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FOR
MILLIMETER COMMUNICATION
PROPAGATION PROGRAM
(1 FEB. 1965 - 1 MAY 1965)

Contract No. NAS 5 - 9523

Prepared by
RAYTHEON COMPANY
SPACE & INFORMATION SYSTEMS DIVISION
Sudbury, Massachusetts
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Second Quarterly Report

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SUMMARY

This document is the second quarterly report for the Millimeter Communication Propagation Program being performed under Contract No. NAS5-9523 by Raytheon's Space and Information Systems Division for Goddard Space Flight Center. This program is an eight-month study to design experiments which will determine the effects of the propagating medium on millimeter-wave (10 to 100 gigacycles) space-earth communications.

The first quarterly report described the effects of the propagation medium as it is known today and recommended a one-year space-earth experiment program using a satellite at an altitude of 6000 nautical miles. This report recommends a one-year space-earth experiment program beginning in 1968 and using a synchronous stationary satellite which will be utilized if the 6000 nmi satellite is not available. It also describes in greater detail the ground and satellite equipment to be used in the experiment, most of which is compatible with either the medium altitude or synchronous altitude Applications Technology Satellites.

The suggested program is divided into two principal phases. The initial phase consists of useful experiments which can be implemented with synchronous Applications Technology Satellites (ATS) which are launched during the year 1968 and whose payloads require no development of millimeter components and technology. This phase represents the next logical step in providing new information about millimeter-wave propagation by providing basic measurements on atmospheric absorption, flat frequency and selective frequency fading, channel time-bandwidth product, and aperture size limitations. The advanced phase consists of experiments which rely upon a one-year component development effort to be conducted mainly in the area of increased efficiency and increased power output of flight qualified

millimeter-wave receiver local oscillator and transmitter sources and in the area of increased sensitivity in flight qualified receivers. In addition to continuing with the basic measurements performed in the first phase, this advanced phase will also concentrate on direct performance evaluation of modulation systems in the presence of atmospheric effects.

The main area of uncertainty relating to the design of useful space-earth communication links is the influence of the condition of the propagation medium on millimeter-waves. Well controlled scientific experiments, using satellites, are needed for an increased understanding of the various physical phenomena which occur and to develop meaningful statistics. Some millimeter-wave propagation data has been obtained from spectroscopic laboratory measurements, link measurements along the surface of the earth, vertical measurements with balloons, and measurements using aircraft. This data verifies, to some extent, the propagation theory which has been developed; however, no amount of extrapolation and interpolation of the available measured data will satisfactorily assess the impact of the effects on future space-earth communication channels.

While reliable absorption data from an assumed water density profile along a communication path can be derived, there is not enough known about the actual profiles which exist during inclement weather. Furthermore, there is a lack of statistical knowledge on the effects of multipathing on flat frequency fading at low elevation angles, especially in bad weather. Finally, there is not enough known about the wideband selective frequency fading characteristics of the medium (that is, what is the maximum coherent bandwidth that the medium will support for different types of modulations?).

Well planned correlative measurements are essential to the propagation program in order to classify the particular weather model involved in each test and to explain why certain things are happening to the received test signals. In addition to basic meteorological surface measurements, sky temperature measurements with radiometers operating at millimeter frequencies are a necessity.

The existing ground facilities to be considered are those located at: the Aerospace Corporation, El Segundo, California; the University of Texas, Austin, Texas; Air Force Cambridge Research Laboratories (AFCRL), Lexington, Massachusetts; and Lincoln Laboratory, Lexington, Massachusetts. A facility at Goddard Space Flight Center (GSFC) is presently being established, which would be the chief participant.

Since the design of space-earth communication links represents the ultimate objective, consideration for the water vapor and oxygen absorption regions around 22 Gc and 60 Gc have been excluded. The design of these experiments is therefore centered around 16 Gc, 35 Gc and 94 Gc as being representative of the 10 Gc to 100 Gc band. From these three frequencies, the primary frequency for the initial phase was chosen to be 35 Gc because most of the existing millimeter ground facilities being considered are easiest to instrument with receivers at this frequency. A 35 Gc satellite transmitter down-link was chosen principally because: (1) instrumenting the ground facilities with transmitters is extremely difficult, since their normal mode of operation has been associated with radio astronomy; (2) simultaneous reception of the satellite transmission by several ground facilities can conserve payload prime power resources; (3) a closed loop between satellite and ground terminal is not needed for acquisition and tracking; and (4) experiments, using multiple-beam receiver configurations to investigate angular and spatial decorrelation, are possible.

For the initial experiments a secondary frequency was chosen to be 16 Gc. Although existing ground facilities are not as well equipped nor are the atmospheric effects as dramatic at this frequency, it nevertheless represents the frequency band in which the next generation of space-earth communication channels will fall. Down-links are recommended for the 16 Gc experiments for the same reasons given for the 35 Gc experiments. However, because of prime power limitations, it is unlikely that 35 Gc and 16 Gc can be transmitted simultaneously.

The third frequency was chosen to be 94 Gc because it represents the useful atmospheric window above the 60 Gc band. Unfortunately, a down-link could not be recommended for the initial experiments because of the risk in attempting to develop a spaceworthy transmitter of adequate power within a two year time period. The 94 Gc link was therefore conceived taking advantage of the 10 watt and possibly the 100 watt transmitters being developed for the Aerospace facility. The 94 Gc satellite receiver can be piggy-backed upon the 35 Gc transmitter at small additional expense in payload weight, volume and prime power. The signal processor in the satellite receiver would function basically like those in the ground facilities except that the processed signals would be transmitted to earth via telemetry before being recorded.

The basic measurement waveform to be transmitted is a simple one (that is, a carrier and one pair of variably spaced AM sidebands), yet it will provide ample information on the propagation channel. Although other more sophisticated waveforms are discussed, these are left for use in future experiments which are based on the results of the initial experiments. A choice between an unmodulated carrier and a modulated carrier will be provided, with the modulating frequency being variable in several discrete steps up to at least 50 megacycles.

Each ground facility receiver should be equipped with identical signal processors and analog tape recorders to minimize data processing expense. Each ground receiver would share its RF head with a radiometer in order to make sensitive sky temperature measurements using the same antenna beam. It should also be noted that the boresight installation for each of the participating ground facilities should be equipped, for calibration and checkout purposes, with a spacecraft simulator consisting of appropriate transmitters and/or receivers which function like those aboard the satellite.

The taped analog data from the satellite and from all the ground facilities would be converted to digital form and processed at a central data processing facility. Real-time analog presentations of the propagation data will be made

at each site for calibration, checkout, and operational monitoring; and to provide the cooperating agencies with immediate access to the raw data. The role of each agency participating in the collection of the propagation data would therefore be: (1) operate and maintain their own facilities; (2) supply the recorded data on a standard analog format to a central processing facility; (3) participate in data evaluation; and (4) participate in experiment schedule planning to insure proper interface between the master schedule for all of the experiments aboard the spacecraft and the schedule of activities at each of the ground facilities.

Existing computer facilities are equipped to handle the data processing required for this program. Special computer programs can be generated, the results of which will provide information such as atmospheric absorption, carrier amplitude distribution and fading spectrum, correlation of sideband amplitude and phase, dependence of fading on receiving antenna beamwidth, spatial decorrelation of carrier amplitude, and cumulative probability distributions of signal-to-noise ratio and bit error rates.

A typical work cycle which would be satisfactory for the propagation experiments would be to operate during a five day work week ten to twelve times spaced seasonally during the course of a year. Each work week would consist of four data collection sessions, each of four to six hours duration, and appropriately spaced so that each station collects data during dawn and dusk and near noon and midnight. These sessions will allow the ground facilities to perform pre-data-collection checkout and calibration. Also during this data collection session the spacecraft millimeter experiment packages would first be put into a programmed warm-up mode. This would then be followed by cycles of data collection and standby with a prime power drain which is totally compatible with the spacecraft. The minimum ON period during each cycle is considered to be 30 minutes. No planning would be made with regard to weather since it is unpredictable and since work schedules must be established well in advance. Enough samples would be taken which would result in a fair cross-section of the normal meteorological variables.

