EXPERIMENT EVOLUTION

The interferometer experiment described herein is primarily directed toward a relatively austere early Sortie Can mission configuration. A logical transition from the Early to the Growth Laboratory is implementation of a two-dimensional interferometer. This would permit a more complete demonstration and evaluation of a typical operational interferometer navigation or surveillance system. In addition, the Growth Laboratory should be configured to accommodate both transmitting and receiving interferometers (see Figures 15-5 and 15-6).

The Total Laboratory would accommodate all the basic two-dimensional interferometer configurations including the one and two-way link receiving and transmitting interferometer configurations shown in Figures 15-5 to 15-8. A ranging capability can also be combined with the two-way link configurations to demonstrate the equipment operation and performance of a three dimensional navigation or surveillance system. The added ranging capability can be obtained by combining the interferometric experiment with the range and range rate experiment.

The use of EVA in the Growth and Total Laboratory configurations to deploy the interferometer antenna booms should not be required. The antenna booms should be automatically deployed to demonstrate and test the types of boom designs that would be used in an operational unmanned satellite. EVA, however, can be used to advantage to install or substitute different boom and antenna designs for comparative in-orbit evaluations. In addition, EVA can be used to correct and/or observe deployment malfunctions.

The participating ground station equipment for the Growth and Total Laboratory configurations would be modified and augmented as required to support the increased requirements of the Laboratory. This would include the use of additional ground station sites and the use of aircraft and ships to simulate systems users. To demonstrate surveillance or search and rescue systems, the unprocessed Laboratory data should be relayed to a central ground data processing center by a "store and forward" data link. If this is implemented, the volume and rate of the data resulting from a large number of participating ground stations may necessitate the use of a dedicated Laboratory-to-ground data link.

Alternatively, the data could be stored on board the Laboratory for future ground processing.

The exact configuration of the Growth and Total Laboratories will be influenced by the results of prior laboratory interferometer experiment results and the anticipated configurations and needs of planned navigation and surveillance systems.

## 15.9 SRT REQUIREMENTS

With the exception of the interferometer antenna booms, the planned experiment instrumentation uses current technology with proven equipment designs. Preliminary antenna boom designs have been formulated and analytically evaluated in previous studies; however, specific boom designs compatible with the Comm/Nav Laboratory configurations remain to be generated, fabricated and evaluated.

The interferometer experiment is predicated on a stiff, stable, baseline which is free from spurious antenna pattern effects due to interference from Shuttle doors and motion. Stowage and deployment are perennial problems which must be investigated. This effort should yield several candidate boom and antenna designs which can be ultimately evaluated in orbit by the Comm/Nav Laboratory.

## 15.10 ACKNOWLEDGEMENTS

The following experiments were used in formulating the candidate radio interferometric navigation and surveillance experiment for the Comm/Nav Laboratory:

| Experiment | Principal Investigator and Association |
|---|---|
| 1. Interferometer Position Location | Tsitsera, IBM |
| 2. Radio-Interferometer Position Location | Perry I. Klein, COMSAT Corporation and Univ. of Pennsylvania |
| 3. Interferometric Navigation Technique | Tankersley, Westinghouse Space Systems |
| 4. Terrestrial Navigation Technique Employing a Satellite-Borne Spinning Interferometer | F. Haber, Univ. of Pennsylvania |

# EXPERIMENT 16

# UNKNOWN LANDMARK TRACKING/ AUTONOMOUS NAVIGATION EXPERIMENT

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APPENDIX A

# 16. UNKNOWN LANDMARK TRACKING/ AUTONOMOUS NAVIGATION EXPERIMENT

## 16.1 EXPERIMENT CLASSIFICATION

The unknown landmark tracking experiment is primarily developmental in nature as equipment and methods are tested in support of an operational system capability. The latter stages of the experiment also include operational testing and demonstration of a system configuration.

## 16.2 EXPERIMENT OBJECTIVES

This experiment consists of a series of orbital tests to determine the feasibility and accuracy of autonomous navigation using unknown earth landmarks. The experiment serves as a valuable adjunct to several related technology studies recently conducted or in planning by USAF SAMSO, NASA, and others. Specifically, the experiment will evaluate a selected hardware implementation for feasibility and accuracy measured against a control precision ground tracking network. Additional experiment objectives include:

a) Compilation of geomorphic data to support a catalog of preferred target areas

b) Evaluation of the need for man-aided target selection vs automatic lock-on and break-lock techniques

c) Evaluation of the effects of operational phenomena such as cloud obscuration, atmospheric effects, parallax, specular reflection, and viewing aspect distortion

d) Evaluation of the feasibility and performance of major autonomous navigation subsystems.

## 16.3 DISCIPLINE BACKGROUND AND STATUS

The feasibility of unknown landmark tracking as a source of navigation data has been extensively investigated using analytical methods (References 1-3). Some basic laboratory tests have been performed using photographic targets and an aircraft flight test of a prototype tracker was conducted by Autonetics (Reference 4). However, an orbital flight test is required to successfully demonstrate tracker operation with realistic targets and operational limitations. Further, an orbital flight test is also required to demonstrate navigation system

performance because the orbital dynamics are fundamental to navigation using unknown landmark tracking.

## 16.4 EXPERIMENT DESCRIPTION

The proposed unknown landmark tracking experiment is comprised of two basic optical tracking systems. One is an automatic tracker and the other an astronaut monitoring telescope. A functional block diagram of the experiment configuration is shown in Figure 16-1. The monitoring telescope is slaved to the landmark tracker line-of-sight to provide the astronaut with a display of the same scene as that presented to the tracker. Mode control functions will be provided so that the tracker may be slewed and automatic tracking initiated or terminated.

## 16.5 EXPERIMENT OBSERVATION/MEASUREMENT PROGRAM

Tracker gimbal angle measurements at 5-10 second intervals will be recorded concurrently with astronaut descriptive comments, spacecraft attitude and spacecraft position for detailed post-mission evaluation. In more advanced experimental configurations, on-board navigation computations would be performed on the tracker angle data to generate near real-time navigation information. Table 16-1 summarizes the measurement data requirements.

Table 16-1. Data Requirements

| Instrument/Signal Identity | No. of Channels | Data Form A or D (Bits) | Bandwidth or Bit Rate | Onboard Destination |
|---|---|---|---|---|
| Error Signals | 2 | 8 | 160 B/S | Control, Display |
| Gimbal Angles | 2 | 16 | 1.6 KB/S | Control, Display |
| Receiver Video SNR | 1 | 8 | 8 B/S | Control, Display |
| Track Command | 1 | 2 | Discrete | Control, Display |
| Slew Command | 2 | 16 | 32 B/S | Control, Display |
| Timing Ref. | 1 | 36 | 36 B/S | Perm. Storage |
| Spacecraft Attitude | 3 | 16 | 48 B/S | Perm. Storage |
| Computed S/C Pos. | 3 | 16 | 48 B/S | Storage, Display |