The behavior of the millimeter channel with varying elevation angle is important because the minimum useful horizon for a given radiated power, channel, bandwidth, and receiver sensitivity is a key factor in the design of useful space-earth communication links. For this reason medium altitude satellites, such as the ATS-MAGGE (Medium Altitude Gravity Gradient Experiment) which is to be inclined 28.5 degrees at an altitude of 6000 n miles, provides an excellent elevation angle propagation profile for each ground facility. However, since it appears that the MAGGE or a similar medium altitude satellite cannot be made available for the initial millimeter communication propagation experiments, this quarterly report has been devoted mainly to useful experiments that are designed for the ATS synchronous satellites and other stationary satellites of similar payload capacity and stabilization limits.

The design of propagation experiments using synchronous stationary satellites is approached from a point of view which is slightly different than that for medium altitude satellites. When using stationary satellites, considerable operational expense is saved by not having to generate precise and timely ephemeris data which is required for acquiring and tracking 6000 nautical mile satellites with narrow millimeter-wave beams. In addition, the existing millimeter-wave facilities will not require costly modifications to the present tracking equipment.

The longitudinal position of the stationary satellite is critical in that the right combination of elevation angles from two or more existing ground stations may not be possible. Under these circumstances, it is reasonable to consider addition of small transportable non-tracking antenna-receiver installations at locations, other than those of the existing facilities, to serve as gap fillers in the elevation angle profile. These auxiliary installations would not have sufficient antenna gain to investigate the coherence bandwidth of the medium but they could supply important signal fading statistics. The existing larger antenna facilities would take care of the necessary demonstrations of coherence bandwidth.

One of these auxilliary stations could be co-located with an existing station so that a comparison of signal fading could be made to determine multipathing effects as a function of beam size. If at least two of these auxilliary installations were to be made available, certain investigations would be performed using an interferometer configuration at a single site. Comparison of signal amplitudes at various baseline lengths would provide a useful estimate of maximum allowable antenna size and indicate the potential of spatial diversity techniques.

The experimental equipment design for the initial phase is conservative in order to guarantee complete ground instrumentation and a reliable payload by 1968. This design, which consists of two satellite packages, represents the minimum capability that can be realistically achieved within this time period and still justify the experiments in terms of the propagation data it will produce. Eighteen months are required to produce three flight models, ready for spacecraft integration, of a 200 milliwatt, 16 Gc transmitter package. It would weigh about ten pounds and consume fifty-five watts of prime power. Twenty-eight months are required to produce three flight models of a 200 milliwatt 35 Gc transmitter with a 94 Gc piggyback receiver. This package would weigh about seventeen pounds and consume less than ninety watts of prime power. Incidentally, a 35 Gc transmitter by itself would weigh ten pounds and consume eighty watts of prime power. Both packages would operate on 24 volts DC and each would easily fit within the nominal 18 by 11 by 8 inch experiment package.

The one year millimeter component development program will lead to the design of advanced wide-band communication experiments which are a natural follow-on to the initial experiments. The component technology resulting from these developments would allow the communication system engineer to design millimeter channels which begin to compete with the present-day lower frequency systems. The millimeter hardware resulting from this development should yield engineering models of 10 watt 16 Gc and 35 Gc satellite transmitters, each of which would weigh 15 pounds and

consume less than 70 watts. The development should also yield a lightweight 94 Gc receiver with a noise figure less than 15 db and consume less than 20 watts. This represents an improvement of 5 db in noise figure and 3:1 improvement in efficiency over designs using present-day components.

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I. INTRODUCTION

This document is the Second Quarterly Report for the Millimeter Communication Propagation Program being performed under Contract No. NAS5-9523 by Raytheon's Space and Information Systems Division for Goddard Space Flight Center. This program is an eight-month study to design experiments which will determine the effects of the propagating medium on millimeter-wave space-earth communications.

The First Quarterly Report, which was a report of work accomplished during the period 1 November, 1964, to 1 February, 1965, described the effects of the propagation medium as they are known today, and recommended a one-year space-earth experiment to be performed with a 6000 nautical mile medium altitude satellite beginning in 1968. This Second Quarterly Report recommends a one-year space-earth experiment using a synchronous stationary satellite which will be utilized if the 6000 nautical mile satellite is not available. It also describes in greater detail the ground and satellite equipment to be used in the experiment, most of which is compatible with either the medium altitude or synchronous altitude Applications Technology Satellites.

The objective of this experiment design study is to design a series of carefully chosen experiments, on a spacecraft availability and cost effectiveness basis, which will show how the objectives of the experiment can be met. Wherever design problems cannot be solved, courses of action in the form of component tests and breadboard design will be recommended. This objective includes development of experiment cost estimates and time schedules, including that for data processing and analysis. Results of the study include equipment design, source of key components, definition of basic measurements and description of how these basic measurements can be used to meet the objectives of the experiment.

The scope of work for this eight-month study program was defined in Exhibit "A" of NASA Contract NAS5-9523 and supplemented by Raytheon Proposal, "A Millimeter Communication Propagation Program," BR-3011, 3 June 1964. Another report which supplements Exhibit "A" of the NASA contract is "Program Definition Plan for Millimeter Communication Propagation Program," FR-4-498-B, January 29, 1965 (Revision of FR-4-498-A, dated December 15, 1965). The Program Definition Plan defines the objectives of the program, lists the tasks to be performed, and describes the various work activities under each task, including their time relationships with one another.

Much of the supporting technology, upon which the medium altitude and synchronous altitude experiments are based, was presented in the First Quarterly Report. It discussed the effects of water vapor and rain on absorption of millimeter waves, flat frequency and selective frequency fading, time-bandwidth product, and antenna aperture limitations. A brief introduction to the effects of rain on antennas and radomes was given, plus a review of the satellite tracking problems due to atmospheric refraction. A review of available literature on propagation through a plasma was also provided as a convenience to the reader interested in evaluating millimeter waves for communication with vehicles re-entering the Earth's atmosphere.

For the basic signal measurements required, various waveforms were discussed in the First Quarterly Report, both from an analytical point of view and from a hardware implementation point of view. It explained how the basic measurements can be used to determine performance of various modulation systems. Also discussed were the correlative meteorological and radiometric measurements required to establish the condition of the atmosphere at the time the propagation measurements are made.

The First Quarterly Report described the capabilities and limitations of experimental millimeter facilities which are candidates for ground terminals in the propagation experiments. Weather descriptions were given for the geographical areas in which the ground terminals are located. The

experiment equipments to be used were defined in terms of general block diagrams, and in weight, volume and power estimates.

Since the First Quarterly Report was published, two interim reports have been written: (1) "Experiments for Applications Technology Satellites" FR 65-151, 9 April 1965, and (2) "Ground Equipment for Millimeter Communication/Propagation Experiments," FR 65-172, 29 April 1965. The Second Quarterly Report includes the technical information contained in these two special reports and therefore supercedes them.

"Initial Millimeter Communication/Propagation Experiments with Synchronous Stationary Satellites" would have been an appropriate title for this Second Quarterly Report. It discusses ground facilities equipment configurations, synchronous satellite orbital analysis, signal processing, data processing and design of ground and spacecraft equipment. The equipment design is an expansion of the general design data given in the First Quarterly and can be applied to experiments using medium altitude satellites as well as synchronous altitude satellites. Most of the information on signal and data processing can be applied to both types of satellites. Section 7 is a presentation of schedule and budgetary costs for a total flight hardware and ground facility hardware program. The recommended experiment design can be conveniently broken down into segments and experimental links, certain combinations of which can be chosen for implementation depending on the limitation of financial resources, urgency for the scientific information, and payload allocations aboard available satellites.

Section 8 of this report outlines the work to be accomplished during the remainder of this study and Section 9 is a bibliography of reports referenced in other sections. A complete descriptive bibliography of reports related to millimeter-wave propagation and millimeter-wave component and system technology will be furnished in the Final Report.

Appendix I, "Component Development for Advanced Millimeter Communication Propagation Experiments," describes a one-year component

development program in the area of transmitting tube design, low noise receivers and solid-state local oscillator sources. Budgetary estimates and development schedules required to develop engineering models of spacecraft packages for advanced communication/propagation experiments are given. A comparison is made between the characteristics of spacecraft equipment using existing components and the characteristics of spacecraft equipment using components resulting from the development program. This development program represents the next logical step in the development of hardware technology needed to design future satellite communication systems.

Appendix II, "Millimeter-Wave Satellite Communications Systems," is a work statement which asks for 10 Gc to 40 Gc millimeter-wave system configurations which could be developed to meet the communication needs of the 1968 to 1975 time period. Appendix II also describes a typical application of millimeter-waves to satellite communication systems. U.S.-Europe FM television links at 4-6 Gc, 15-16 Gc and 33-35 Gc are compared to show feasibility of future millimeter communication systems and to illustrate those areas where subsystem and component development is most necessary. Equipment configurations for applications such as U.S. to Europe TV should be developed in order to identify specific requirements.

Appendix III, "Millimeter-Wave Space Communication Systems," is another work statement which asks for specific identification of useful applications in 10 Gc to 300 Gc millimeter-wave space communications for lunar missions, interplanetary probes and earth orbiting missions. As in the satellite communication system area, system configurations should be developed in order to identify applications and establish long range R & D goals.

Appendix IV, "Design of Millimeter-Wave Communication/Propagation Experiments for Manned Earth-Orbiting Missions," is a work statement which asks questions dealing with the usefulness of man in space in performing space-earth and space-space millimeter-wave communication/propagation experiments.

Appendix V, "Spacecraft Millimeter Radiometers for Vertical Sensing, Cloud Mapping and Ground Mapping," discusses possible applications of satellite millimeter-wave equipment to areas other than communications.

2. FORMULATION OF EXPERIMENTS

The general ground rules that were observed when formulating the experimental approach contained in this report are:

1. Design reliable space-qualified payload equipment with no requirements for major component development.
2. Assume that only synchronous altitude stationary satellites will be available as the space terminals for the initial experimental links. The capabilities of these satellites are assumed to be equivalent to the Synchronous Altitude Spin Stabilized Experiment (SASSE) and the Synchronous Altitude Gravity Gradient Experiment (SAGGE) Applications Technology Satellites.
3. Use measurement frequencies near 16 Gc, 35 Gc and 94 Gc.
4. Design the spacecraft electronics in modular form with each unit not to exceed 25 pounds in weight and 80 watts in peak power consumption.
5. Make maximum use of existing or planned millimeter wave experimental ground facilities located at Aerospace Corporation, University of Texas, Lincoln Laboratory, Air Force Cambridge Research Labs and GSFC.

This section of the report briefly describes the available millimeter facilities within the Continental United States plus a new facility being established at Goddard Space Flight Center. This section also discusses the feasibility of using stationary synchronous altitude satellites with a specific emphasis upon the position of the satellites relative to the ground terminals. The general results of orbital analysis for medium altitude satellites from the First Quarterly Report are included. Inclined synchronous satellites are also discussed in the event these types of spacecraft become available. A discussion on operation analysis associated with a one-year propagation data

collection period is given. It describes possible data collection schedules and the limitations imposed by availability of prime power aboard the satellite. Test waveforms to be used were described in detail in the First Quarterly; however, a brief review is given in this section.

Finally, up-links are compared with down-links, that is, the use of satellite receivers versus the use of satellite transmitters with mention of the equipment design problems and equipment operational problems involved. The use of down-links is most desirable from an overall viewpoint except in the area of transmitting tube efficiency and reliability.

2.1 Ground Facilities Configurations

GSFC is developing a millimeter-wave experimental facility for performing space-earth communication/propagation experiments. This facility will serve as the major participant in this data collection program. Other facilities which are considered are those which presently exist at Aerospace Corporation, The University of Texas, Air Force Cambridge Research Laboratories (AFCRL), and Lincoln Laboratory.

An evaluation of the above U.S. facilities was given in the First Quarterly Report. These facilities and their geographic locations are listed in Table 2-I.

TABLE 2-I
GROUND FACILITY GEOGRAPHICAL CHARACTERISTICS

Facility	Area	Latitude °N	Longitude °W	Altitude - Ft.
Aerospace	El Segundo, Calif.	33.9	118.4	157
Univ. of Texas	Austin, Texas	30.5	97.7	600
GSFC	Greenbelt, Md.	39.7	76.8	220
AFCRL	Waltham, Mass.	42.4	71.2	478
Lincoln	Lexington, Mass.	42.5	71.3	250
Haystack	Tyngsboro, Mass.	42.7	71.4	-

The antenna-pedestal systems for each of the above existing facilities, which are adequately equipped to operate with synchronous satellites, are described in Table 2-II. Figure 2-1 has been prepared to show antenna gain versus wavelength for each existing facility.

TABLE 2-II
GROUND FACILITY ANTENNA SYSTEM
CHARACTERISTICS

Facility	Type of Mount	Type of Antenna	Antenna Diameter
Aerospace	Equatorial	Cassegrain	15
Univ. of Texas	Equatorial	Feed at Focus	16
GSFC	Azimuth-Elevation	Cassegrain	15
AFCRL	Azimuth-Elevation	Cassegrain	29
Lincoln	Azimuth-Elevation	Degenerate Cassegrain	28
Haystack	Azimuth-Elevation	Cassegrain	120

It should be noted that these facilities represent an excellent cross-section of engineering technology in the assembly of each of these facilities. There are four basically different and unique approaches to the fabrication of high-precision parabolic reflectors. This cross-section of technology is shown most drastically in the invar honeycomb construction technique utilized by the University of Texas in direct contrast with the machined aluminum panel technique utilized by Aerospace Corporation. Further comparison can be drawn with the Lincoln Laboratory spuncast technique and finally a fourth fabrication technique utilizing a machined foamed plastic surface with two radii pendulous routing. All of these techniques have been utilized successfully for the fabrication of high precision parabolic reflectors. In addition, several mount configurations and several servo drive configurations have been implemented and tested, namely, the differential torque drive technique utilized by the University of Texas, the hydraulic servo constant displacement type of drive implemented on the Aerospace facility, and the more conventional torque drive utilized by the AFCRL facilities.

Each of these facilities has been evaluated as a site and performance measurements have been conducted on the gain, efficiency and antenna