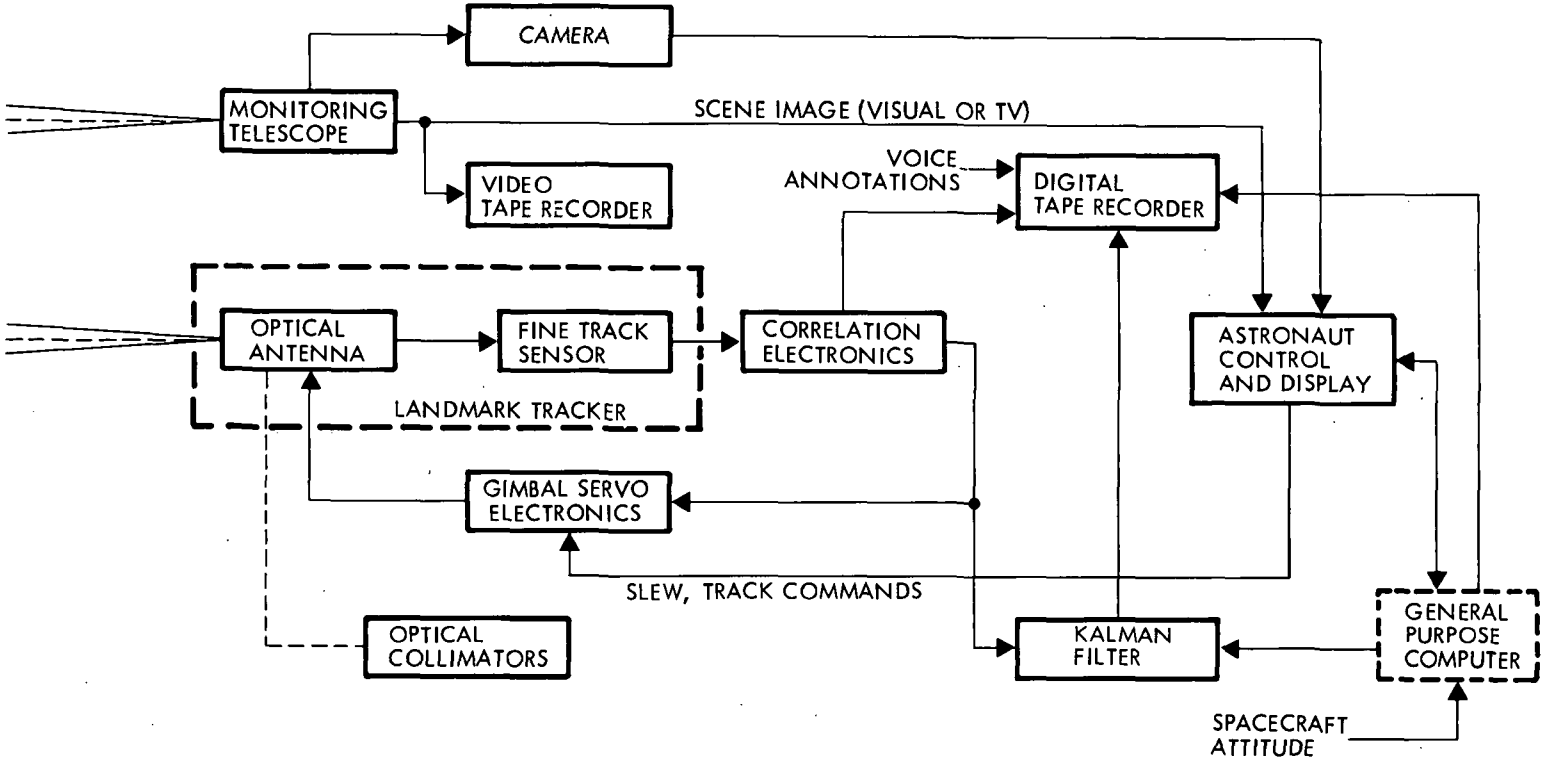



Figure 16-1. Functional Block Diagram – Landmark Tracking Experiment

The independent knowledge of spacecraft position required for this experiment will require ground tracking support during the experimental program. Orbit altitudes between 100-500 n. mi. are recommended for this experiment. The inclination of the orbit is not critical.

## 16.6 INTERFACE, SUPPORT, AND PERFORMANCE REQUIREMENTS

### 16.6.1 Environmental Requirements

Thermal control and vibration isolation will be required for the optical antenna and fine track sensor. Quantitative specifications are dependent upon the selected design.

### 16.6.2 Pointing Requirements

An accurate (3 $\hat{\text{sec}}$) knowledge of spacecraft inertial attitude is required for this experiment. Ideally, this information will be obtained from the Shuttle; however, this data could be supplied as part of the experiment at some increase in equipment complexity if desired.

### 16.6.3 Mounting/Structural Requirements

The precision to which angles are measured in this experiment will require that relative alignment of the tracker with the spacecraft inertial attitude reference be calibrated and held to a few seconds of arc.

## 16.7 POTENTIAL ROLE OF MAN

The presence of the astronaut in this experiment facilitates collection of a wide range of orbital evaluation data in a relatively short period of time. The initial experiments will emphasize the evaluation of the tracker performance, including automatic acquisition and tracking, in the presence of variations in the earth scenes and cloud cover effects. The astronaut will be required to set up this phase of the experiment through open loop slewing and monitoring of the tracker to select scenes for evaluation. His comments and evaluation of tracker response and performance with the test scenes will augment the quantitative measurements, particularly during the preliminary experimental phases.

During the advanced experimental phases involving evaluation of automatic navigation using unknown landmark tracking, the astronaut will monitor the tracker performance and navigation computations to provide qualitative performance evaluations and re-initializations as

required. This task will require limited familiarity with orbital dynamics and orbital navigation, probably not exceeding the level an astronaut would normally possess.

## 16.8 EXPERIMENT EVOLUTION

The unknown landmark tracking experiment will be initially configured with the tracker and astronaut monitoring telescope. These early experiments will concentrate on the collection of geomorphic data and the evaluation of tracker performance in the presence of cloud and various scene effects. The Growth and/or Total Research Laboratory would also contain the on-board computational capability to allow autonomous navigation using unknown landmark tracking to be evaluated. Other sensors such as drag accelerometers may be added to enhance overall navigation accuracy.

## 16.9 SRT REQUIREMENTS

An unknown landmark tracker suitable for this experiment does not currently exist. Design studies have been performed but additional supporting research and development will be required to design, develop, fabricate and test a suitable tracker for this experiment.

## 16.10 ACKNOWLEDGEMENTS

### 16.10.1 Related Experiments

| Experiment | Principal Investigator and Association |
|---|---|
| 1. Autonomous Navigation Using Coherent Optical Filter Techniques | J. Welch<br>General Electric Space Systems |
| 2. Unknown Landmark Availability Study | R. Seibert<br>McDonnell Douglas Astronautics |
| 3. Unknown Landmark Tracking | J. Williams<br>TRW Systems |
| 4. Autonomous Navigation Systems for Space | Blue Book, Vol. V, Jan. -1971 |

16.10.2 References


1. N. F. Toda and F. H. Schlee, "Autonomous Orbital Navigation by Optical Tracking of Unknown Landmarks," AIAA/JACC Guidance and Control Conference, pp 489-499, 1966.

2. J. F. Bellantoni, "Unidentified Landmark Navigation," AIAA Journal, vol. 5, No. 8, pp 1478-1483, August 1967.

3. H. T. Hendrickson, "A Study of an Unknown Landmark Tracking Navigation System - First Set of Results," Report No. TOR-0059(6311)-18, The Aerospace Corporation, El Segundo, Ca., December-1970.

4. H. L. Dibble, (U) "Unknown-Landmark Tracking Feasibility Study," AFAL-TR-69-21, vols. I and II, Air Force Avionics Laboratory, Wright Patterson Air Force Base, Ohio, March 1969 (Secret).

# APPENDIX A

## EQUIPMENT CONCEPTUAL DESIGN

The unknown landmark tracking system described herein consists of:

- Gimballed correlation landmark tracker
- Gimballed monitoring telescope
- On-board Kalman filter
- Low-level drag accelerometer.

The system will utilize existing spacecraft attitude reference and gyro reference capabilities for establishing an initial estimate of coordinates. It is also assumed that precision timing references will be provided.

In the proposed configuration, a single sensor is utilized as a star tracker and landmark tracker, time sharing the two tracking functions. If the host vehicle navigation system includes a precision star tracker, the requirement for an experiment-unique unit may be deleted for unknown landmark navigation experiments. The Kalman filter provides digital data processing to optimize the running estimate of spacecraft coordinates. It is highly probable that available on-board computing equipment can provide the major portion of this processing. Equipment characteristics presented in the following sections were developed under Air Force contract No. FO4701-71-C-0340.

### Landmark Tracker

The tracker pointing control must be capable of directing the sensor line-of-sight to an accuracy of a few arc-seconds in both star and landmark tracking modes. Tracking circuitry must be provided to permit lock-on of point targets in the star mode and extended scenes in the landmark mode. A search mode must also be provided for star acquisition as well as a landmark acquisition mode.

The tracker optical system must be capable of maintaining image distortion to a few arc-seconds and a blur circle of a few tens of arc-seconds. Typical optics consist of a conventional design reflective Cassegrain telescope with the characteristics identified in Table A-1.

Table A-1. Typical Optics Characteristics

| | |
|---|---|
| 1. Telescope type | Reflective Cassegrain<br>Parabolic Primary -<br>Hyperbolic Secondary |
| 2. Collection aperture | 4-inch diameter<br>1.2-inch central obstruction |
| 3. Equivalent focal length | 32 inches |
| 4. Field of view | $0.5^{o} \times 0.5^{o}$ |
| 5. Resolution | 30 arc-seconds |
| 6. Overall dimensions | 4" Diameter x 11" Long |

A candidate configuration for the tracker assembly is illustrated in Figure A-1.

The recommended detector consists of a conventional 1-inch magnetically focussed and deflected image dissector tube equipped with an S-20 or equivalent photocathode. Typical operating characteristics are identified in Table A-2.

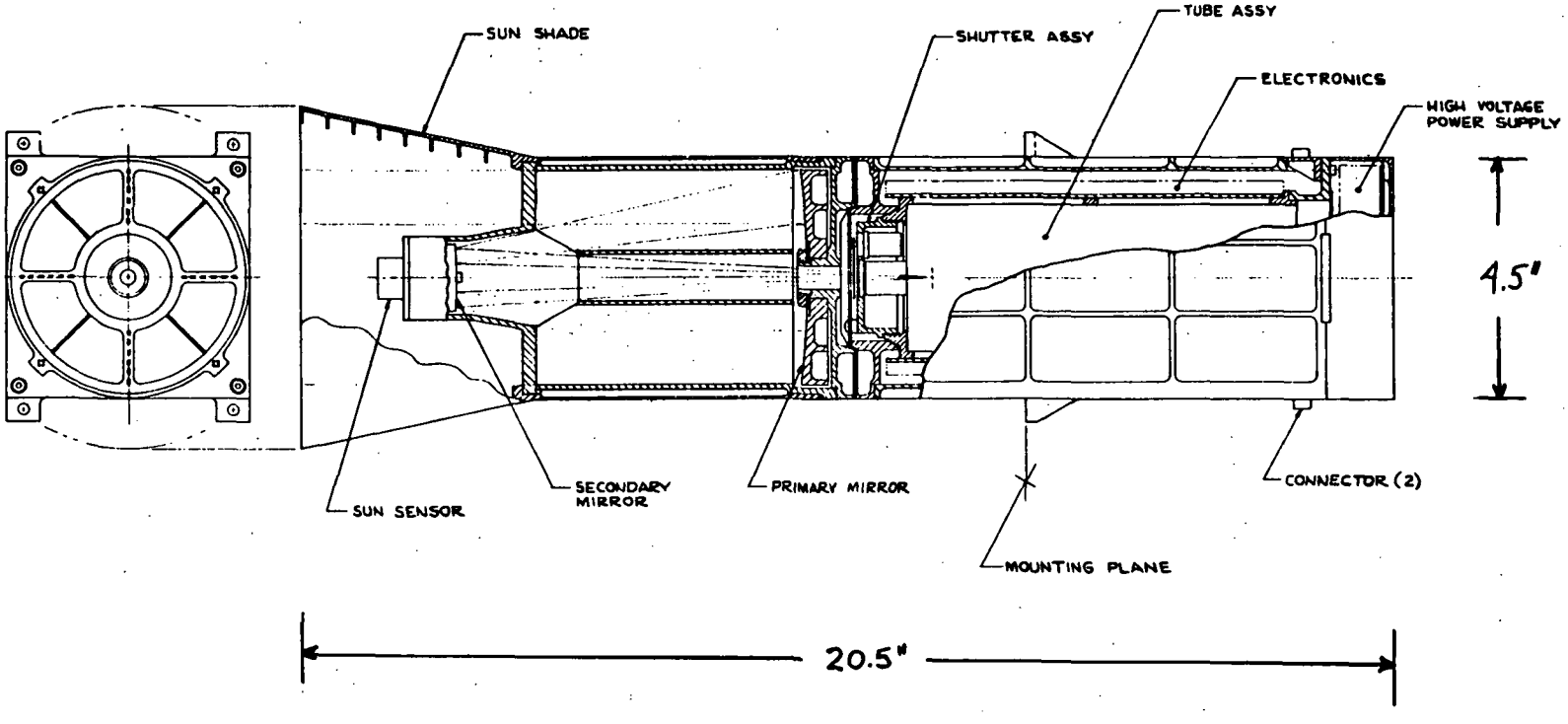
Table A-2. Detector Characteristics

| Type | Image Dissector |
|---|---|
| Format | 1" |
| Resolution | .005" |
| Sensitivity | S-20 |
| Frame Time | TBD sec |
| Focus | Magnetic |
| Deflection | Magnetic |

Monitoring Telescope

The gimballed telescope required for astronaut monitoring activities can be implemented in several different ways using available equipment. A straightforward approach is to use a two-gimbal camera mount with a television camera and suitable optics. The display provided the astronaut

Figure A-1. Tracker Assembly Configuration
Total Weight = 10 Pounds



would then be a conventional television image. Alternatively, the image dissector video output from the landmark tracker itself can be displayed thus providing an identical image of the tracker field-of-view. However, this image may be inferior quality for astronaut evaluation. A direct viewing optical telescope could satisfy this requirement, but this approach has the disadvantages of complicated equipment interfaces and the absence of electrical image representation for storage.

On-board Kalman Filter

A suitable on-board software program is being developed under Air Force Contract No. F04701-71-C-0340. This software will perform all the computations required to process the gimbal angle measurement to generate estimates of spacecraft position. Computational requirements for the computer are a memory size of 8000 words and a word length of at least 26 bits.

Low-Level Drag Accelerometers

Low-level accelerometers have been developed for the measurement of atmospheric drag forces at orbital altitudes. The Bell Aerosystems Miniature Electrostatically Suspended Accelerometer (MESA) has been developed with Air Force and NASA funds for this application.

# EXPERIMENT 17

# LASER RANGING

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# 17. LASER RANGING

## 17.1 EXPERIMENT CLASSIFICATION

Developmental and Applied Research.

## 17.2 EXPERIMENT OBJECTIVES

On-board laser ranging provides an autonomous means of accurately measuring distances between the spacecraft and other points of interest, e.g., earth, moon and other spacecraft. This ranging data can be used in related applications including navigation aid, rendezvous and docking aid, aid to the navigation of other cooperative spacecrafts and in astronomical observations. The objectives of this experiment are to:

- Evaluate the utility and accuracy of an on-board laser ranging system for use with cooperative and uncooperative targets
- Evaluate laser target acquisition and pointing techniques
- Evaluate the effects of various background illumination conditions on the performance of the system
- Evaluate target parameters in a space environment
- Determine optimal engineering parameters for laser rangefinders under various modes of operation
- Determine the effects of clouds and weather phenomena upon laser altimeters
- Collect data on the reflectivity statistics of land and sea areas for purposes of laser altimetry.

## 17.3 DISCIPLINE BACKGROUND AND STATUS

Both laser and RF ranging systems have demonstrated important capabilities for space application. Each of these types has distinct advantages and disadvantages. Particular advantages of laser radars include:

- Precision tracking capabilities
- Small aperture size
- Small beam footprint (i.e., narrow beam)
- Capability to operate at very short range.

Laser ranging is particularly appropriate for those space applications in which transmission through the earth's atmosphere is not required. Atmospheric scattering and absorption are major limitations for terrestrial laser ranging. For space applications requiring atmospheric penetration, propagation problems can be alleviated by selecting the best available wavelength.

A laser altimeter was developed by RCA for the Apollo program to provide ranging from the command module to the lunar surface. This altimeter utilizes a pulsed ruby laser, and does not perform tracking. It provides a ranging accuracy of approximately one meter, at altitudes up to 80 n. mi. from the lunar surface. This unit was operated successfully on the Apollo 15 spacecraft for 24 orbits until a failure occurred. The experiment was included again on the Apollo 16 mission with minor design modifications.

A laser rendezvous and docking radar system has been developed by ITT under contract to NASA/MSFC. This unit is intended for use on the space Shuttle and space station projects. The system currently employs gallium-arsenide semi-conductor lasing devices; however, it is planned to develop a space-qualified Nd:YAG laser which would increase the useful range.

Both short range and long range tests were conducted on an early prototype of the ITT system. Short range tests were performed on the docking simulator at Martin Marietta Company in Denver, Colorado. All docking runs (approximately 200) were successful, and the results showed rms errors of $<0.1$ meter range at the point of docking. Laterial and vertical positioning accuracy was approximately 0.3 inch. Long range tests were carried out between a helicopter and the University of California Research Station on White Mountain. Successful acquisition and tracking tests were performed against sunlit and cloud backgrounds. Extrapolating the maximum range measured in these tests to space conditions yielded a maximum range of 95 miles. The helicopter was a cooperative target, with reflectance augmentation in the form of a 6-inch corner cube reflector.

In general, systems for short range applications (less than a mile) can be evaluated adequately by means of terrestrial tests. Longer range

systems cannot be adequately tested on the ground due to atmospheric effects. Thus, the emphasis of the Comm/Nav Research Laboratory ranging experiments should be focused on long range operation. Additional measurements which are well suited to a space laboratory program include:

- Reflectivity statistics of ocean and land terrain for purposes of altimetry ranging
- Atmospheric and weather effects upon laser altimetry
- Effects of various background conditions upon ranging and tracking performance.

Laser ranging experiments for the Comm/Nav research laboratory will provide an opportunity to investigate these phenomena, while supporting the development of components for a wide range of future applications.

## 17.4 EXPERIMENT DESCRIPTION

The recommended implementation concept employs pulsed radar techniques and lends itself primarily to long range applications. Alternate techniques, using modulated CW lasers or light emitting diodes, are better suited to short range applications and can therefore be evaluated adequately by means of testing on the ground.