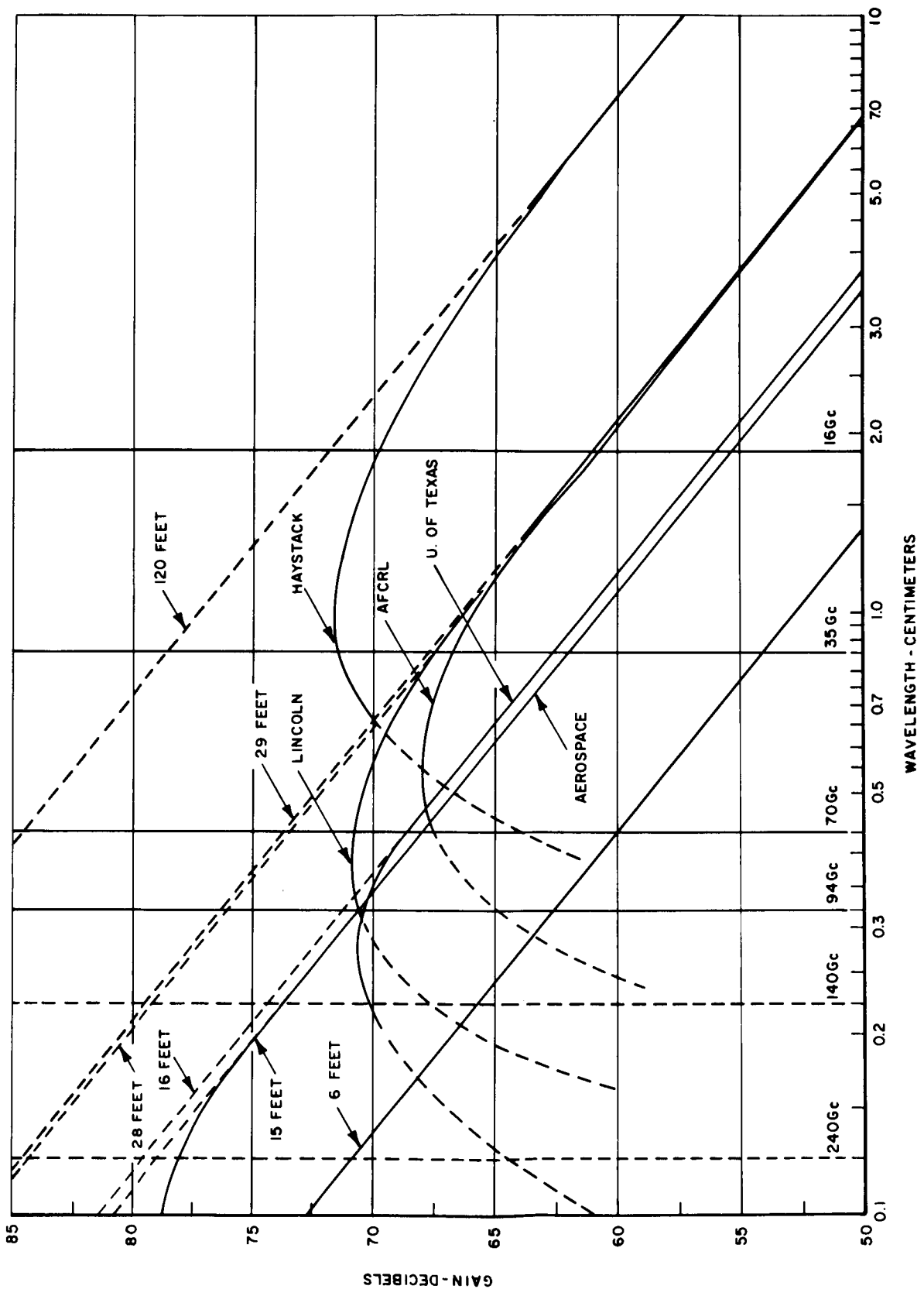


Figure 2-1. Antenna Gain at Ground Station Facilities

patterns, all in the millimeter regions. In addition, pointing accuracies and dynamic tracking accuracies have been checked primarily through the utilization of celestial body radio astronomy. It is felt that the designers of future millimeter facilities will have at their disposal many design curves and techniques which have been implemented and tested and, therefore, may be directly compared on a cost effectiveness basis. This information should permit the communication system designer to perform an excellent trade-off analysis in order to choose the most efficient design and fabrication techniques for utilization in an operational communications network.

The remainder of this section discusses the general ground equipment configuration and the design details of the actual hardware are given in Section 3 and 4.

2.1.1 GSFC Facility

The general equipment configuration for the GSFC facility is shown in Figure 2-2. An antenna system, consisting of a 15-foot parabolic reflector mounted on an elevation over azimuth pedestal with its 32-foot tower, is one of the major items in the GSFC facility. A receiver system, shown in Figure 2-3, is required for this antenna system in order to provide a ground terminal for experimental space-earth propagation links. It is intended that the antenna system will be equipped to track satellites via programmed ephemeris data utilizing a single lobe receiver pattern and by later modifications, it will be equipped to automatically track satellites by means of multiple channel millimeter-wave receivers. The final receiver system should consist of: interchangeable RF heads for specific frequencies within the 8 Gc to 94 Gc frequency range (mounted in a compartment behind the reflector); communication, radiometric and tracking IF receivers; signal processors; and analog data recorders.

The GSFC complex should also have a system of millimeter-wave signal sources to be installed at a remote location which operates with the receiver system in the main facility. The sources are required for antenna boresighting and beam pattern measurement. These signal sources with

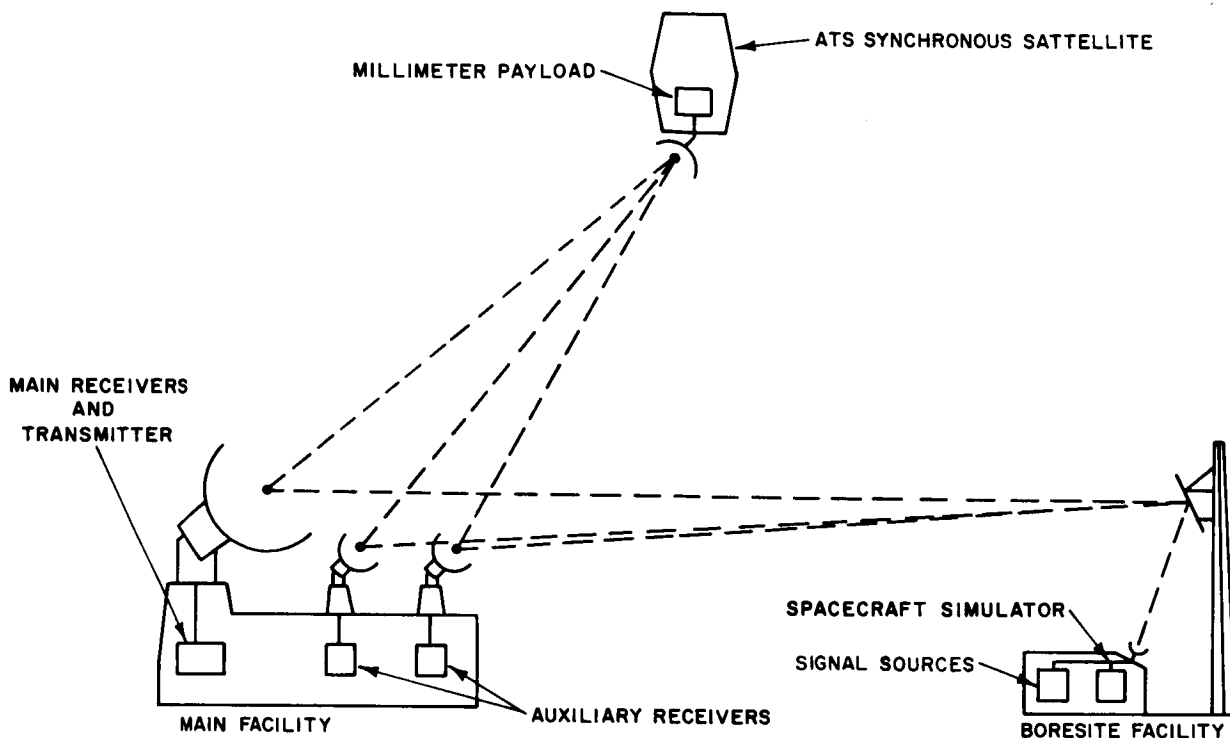
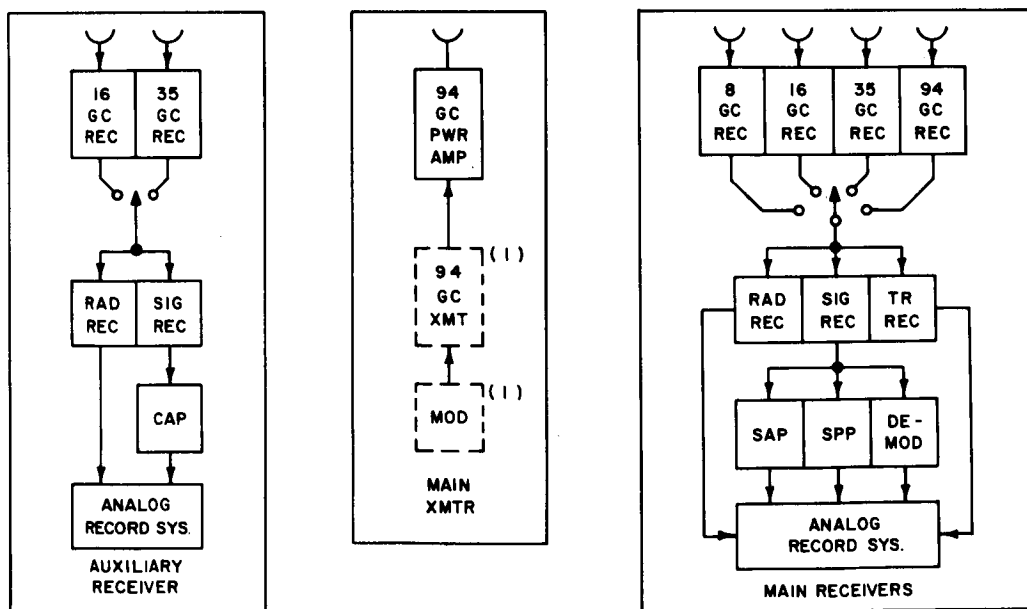


Figure 2-2. Equipment Layout for ATS Synchronous Satellite and GSFC Millimeter Experimental Ground Facility



(1) BORROWED FROM SIGNAL SOURCES IN BORESITE FACILITY
 CAP -- CARRIER AMPLITUDE PROCESSOR
 SAP -- SIGNAL AMPLITUDE PROCESSOR
 SPP -- SIGNAL PHASE PROCESSOR

Figure 2-3. Component Layout for GSFC Main Facility

appropriate modulators will also establish ground-to-ground links, which will be useful in developing millimeter system technology to be applied to the instrumentation of space-earth experimental communication links. The signal sources should be designed and packaged such that the 94 Gc klystron and associated components can be used to drive a 94 Gc power amplifier employed in the antenna compartment at the main facility.