A conceptual block diagram of the laser ranging and tracking system is shown in Figure 17-1. It is comprised of the following major components:

- Q-switched Laser. The laser produces short pulses of extremely high peak power upon command.
- Transmitting Optics. The transmitting optics collimate the transmitted optical pulse to the desired beamwidth.
- Collecting Optics. The collecting optics collect pulse return energy for the range receiver and tracking system.
- Pulse Monitor. The pulse monitor is a fast-response photodetector which provides a timing pulse to initiate the range counter and range gating circuits.
- Tracking Sensor. The photodetector provides timing and tracking information from return pulse echos, for use in the ranging and pointing control systems respectively.

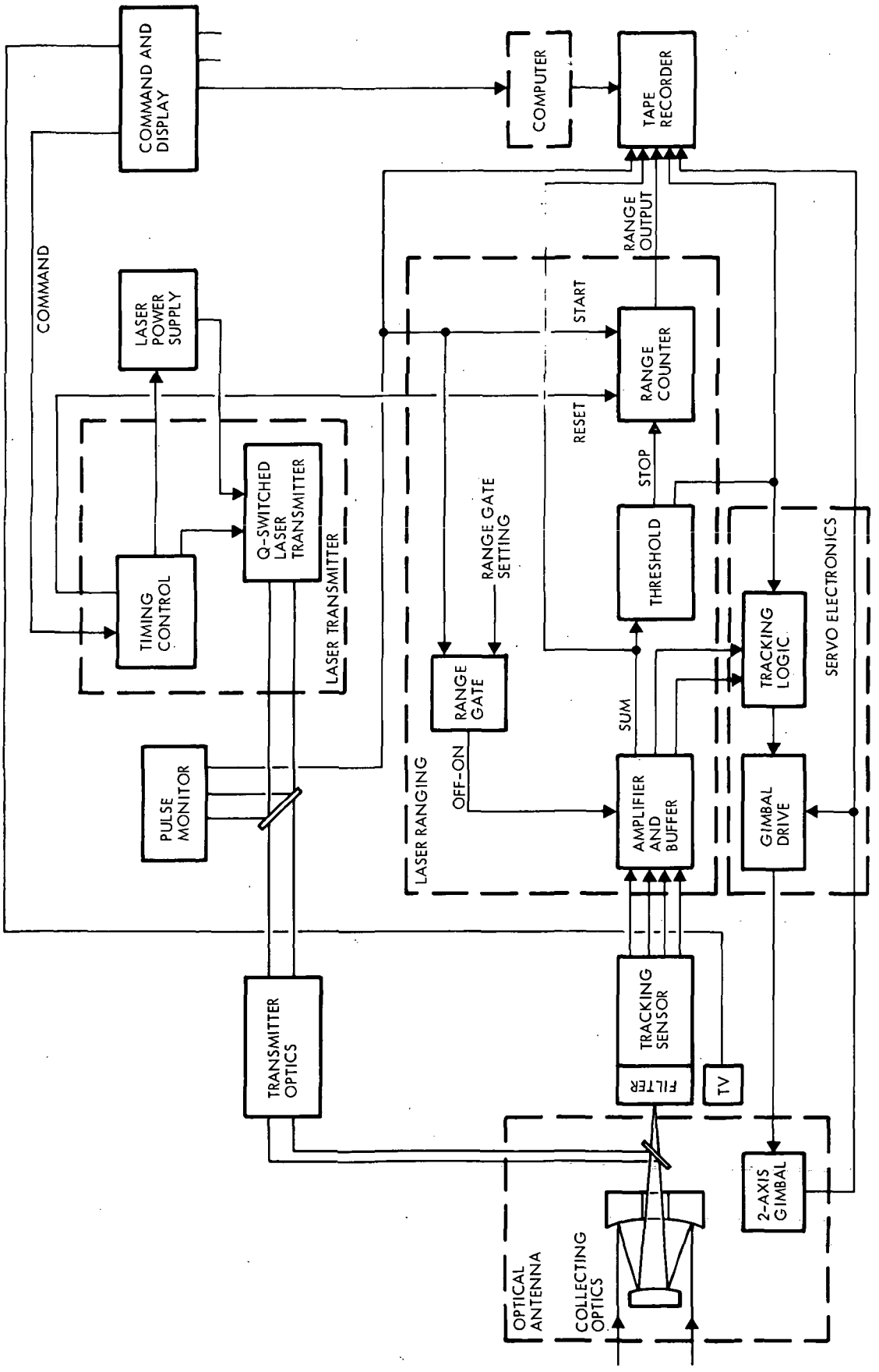


Figure 17-1. Rangefinder/Tracker Conceptual Block Diagram

- Ranging Electronics. The ranging electronics provide accurate measurement of the elapsed time between the start pulse and the detection of the return pulse. The detector preamps are disabled except during a time gate centered about the expected arrival time, thereby reducing false alarms and the possibility of detecting spurious scattered energy as the pulse is transmitted.

- Tracking Logic. The tracking system generates control signals to maintain pointing of the gimballed optics toward the direction of the reflected energy.

Q-switched laser operation provides high peak power, thereby facilitating discrimination against background radiation and receiver internal noise. Furthermore, the short pulse widths which are obtainable with Q-switched lasers permit accurate range determination by means of simple threshold detection of pulse echos, avoiding complex signal processing. Two limitations of pulsed laser ranging systems should be noted, however:

1) Pulsed rangefinders do not operate up to zero range; a minimum as well as a maximum range limit exists.

2) Tracking systems for tracking reflected energy must be be designed to track a pulsed target. Tracking accuracy may be limited by the pulse rate.

The type of laser selected for the ranging experiments will probably be either Nd:YAG or a ruby. Several factors must be considered in comparing the relative merits of these two devices:

Nd:YAG lasers are more efficient and are able to provide significantly higher pulse repetition rates than a ruby (approximately 50 pulses per second maximum versus 0.3 pulse per second). Further, they are superior for applications with less stringent maximum range requirements. Frequency doubling from 1.06 micron to 0.53 micron wavelength may be employed for the Nd:YAG laser to take advantage of improved detectors which are available at the shorter wavelength. However, development of better 1.06 micron detectors would tend to equalize the range capabilities of the two types of lasers. Frequency doubling requires technological advances in doubling efficiency and damage resistance in doubling crystals. Finally, atmospheric effects, which are important for earth-orbiting satellite altimeters, favor the 1.06 micron wavelength of the Nd:YAG laser.

Ruby lasers, on the other hand, offer somewhat higher output power capability with a wavelength (0.694 micron) which can be readily detected. As mentioned above, ruby lasers have a strong advantage from the standpoint of maximum range capability. For atmospheric penetration applications the ruby is significantly superior to the 0.53 micron wavelength which is characteristic of the doubled Nd:YAG. Carbon dioxide lasers at 10.6 microns offer the best wavelength for atmospheric propagation but are not well suited to pulse rangefinder applications.

Quadrant trackers have often been used to track pulsed laser sources since they lend themselves well to low duty cycle sources. Quadrant trackers can be implemented at any of the candidate wavelengths and with any of the candidate detector types. The tracker field-of-view should be made sufficiently small to minimize background radiation effects.

Figure 17-1 illustrates separate optics for transmitting and receiving, slaved to point in a common direction. Alternatively, it is possible to use combined optics. However, provisions for isolating the transmitter and receiver must be provided. This can be accomplished by means of an electro-optic transmit/receive switch, or by using different zones of the optics. As an example of the latter approach, energy could be received in an annular zone and transmitted through the central portion of the annulus.

Functional characteristics of a representative laser ranging experimental system are summarized in Table 17-1. The geometry of various candidate ranging experiments is shown in Figure 17-2.

## 17.5 EXPERIMENT OBSERVATION/MEASUREMENT PROGRAM

The general procedure for performing range measurements is outlined below:

1) Initial line-of-sight pointing angles are computed or measured by peripheral sensors.

2) The laser ranging optics are slewed to point in the desired direction.

3) Range gate control commands are provided to the range count electronics.

4) The pulse repetition rate is selected.

Table 17-1. Preliminary Ranging System Characteristics

| Component/Parameter | Performance Requirement |
|---|---|
| 1. Laser | |
| Type | Nd:YAG, optional frequency doubling |
| Operating Mode | Q-switched |
| Energy per Pulse | 500 mj at 1.06μ (or 100 mj at 0.53μ) |
| Pulsewidth | 10 ns |
| Wavelength | 1.06μ or 0.53μ |
| Pulse Repetition Rate | Single shot to 20 pps |
| Efficiency (incl. power supply) | 1% at 1.06μ, 0.2% at 0.53μ |
| 2. Collecting Optics | |
| Type | Cassegrain |
| Aperture Size | 1 to 2 ft diameter |
| Optical Quality | λ/4 or better |
| Coatings | Multilayer dielectric or metallic |
| 3. Transmitter Optics | |
| Aperture Size | 5 cm diameter |
| Beamwidth | Variable by means of external optics, 0.01° to 1° |
| 4. Detector and Preamplifier | |
| Type | Quadrant photomultiplier |
| Photocathode | S-1 for 1.06μ system; S-20 for 0.53μ system |
| Internal Gain | $10^6$ |
| Preamp Bandwidth | 40 MHz |
| Optical Filter | 50Å spectral width |
| Sensor Field of View | 1° cone |
| 5. Tracking System | |
| Type | Quadrant seeker, pulsed input ("bang-bang" control) |
| Tracking Loop Bandwidth | 1 to 20 Hz |
| Accuracy | 0.005° |
| Angular Range | TBD |
| 6. Ranging Electronics | |
| Clock Rate | 200 MHz |
| Clock Stability | $10^{-7}$ |
| Minimum Range | 1000 ft |
| Maximum Range | 300 NM |
| Range Gate Width | 2% of nominal round trip time |
| False Alarm Rate | $10^{-3}$ per range attempt |
| Ranging Accuracy | ±2 meters |

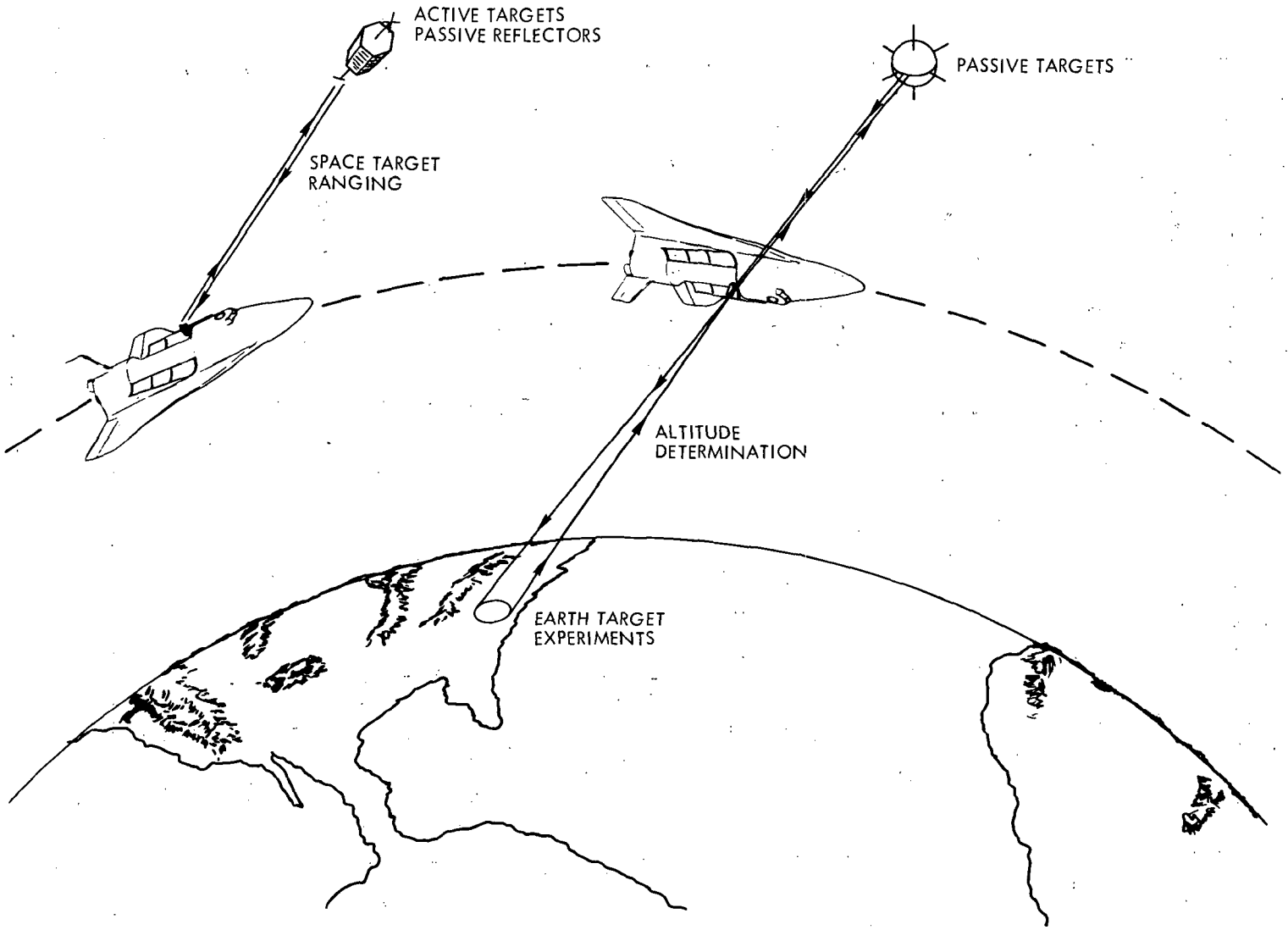


Figure 17-2. Laser Ranging Experiment Geometry

5) Rangefinder operation (pulsing) is initiated.

6) If the target is small, as in the case of satellite-to-satellite ranging, a search/acquisition sequence is begun.

7) When pulse return signals are sensed by the tracker, pointing control is handed over to the automatic tracking system.

A preliminary summary of measurement parameters is given in Table 17-2. Items for display to the crew are also indicated. The data will be recorded on magnetic tape and transmitted to the ground station at a convenient opportunity.

On-board computing equipment may be useful for signal processing, display controls, and to compute pointing angles for the ranging experiments.

Table 17-2. Typical Measurement Parameters

| Parameter | Measurement Accuracy | Dynamic Range | Max. Data Rate | Display |
|---|---|---|---|---|
| Range attempt number | N/A | N/A | 20 samples/sec | Yes |
| Range value | ±2 meters | 1000 ft to 300 nm | | Yes |
| Tracker error signals | 0.002° | 0.1 degree | | Yes |
| Spacecraft attitude | 0.05°/axis | ±180°/axis | | Yes |
| Gimbal angles | 0.002°/axis | ±60 deg/axis | | Yes |
| Timing reference | 0.1 sec | TBD | | No |
| Beamwidth | N/A | 3 discrete settings | | Yes |
| Transmitted pulse waveform | 2 ns resolution | N/A | 1/sec | Yes |
| Return pulse waveform | 2 ns resolution | N/A | 1/sec | Yes |
| Transmit pulse energy | ±10% | 2:1 | 20/sec | Yes |
| Receive pulse energy | ±10% | $10^5$ | 20/sec | Yes |

For altimetry experiments, a ground truth site may be desirable. This site would provide means for ranging to the satellite by a ground-based system and a retroreflector to facilitate ranging from the satellite to ground. Thus, simultaneous ranging in both directions could be performed to check the absolute accuracy of the on-board laser altimeter.

There are no unique host vehicle orbital constraints imposed by these experiments. However, viewing coverage of the laser ranging system should permit earth pointing, for altitude measurements or pointing latitude for ranging with other targets.

## 17.6 INTERFACE, SUPPORT, AND PERFORMANCE REQUIREMENTS

This experiment has no real time data transmission requirements. Data would be recorded and transmitted at low rates when link capacity allowed. Waveforms of laser pulse echos can be recorded by means of oscilloscope photographs, taken at times specified by the operator and returned for post-flight evaluation.

For preliminary planning purposes, it may be assumed that the transmitting and receiving optics (and associated gimbals) will be external to the laboratory module. These components must withstand the vacuum and thermal environment of the exterior spacecraft equipment platform (pallet). The remaining components will be located in the relatively benign environment of the pressurized laboratory interior. The physical separation of components will impose constraints on structural rigidity to maintain alignments.

Provision for inertial reference equipment would enhance the flexibility of laser ranging experiments and alleviate problems of target acquisition. An inertial reference accuracy of $\pm 1$ arc minute would satisfy most operational requirements.

Laser electro-magnetic interference (EMI) generation may be a problem for other laboratory instrumentation. EMI is generated by three major effects:

1) Flashlamp breakdown
2) Main discharge current
3) Modulator voltage switching.

These effects can be minimized by careful equipment design; however, components which are highly susceptible to interference should be physically separated and electrically isolated from the laser transmitter, to the maximum practical extent.

Eye damage safety hazards must be considered in experiment planning and resolved. Safety precautions for the laboratory crew, target satellite crews, and terrestrial beings (including aircraft passengers) must be evaluated.