Also at this remote boresight facility, a spacecraft simulator is required which operates with the main facility and performs the same functions intended for the spacecraft equipment. For the GSFC facility this simulator can be the engineering model of the flight hardware which is recommended for the initial experiments. The flight hardware is discussed in Sections 2.2 and 2.4. The signal sources and the spacecraft simulator are illustrated in Figure 2-4.

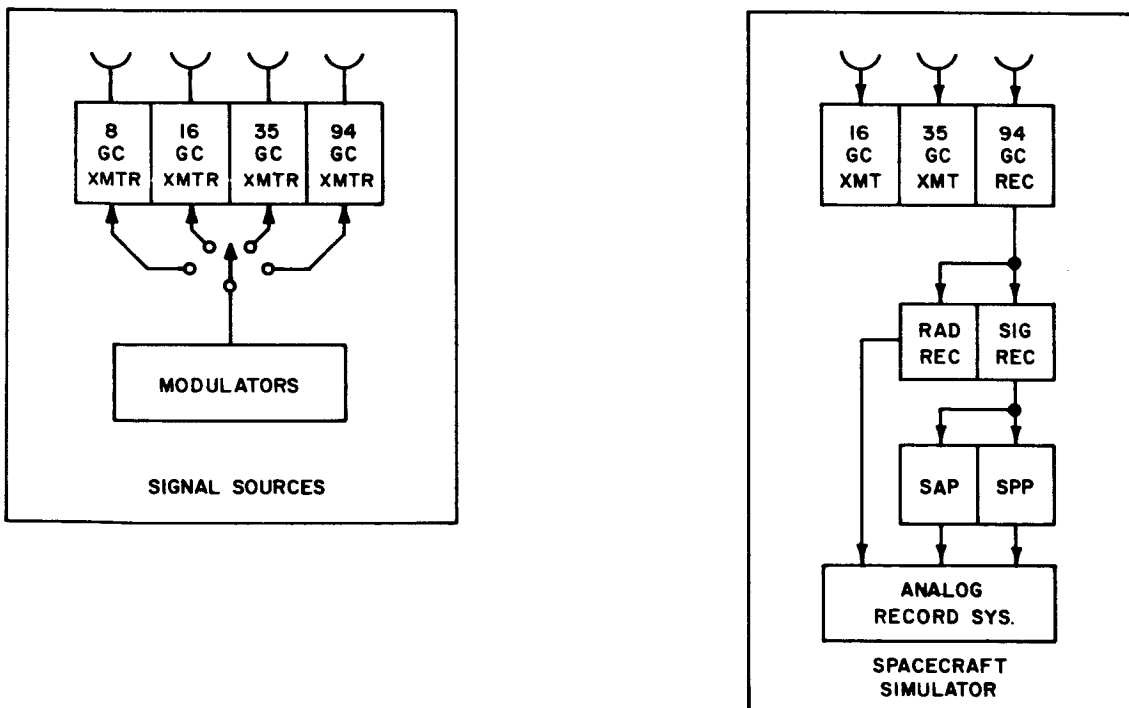


Figure 2-4. Equipment Layout for GSFC Boresight Facility

Finally, auxillary receivers are suggested which consist of subsystems that are identical to some of the main receiver subsystems and are incorporated into smaller antenna systems. These receivers are shown in Figure 2-3 and the usefulness of these auxillary receivers is illustrated in Figure 2-5, where three possible modes of operation at the GSFC facility is presented. These three modes of operation can exist simultaneously and the data results to be obtained from these modes of operation are tabulated in Table 2-III.

With the use of mirrors, Mode 3 could be expanded as shown in Figure 2-6. The reason for the mirrors is to allow the receivers to share a common millimeter-wave local oscillator so that relative phase measurements can be made. The data results obtained from this configuration are also given in Table 2-III. However, this configuration is not recommended as an initial experiment since its useful design depends upon results from Mode 3.

The auxillary receivers can also be moved to some other location such as Rosman, North Carolina, or WSMR, New Mexico, to assist in establishing an elevation profile of carrier fading statistics.

2.1.2 Other Facilities

The other facilities being considered should be equipped with new interchangeable RF heads which are custom-packaged to interface with the existing antenna system and specifically designed to operate with receiver IF units identical to those used in the GSFC facility. The packaging of the IF units, the signal processor and the analog recording system can be identical for all of the installations. A spacecraft simulator, whose subsystem electrical design is identical to the engineering model of the flight hardware, should be installed at each facility's boresight location. The system make-up of the simulators will vary depending upon the frequencies of operation at each facility.