## 17.7 POTENTIAL ROLE OF MAN

The potential role of man in this experiment includes the following functions:

1) Maintenance and reconfiguration work on the laser subsystem and associated electronics

2) Manual aiming at short ranges from target

3) Visual interpretation of oscilloscope displays

4) Observation of target and background via auxiliary sighting telescopes

5) Control of photographic recording equipment

6) Selection of power level and pulse repetition rate

7) Monitoring of target acquisition and lock-on.

It is anticipated that additional opportunities for utilizing man's judgement and adaptability will be identified during detailed development of the experiment.

## 17.8 EXPERIMENT EVOLUTION

The experiment evolution is expected to provide increasing range capability, ranging accuracy, and tracking accuracy. Initial experiments will emphasize use of cooperative targets (augmented passive reflector) with relatively close ranges. In later phases, ranging with uncooperative targets will be included.

Target acquisition in angle and in range will be part of all range performance evaluations. Succeeding phases of the experiment will demonstrate progressively sophisticated acquisition techniques. This may be accompanied by higher repetition rates of the laser transmitter.

Growth of ranging capability will be linked to technological advances in the design of laser transmitters and receivers. New detectors, especially at the 1.06 micron wavelength, are expected to be a major factor in range receiver evolution. Larger optics and higher power lasers are also expected to contribute to experiment growth.

## 17.9 SRT REQUIREMENTS

Supporting research and technology on high quantum efficiency detectors operating at 1.06 microns currently underway should be continued.

## 17.10 ACKNOWLEDGEMENTS

Portions of the following experiments were used in defining this candidate laser ranging experiment:

| Experiment | Principal Investigator and Association |
|---|---|
| 1. Precision Ranging | T. Kinsel, Bell Laboratories |
| 2. On-Board Laser Ranging | Blue Book, Vol. V, January 1971 |

# EXPERIMENT 18

# HORIZON ALTITUDE AND RADIANCE PROFILE MEASUREMENT

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APPENDIX A

# 18. HORIZON ALTITUDE AND RADIANCE PROFILE MEASUREMENTS

## 18.1 EXPERIMENT CLASSIFICATION

The experiment is classified as applied research. The data and understanding realized through the measurements described herein will facilitate development of improved (more accurate) versions of present vehicle orientation sensors and lead to new sensors employing different wavelength ranges. Extensive radiance data measured over large areas of the earth and through the seasons can also provide useful auxiliary information for laser communication and weather forecasting activities. Horizon sensor orbital navigation is a prime candidate for the space Shuttle. Present data is inadequate to permit statistical analysis in most parts of the spectral range of interest; the candidate experiment will collect data which, when processed with inertial attitude reference data and ground tracking ephemeris data, determine a statistical horizon altitude uncertainty model for guidance in the design of earth pointing sensors.

## 18.2 EXPERIMENT OBJECTIVES

The objective of the experiment is to measure the spectral radiance profile of the earth, particularly the horizons, over large areas of the earth and accounting for the diurnal and seasonal variations. The wavelength range has been tentatively chosen as 0.2 to 30 microns. Radiance data will be correlated with pointing direction data. Ideally the measurement should be repeated for a given area of the earth with sufficient frequency to permit evaluation of short term statistical variations as well as seasonal variations. Correlation of such data with surface meteorological measurements, where this is possible, is desirable. In summary, the detailed objectives are:

- Collect data simultaneously across four spectral bands, recording output level and wavelength
- Simultaneously record pointing angle data
- Convert output readings to radiance
- Process radiance data and position data to give points in a set of spectral radiance maps or other selected output formats to generate a statistical model of earth radiance

- Determine the uncertainty in the earth's horizon altitude which will permit evaluation of the ultimate accuracy of horizon sensor orbital navigation.

## 18.3 DISCIPLINE BACKGROUND AND STATE

Present spacecraft orientation systems use infrared horizon sensors for most earth-pointing applications. Even in the spectral region of operation of most of these sensors, the horizon profiles are not well known and design is based on limited empirical data coupled with theoretical radiation calculations. A knowledge of profile shapes, mean values and variances is of vital importance in estimating probable pointing errors. New or special sensors may employ techniques dependent on ultraviolet air glow or operate in different parts of the infrared or visible range. Therefore, profile data in other spectral regions is vital.

Other activities in which earth radiance data may be required are satellite laser communication systems and weather forecasting. In laser communication systems the nature of the radiance profile may affect the acquisition problem when the responding station is near the horizon. In the case of weather forecasting such data may provide better estimates of local and global heat balance.

The empirical data which has been obtained from satellites to date is quite limited, both in spectral range and quantity.

The state of the radiometric measurement art can support the experiment requirements without fundamental improvements in capability in the visible and infrared regions but measurement capability in the ultraviolet will require further development. Present pointing capabilities are adequate to acquire useful data. Data rates are such that state of the art capabilities are entirely adequate.

## 18.4 EXPERIMENT DESCRIPTION

A functional block diagram of the equipment interconnection concept is illustrated in Figure 18-1. The Comm/Nav Laboratory provides a stable platform and suitable control signals for the pointing and scanning requirements. Onboard computing capability will be used to program data acquisition sequences and possibly for data reduction.

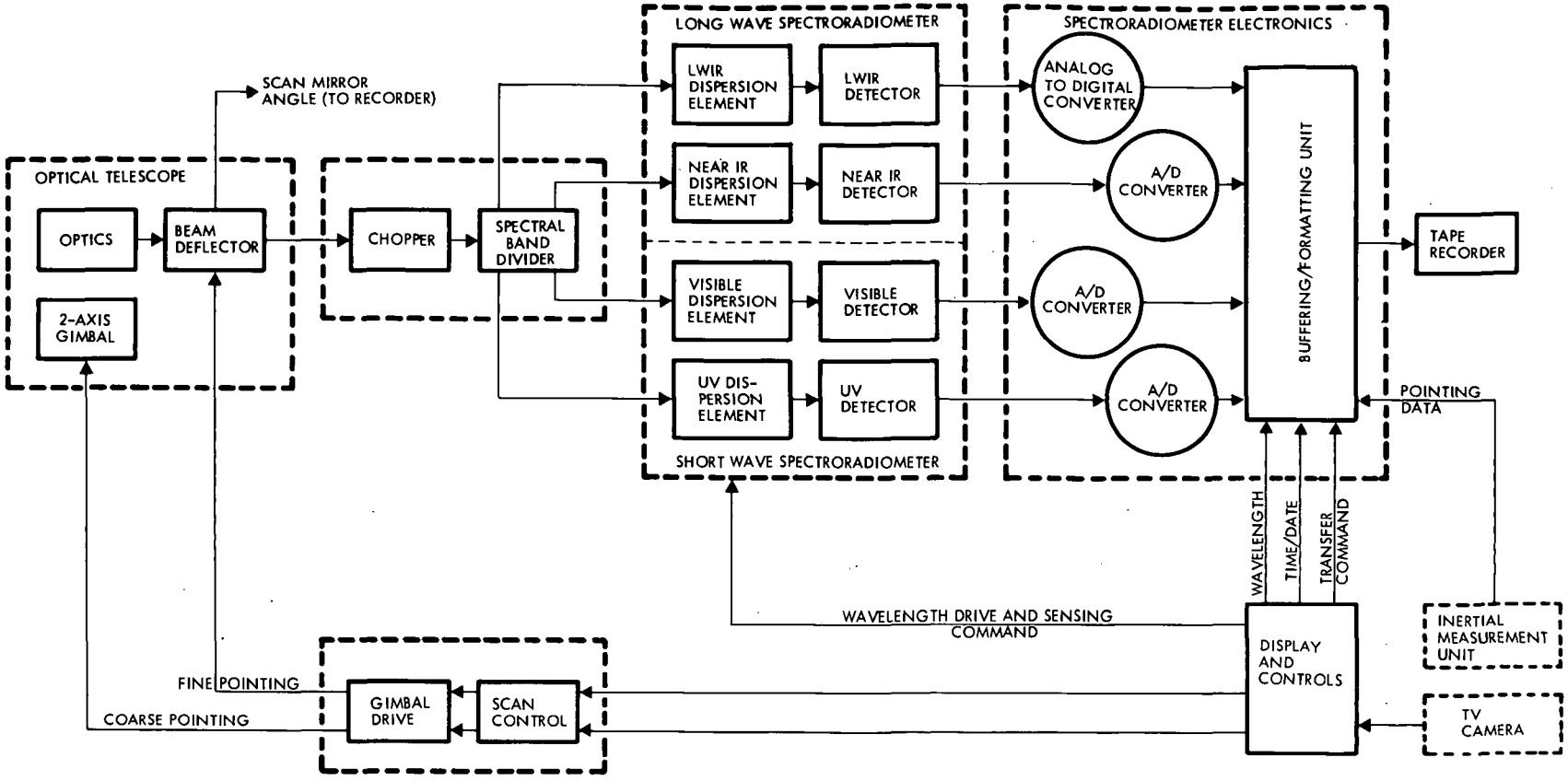


Figure 18-1. Functional Block Diagram – Radiance Profile Measurements

The implementation concept of the experiment involves step scanning an optical telescope across the earth's horizon, collecting radiation measurements over the spectral range of interest. At each positional step the instrument will scan across the wavelength band. Because of limitations in wavelength range of detecting and dispersing equipment, the spectrum is initially divided into four bands which are individually dispersed and detected. The analog output data from the detectors, the related wavelength identifier readouts and the pointing coordinates will be digitized and recorded on magnetic tape for later off-line processing. A timing signal to identify the orbital position at the time of the measurement for correlation with the radiation data is also recorded. Table 18-1 summarizes radiometer instrument requirements and specifications. The experiment geometry is illustrated schematically in Figure 18-2.

Table 18-1. Radiometer Requirements

| | |
|---|---|
| 1. Spectral Range | 0.20 to 30 microns |
| 2. Spectral Resolution | 3% of center wavelength |
| 3. Sensitivity (NEP vs $\lambda$) | To be determined (TBD) |
| 4. Spatial Resolution | ~0.2 degree |
| 5. FOV Orientation | Earth pointing |
| 6. Dynamic FOV (Gimbal Freedom) | $80^{\circ}$ half-angle cone |
| 7. Instantaneous FOV | ~$0.2^{\circ}$ x $0.2^{\circ}$ |
| 8. Scanning Capability: | |
| Scan Direction | Variable by command |
| Scan Amplitude | Variable by command |
| Scan Rate | TBD |
| 9. Pointing Measurement Accuracy | $0.02^{\circ}$ (goal) |
| 10. Collecting Optics: | |
| Type | Reflective Cassegrain |
| Aperture Size | ~5" diameter |
| Focal Length | ~25" |
| Efficiency | TBD for each spectral band |
| 11. Output Channels | 4 (one per spectral band) |
| 12. Data Rate | TBD |

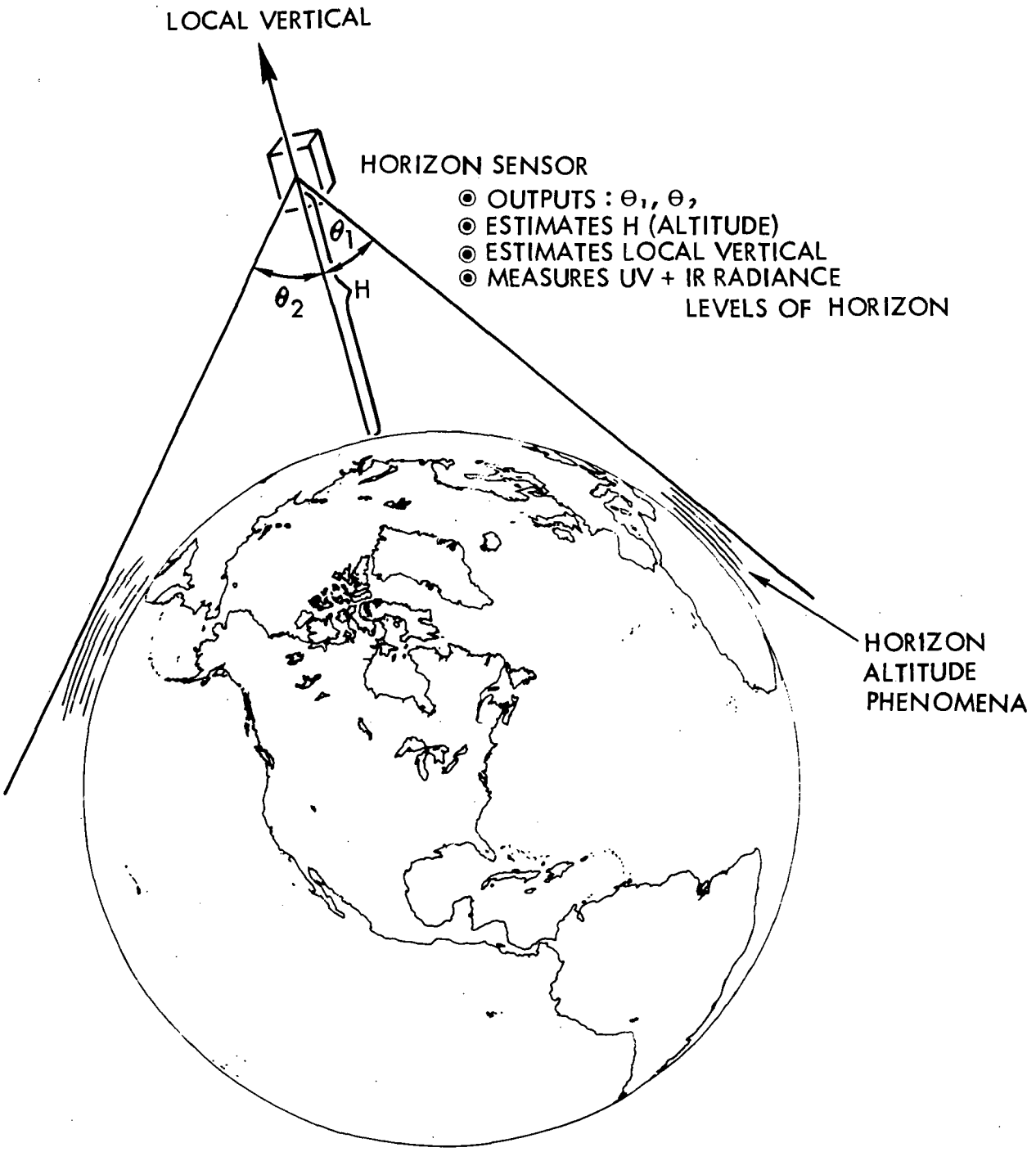


Figure 18-2. Horizon Altitude and Radiance Profile Measurements

Horizon radiance measurements are needed to develop accurate statistical models of the earth as seen from space. Existing data is not sufficient to permit statistical analysis and does not cover the entire spectral range of interest. The Comm/Nav Laboratory provides an excellent opportunity to collect measurements of the required type. Reasons for utilizing this mission to perform horizon measurements include:

1) Orbit. The low altitude orbit facilitates high resolution measurement of radiance profiles.

2) Platform. The Comm/Nav Laboratory will provide a stable platform convenient for earth pointing experiments.

3) On-board Computing. On-board computing capabilities should facilitate pointing control for radiance measurements.

4) Commonality. Equipment commonality between the radiometer experiment and other laboratory experiments appears to be considerable, as discussed in sections which follow.

5) Laboratory Crew. Participation of the crew ill permit the use of relatively sophisticated experimental procedures without complexity of equipment design.

## 18.5 EXPERIMENT OBSERVATION/MEASUREMENT PROGRAM

Table 18-2 summarizes the requirements of the principal measurement parameters.

Table 18-2. Measurement Requirements

| Parameter | No. of Channels | Bandwidth | Dynamic Range | Measurement Accuracy |
|---|---|---|---|---|
| Spacecraft Attitude Data | 3 | 1 Hz | ±180 deg. | 0.02 deg. (goal) |
| Timing Clock Signals | 1 | 10/sec | N.A. | 1 ms |
| Selected Spectral Band(s) | 4 | Discrete | 10-level | N.A. |
| Telescope Gimbal Angles | 2 | 10 Hz | ±80 deg. | 0.01 deg. |
| Scan Mirror Angle | 1 | 100 Hz | ±30 deg. | 0.01 deg. |
| Radiance Channel Outputs | 4 | 200 Hz | TBD | ±5% or ± TBD watt/ster $cm^2$, whichever is smaller |

The experiment observation/measurement program is characterized as follows:

- Measurements are automated following set-up and initiation by laboratory personnel.
- No truth sites are required. Calibration using on-board standards is the preferred mode.
- There are no special orbital requirements for the acquisition of useful data. A nearly circular polar orbit provides optimum coverage and facilitates data reduction.
- In order to generate a statistical model of earth radiance which is of broad utility, data should be acquired at many points in each hemisphere and at intervals which permit assessment of seasonal and diurnal variations as well as geographical variations.
- The data is recorded on magnetic tape for transmission to the ground station at a later time.
- Data processing including correlation of radiance data with related pointing data will be performed at a ground site.

On the basis of the specified spectral resolution and measurement accuracy it is estimated that approximately 80 data points of 7-bit accuracy will be associated with the radiometric output at each pointing angle, a 7-bit word may be associated with each of the wavelength readouts, and a 10-bit word with each of two pointing angles.