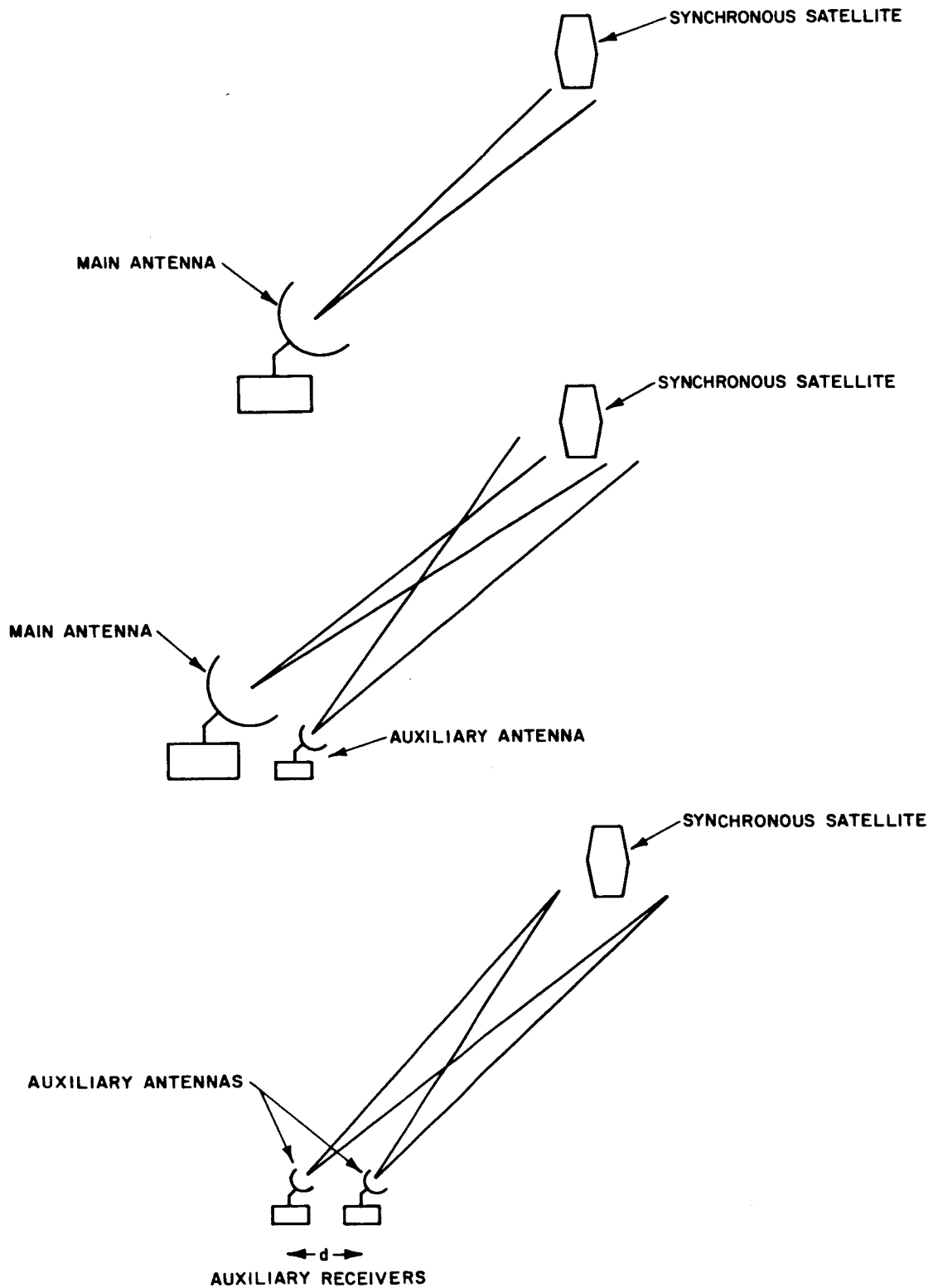


Figure 2-5. Modes of Operation at GSFC with a Synchronous Satellite

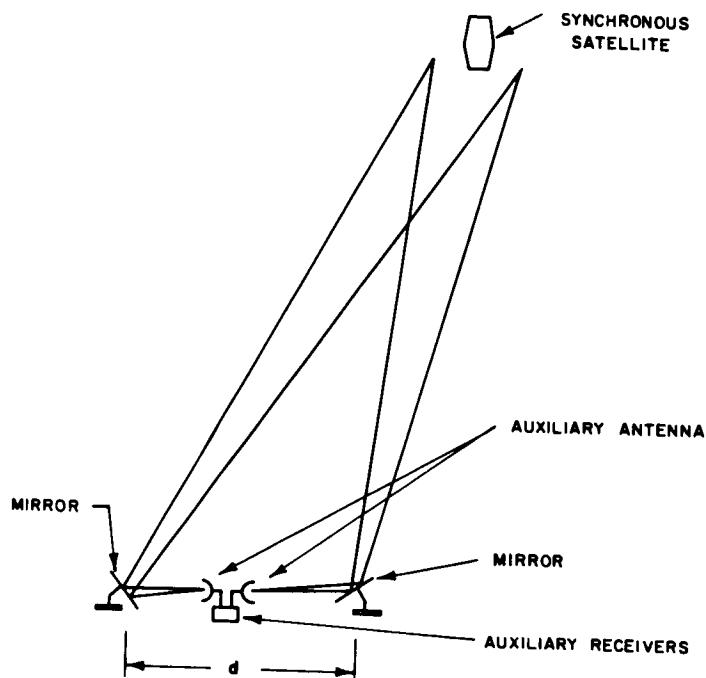


Figure 2-6. Possible Future Mode of Operation with Two Auxillary Receivers

TABLE 2-III
PROPAGATION DATA RESULTS FOR DIFFERENT
MODES OF OPERATION

Mode	Equipment	Data Results
1	Main Antenna	Atmospheric absorption, carrier amplitude fading, correlation of carrier and sideband fading and relative phase of sidebands as a function of AM modulation frequency by receiving signals at 16 Gc and 35 Gc and transmitting signals at 94 Gc. Wavefront tilt by observing tracking receiver error signals.
2	Main Antenna & Auxillary Antenna	Correlation of carrier fading for two different beamwidths by receiving signals at 16 Gc and 35 Gc.
3	Two Auxillary Antennas	Correlation of carrier fading as a function of distance, d , by receiving signals at 16 Gc and 35 Gc in two auxiliary receivers.
Future	Two Auxiliary Antennas and Two Mirrors	Correlation of carrier fading and reflective phase of received carriers as a function of distance, d .

2.1.3 Ground Equipment List

A list of ground equipment is given in Table 2-IV. In order to insure a well-coordinated propagation data collection program, it is considered worthwhile that the components denoted by an asterisk be purchased by NASA funds if necessary. These components should be built to GSFC specifications since commonality of equipment increases the value of experimental results and reduces data processing expenses.

This list of ground equipment represents an ambitious hardware program, especially when it is coupled with a flight hardware program. It is therefore necessary to talk about alternate configurations. These configurations which are mentioned below are later discussed in detail in Section 2.6 "Program Schedules and Cost Estimates." With reference to Table 2-IV, they are:

- Configuration 1 - All equipment listed for GSFC
- Configuration 2 - All equipment listed for GSFC except the
Signal Sources and the 8 Gc and 94 Gc RF heads
in the main facility receiver.
- Configuration 3 - All equipment of Configuration 2, plus the
asterisked items for Aerospace, U. of Texas,
AFCRL and Haystack.
- Configuration 4 - All asterisked items in Table 2-IV.

There are some important observations to be made on the ground equipment which is needed for the data collection program. They are:

1. The radiometric IF receivers which share the same RF head as the Signal IF receivers are essential to the program as the chief source of correlative data.
2. A spacecraft simulator is essential at the boresight installation for each participating facility in order to properly calibrate and check-out the data collection system before each data collection test.

3. The auxiliary receivers are considered good insurance for a successful propagation experiment associated with a synchronous satellite. The additional knowledge gained for the fractional increase in the total program cost is considered to be an excellent bargain.

TABLE 2-IV
GROUND EQUIPMENT LIST
FOR
MILLIMETER COMMUNICATION/PROPAGATION PROGRAM

Subsystem & Components	GSFC	Aero-Space	Univ. of Texas	(1) AFCRL	(1) Lincoln	Haystack	DRTE
<u>SIGNAL SOURCES</u>							
8 GC trans-mitter	1*						
16 GC "	1*						
35 GC "	1*						
94 GC "	1*						
Modulators	1*						
Antennas	1*						
<u>MAIN FACILITY</u>							
Antenna	1*	1	1	1	1	1	1
8 GC rf Receiver	1*						
16 GC rf "	1*		1*	1*	1	1*	1
35 GC rf "	1*		1*	1*	1	1	
94 GC rf "	1*						
94 GC Power Amplifier	1*	1					
Radiometric IF Receiver	1*		1*	1*	1	1*	1
Signal IF Receiver	1*		1*	1*	1	1*	1
Tracking IF Receiver	1*		1*	1*	1	1*	1
Signal Processor	1*		1*	1*	1	1*	1
Demodulators	1*						
Analog Recording System	1*		1*	1*	1	1*	1

(1) AFCRL and Lincoln facilities are interchangeable. It does not appear essential to have both facilities participating.

* Should be built to GSFC Specifications.

TABLE 2-IV (concluded)
GROUND EQUIPMENT LIST
FOR

MILLIMETER COMMUNICATION/PROPAGATION PROGRAM

Subsystem & Components	(2) GSFC	Aero- Space	Univ. of Texas	(1) AFCRL	(1) Lincoln	Haystack	DRTE
SPACECRAFT SIMULATOR							
Antenna	1*	1	1	1	1	1	1
16 GC Trans- mitter	1*	1*	1*	1*	1	1*	1
35 GC "	1*	1*	1*	1*	1	1	
94 GC Receiv- er	1*	1*					
Radiometric IF Receiver	1*	1*					
Signal IF Receiver	1*	1*					
Signal Pro- cessor	1*	1*					
Analog Record- ing System	1*	1*					
AUXILIARY RECEIVER							
Antenna	2*	1					
16 GC Receiv- er	2*	1*					
35 GC "	2*	1*					
Radiometric IF Receiver	2*	1*					
Signal IF Receiver	2*	1*					
Carrier Ampli- tude Processor	2*	1*					
Analog Receiv- ing System	2*	1*					

(2) Spacecraft Simulator at GSFC is actually the Engineering Model of the flight hardware.

2.2 Orbital Analysis

The three ATS spacecraft considered for the initial experiments are: A Stationary Synchronous Altitude, Spin Stabilized Experiment (SASSE) Satellite and two Stationary Synchronous Altitude, Gravity Gradient Experiment (SAGGE) Satellites. The orbital analysis necessary for the design of the stationary satellite experiments is given in this section. The results of the orbital analysis on the medium altitude (6000 nmi) satellites is summarized and some information is given on inclined synchronous satellites to show their potential as a millimeter transmitter platform.

2.2.1 Synchronous Stationary Satellites

Two basic work charts, Figure 2-7 and Figure 2-8, were used to derive the elevation angle versus synchronous satellite longitude. Figure 2-7 gives ground range on the surface of the earth in degrees of arc versus ground station latitude for various values of longitude difference between the ground station and the sub-orbital point of the stationary satellite. Figure 2-8 provides ground range versus ground station elevation angle for a synchronous altitude satellite. From these two charts, Figure 2-9 was derived, which gives elevation angle versus differential longitude for various ground latitudes. Elevation angle versus longitude for any given ground station which is located at latitudes between 30° and 50° can be quickly sketched from Figure 2-9. Figures 2-10 through 2-12 were derived in this manner.