## 18.6 INTERFACE, SUPPORT AND PERFORMANCE REQUIREMENTS

### 18.6.1 Operational Requirements

Operations encompassing broad spatial and spectral coverage will generate substantial quantity of data over the period of even a 7-day Sortie mission. A detailed study of various tradeoffs pertaining to the implementation of effective data processing/interpretation is an essential prerequisite task.

### 18.6.2 Special Pointing Requirements

The experiment requires off-axis pointing to the accuracy specified in Table 18-1. Dwell times are a function of detailed design parameters and are not available at this time.

### 18.6.3 Mounting/Structural Requirements

The experiment is gimbal mounted on a stable platform.

### 18.6.4 Electric Power/Thermal Requirements

No unique electrical power or thermal requirements are foreseen at this time. Power conditioning within subsystem electronic packages is assumed. A thermal environment suitable for human occupancy without special garments is also assumed.

## 18.7 POTENTIAL ROLE OF MAN

Representative functions that will be performed by the astronaut-crew include:

1) Configure equipment for calibration or data collection operating modes

2) Equipment functional verification prior to initiation of experimental procedures

3) Diagnostic testing and component replacement in the event of a malfunction

4) Monitor visual displays and provide voice link liaison with earth-based principal investigator

5) Exercise control function in optimizing data collection and recording activities.

Skills required by personnel monitoring or controlling the experiment are principally those associated with interpreting displays and performing appropriate control functions. Familiarity with optical alignment methods is desirable.

## 18.8 EXPERIMENTAL EVOLUTION

The earliest phase of this experiment will focus attention on the spectral radiance data collection objectives. Multiple flights will be required to provide the required seasonal coverage. Concurrent with these investigative objectives, opportunity is afforded to evaluate the performance of new vehicle orientation sensors in a realistic environment.

As the program progresses, the emphasis is expected to shift from empirical data collection to sensor evaluation. Technique refinements as well as radical new concepts based on the increased knowledge of the

spectral radiance profile will be incorporated into prototype instruments requiring in situ performance evaluation. The Comm/Nav Laboratory provides an ideal test bid for these devices.

## 18.9 SRT REQUIREMENTS

1) No technological problems are foreseen in implementing the visible and infrared portions of the radiometer. The ultraviolet (UV) portion, however, requires further development since it is difficult to obtain suitable optics: UV radiation also tends to degrade many common materials, thereby requiring care in the selection of components. Calibration of the radiometer in the UV spectrum may also require special investigation.

2) Efficient band splitting elements for the specified bands are not currently available. While it is not anticipated that new technology will be required, a development program for the component will be necessary.

## 18.10 ACKNOWLEDGEMENTS

### 18.10.1 Related Experiments

The following related experiments were used in the derivation of the candidate experiment defined herein:

| Experiments | Principal Investigator and Association |
|---|---|
| 1. Horizon (UV and IR) Radiance Profile | Langley Space Flight Center/ North American Rockwell |
| 2. Horizon Altitude Uncertainty | J. Williams, TRW |

### 18.10.2 References

The following documents provide a summary of current information regarding horizon profile measurements:


1. John R. Thomes, Ennis E. Jones, Robert Carpenter and George Ohring, "The Analysis of Infrared Horizon Radiance Profile Variations over a Range of Meterological, Geographical, and Seasonal Conditions," NASA CR-725.

2. Raymond Kirk, Bruce F. Watson, Edward M. Brooks and Robert Carpenter, "Infrared Horizon Definition," NASA CR-722.

3. Roy E. Peterson, John Schuetz, William E. Shenk and Wen Lang, "Derivation of a Meteorological Body of Data Covering the Northern Hemisphere in Longitude Region Between 60°W and 160°W from March 1964 through February 1965," NASA CR-723.

4. Jerry C. Bates, David S. Hanson, Fred B. House, Robert Carpenter and John C. Gille, "The Synthesis of Infrared Horizon Radiance Profiles from Meteorological Data Inputs," NASA CR-724.

5. John R. Thomas, "Deviation and Statistical Comparison of Various Analytical Technique Which Define the Location of Reference Horizon in Earth's Horizon Radiance Profile," NASA CR-726.

6. Ruth I. Whitman, Thomas B. McKee, and Richard E. Davis, "Infrared Horizon Radiance Profiles for Winter Conditions from Project Scanner," NASA-TN-D-4955.

7. Thomas B. McKee, Ruth I. Whitman, Richard E. Davis, "Infrared Horizon Profiles for Summer Conditions from Project Scanner," NASA TN-D-4741.

8. Ruth I. Whitman, Thomas B. McKee and Richard E. Davis, "Infrared Profiles for Winter Conditions from Project Scanner," NASA-TN-D-4905.

9. Stillman C. Chase, "Dual Radiometer Assembly for Project Scanner," NASA CR-1086.

# APPENDIX A

## EQUIPMENT SELECTION RATIONALE

The basic equipment and support equipment for the horizon altitude and radiance profile experiment are indicated in Table A-1. The A/D and formating equipment shown in Figure 18-1 are included under the heading of receiver electronics, the gimbals are assumed to be part of the optical telescope package, and the attitude reference platform is designated by IMU. Preliminary estimates of size, weight and power for the basic equipment packages are also listed.

Table A-1. Equipment Matrix

| Basic Equipment | Size (in) | Weight (lb) | Power (watts) |
|---|---|---|---|
| Optical Telescope | 10 x 24 x 24 | 30 | 6 |
| Servo Electronics | 4 x 4 x 4 | 13 | 20 |
| Beam Deflector | Included in Telescope | | |
| Short Wave Spectroradiometer | 4 x 4 x 6 | 5 | 10 |
| Long Wave Spectroradiometer | 4 x 4 x 6 | 5 | 10 |
| Spectroradiometer Electronics | 4 x 4 x 4 | 5 | 15 |
| Chopper and Spectral Splitter | 4 x 4 x 4 | 6 | 2 |
| Support Equipment Required from Basic Laboratory | | | |
| Oscilloscope | | | |
| Digital Recorder | | | |
| Data Camera | | | |
| Inertial Measurement Unit (IMU) | | | |
| Television Camera and Display | | | |

The recommended experiment configuration specifies a five-inch diameter, f/5 reflective collecting optics with a spectral splitter which divides the band into four parts. Each of the four channels is supplied with a narrow band selection system including filters or gratings and with detectors appropriate to the spectral range of interest.

The size of the collection optics required to provide a discernible signal is determined by the irradiance of the source, the spectral bandwidth of the sample, the dwell time, the solid angle subtended by the

source at the detector, and by detector performance characteristics. When a physical configuration is chosen the only operational parameter which can be readily varied is the dwell time, and that is also limited because of orbital motion. The choice of a five-inch optical system is an estimate which falls between the extremes of aperture used in present horizon sensors (one inch) and radiometers (nine inches for Project Scanner) and assumes that with continuous pointing control the dwell time can be made sufficiently flexible to permit acquisition of the required data.

A chopper is used because this permits the use of AC coupling and phase sensitive detection methods to minimize noise and drift. The element which divides the spectrum into four broad bands has not yet been defined. For the present, a combination of suitable interference filters and reflective elements was assumed. A four-band system which covers the 0.5 to 1.5 micron range with a series of dichroic filters on prisms which act as reflective elements has been manufactured by Perkin-Elmer for a multispectral camera for TRW; a similar configuration is assumed for this experiment.

Depending upon the detailed experimental design, various devices may be chosen for obtaining a narrow-band spectral sample. In cases where samples at discrete wavelengths will be satisfactory, a series of interference filters on a wheel which can be stepped into position will be used. In cases where continuous coverage is required, a grating monochrometer is assumed. The McPherson Model 218 monochrometer, for example, can cover the range from 0.1040 microns to 16 microns with a series of 30 different snap-in gratings, with an effective f-number of 5.5. The coverage required may demand the inclusion of an automatic grating changing mechanism for such a monochrometer.

The detectors for the radiometer have not been chosen. From the operational point of view it is desirable to avoid cooled detectors when possible, but these requirements will be defined by detailed analysis of experimental requirements when they have been more fully determined. It is also true that detector technology is progressing rapidly, and in the time period of 1980 - 1990 photomultipliers with stable characteristics may be available for a much broader spectral range than at present,

giving enhanced performance characteristics from ultraviolet through near infrared. Improvements in uncooled detectors for the far infrared seem less probable, but cooled detectors may be easier to use. For these reasons, detector selection has been deferred.

The remaining equipment is defined at this time by functions only; these functions include data logging, pointing and control functions whose details will depend upon detailed experimental requirements. The electronic functions which must be performed include amplification, analog-to-digital conversion, temporary storage tape recording and command and control functions. The mechanics of coarse pointing is assumed to be done with a 2-axis gimbal mount, with possibly a beam deflector for fine pointing if analysis indicates this to be necessary.