Figure 2-10 covers the ATS ground station at: Rosman, North Carolina; Mojave, California and Canberra, Australia. As a point of interest, London and Berlin are also shown. It is important to note that the most likely satellite positions were assumed to be near those given in Table 2-V. These positions were chosen because they optimize the elevation angles for the links or combinations of links mentioned in Table 2-V.

Figures 2-11 and 2-12 give elevation data for the millimeter ground facilities located at Aerospace Corporation, University of Texas, Goddard Space Flight Center (GSFC), Defense Research Telecommunications

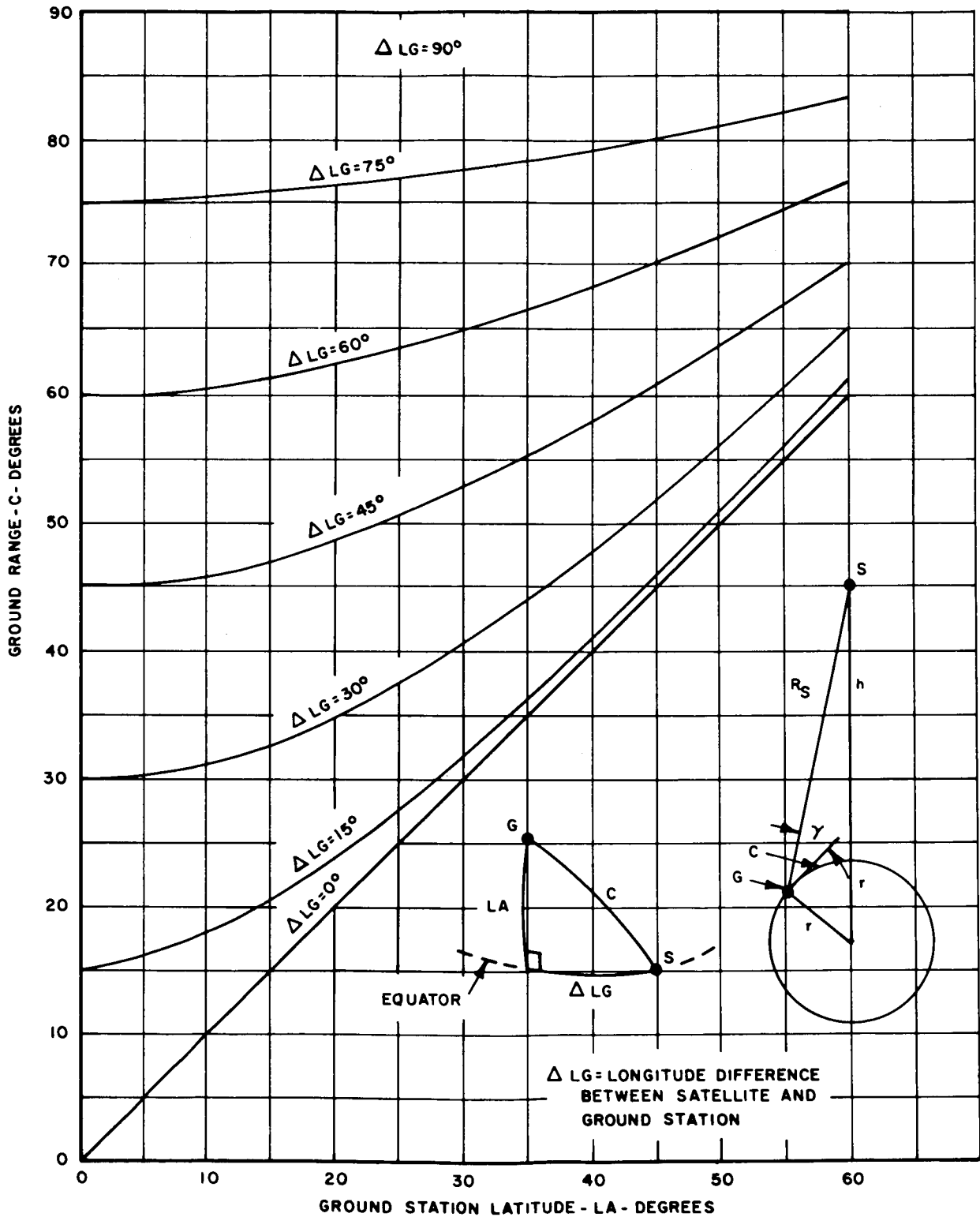


Figure 2-7. Ground Range vs Ground Station Latitude for a Synchronous Satellite

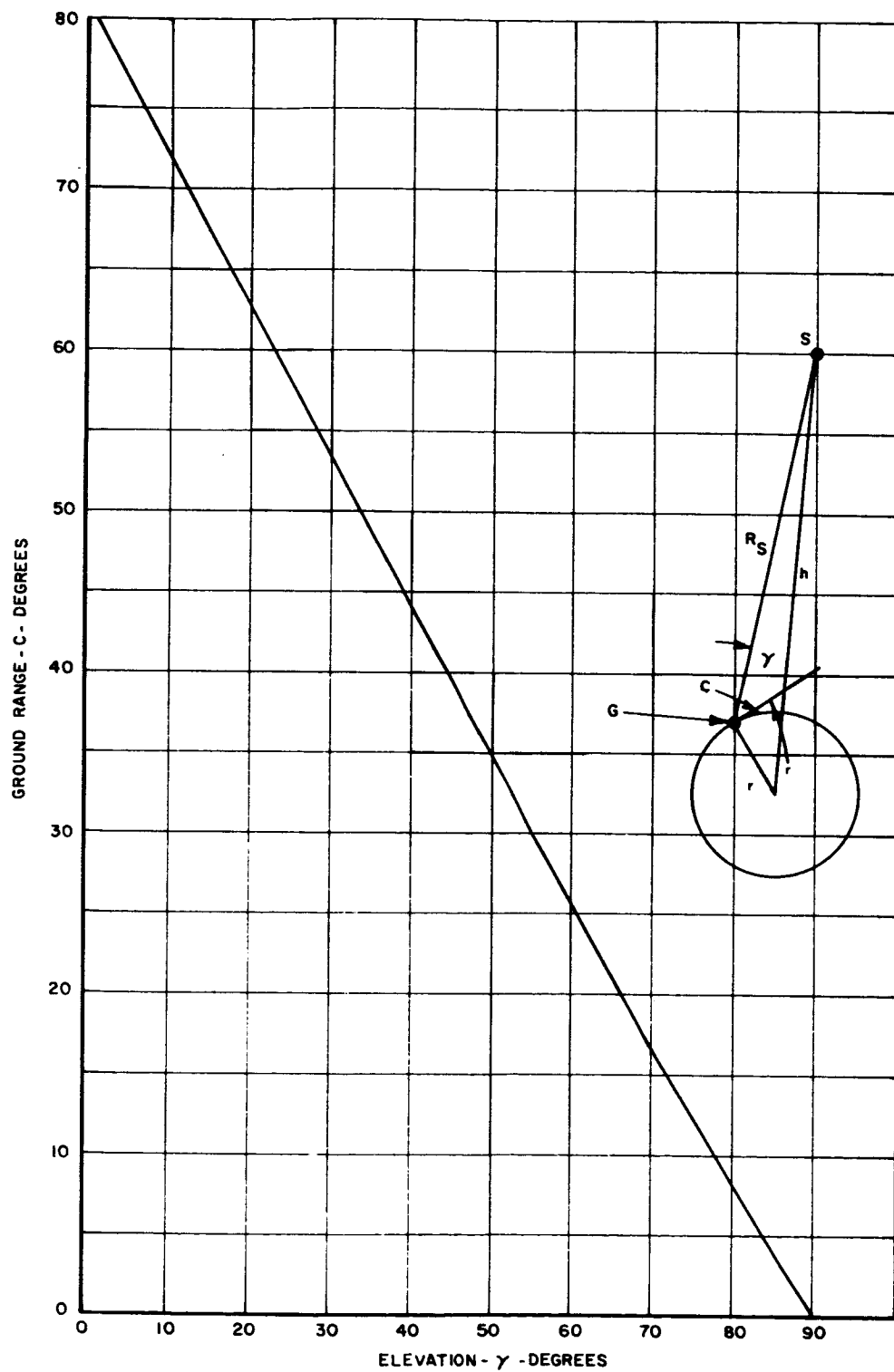


Figure 2-8. Ground Range vs Elevation Angle for a Synchronous Altitude Satellite

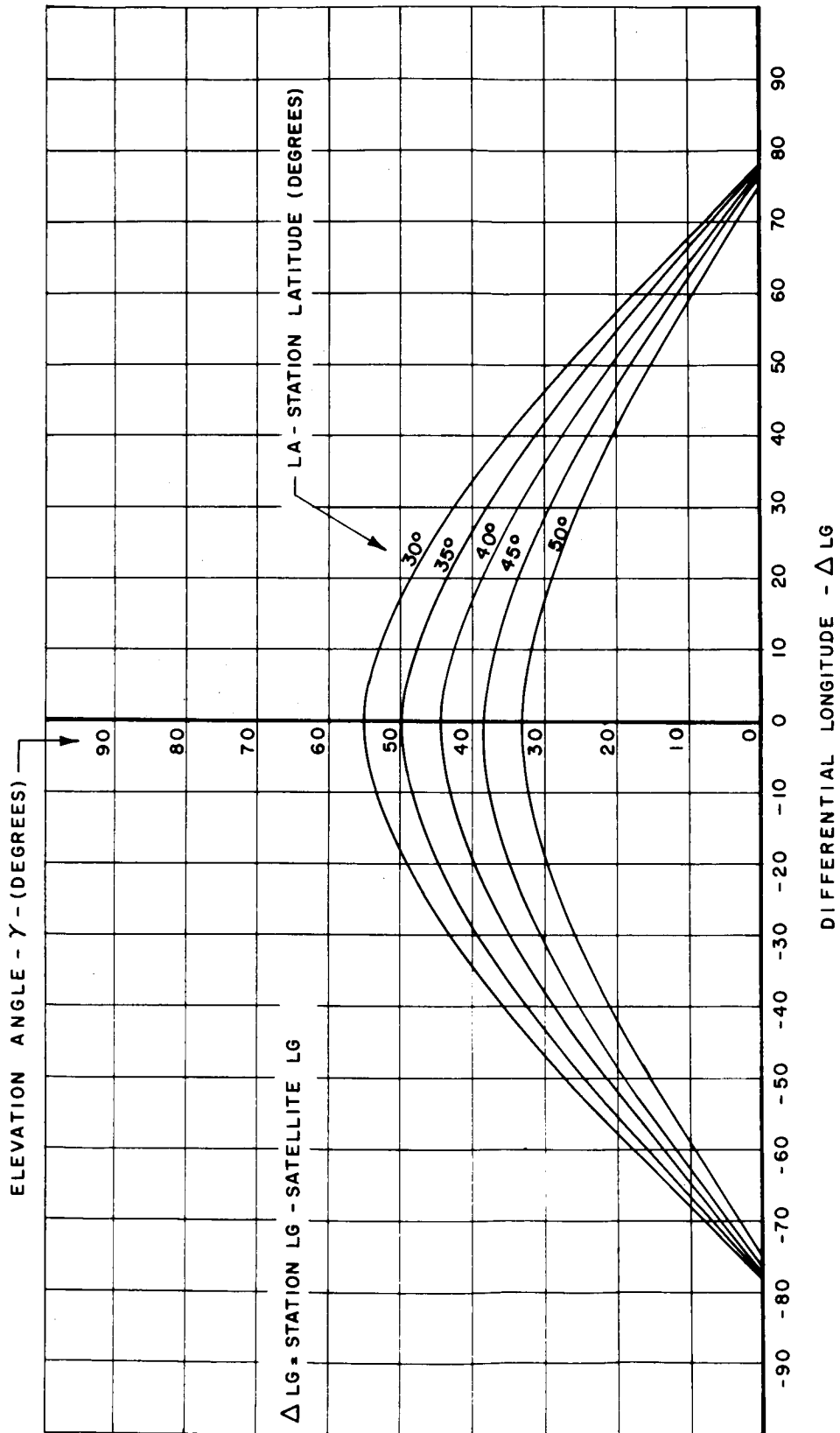


Figure 2-9. Elevation Angle as a Function of Ground Station Latitude and Longitude and of Synchronous Stationary Satellite Longitude

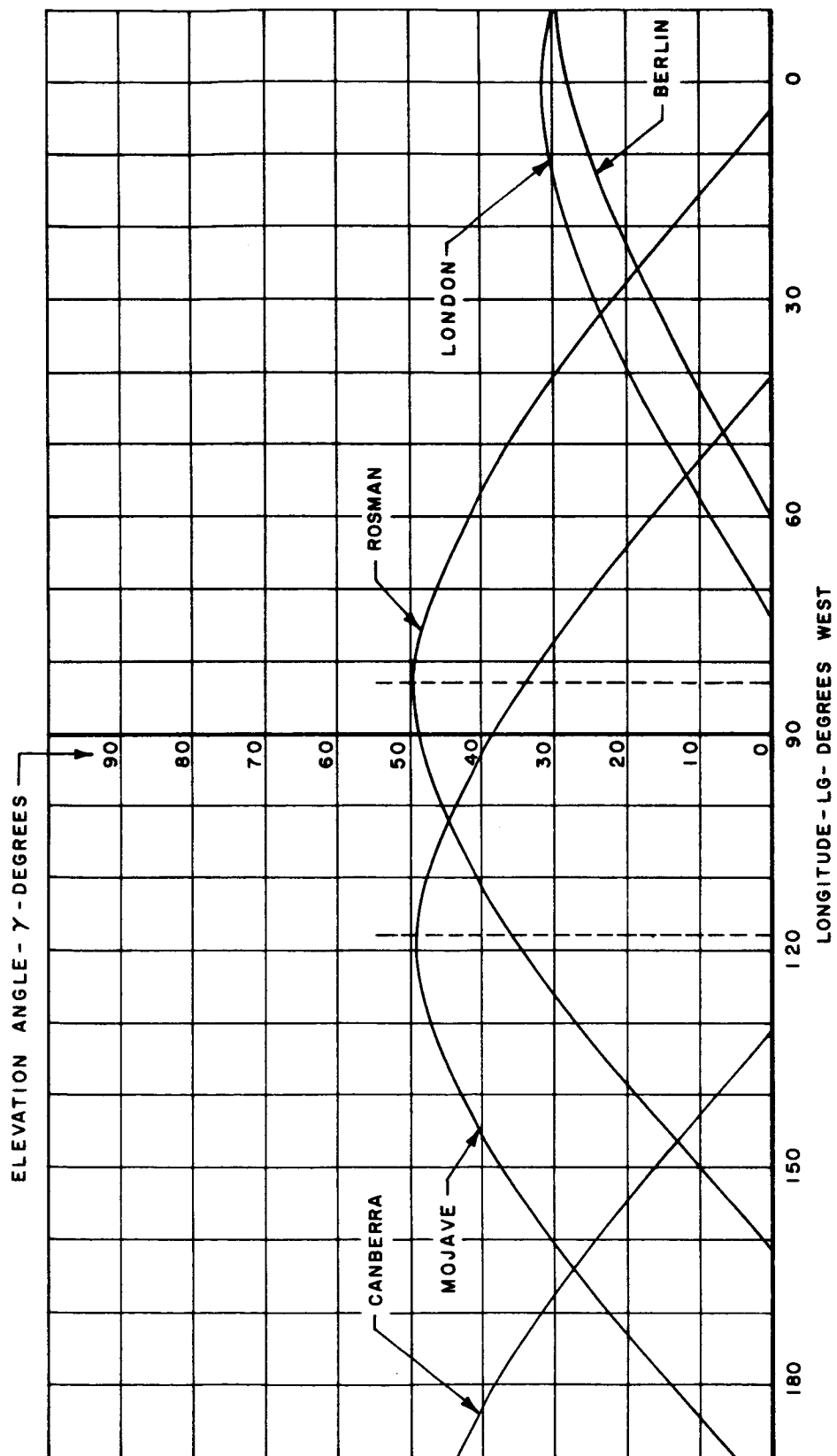


Figure 2-10. Elevation Angle vs Synchronous Satellite Longitude for the ATS Ground Stations

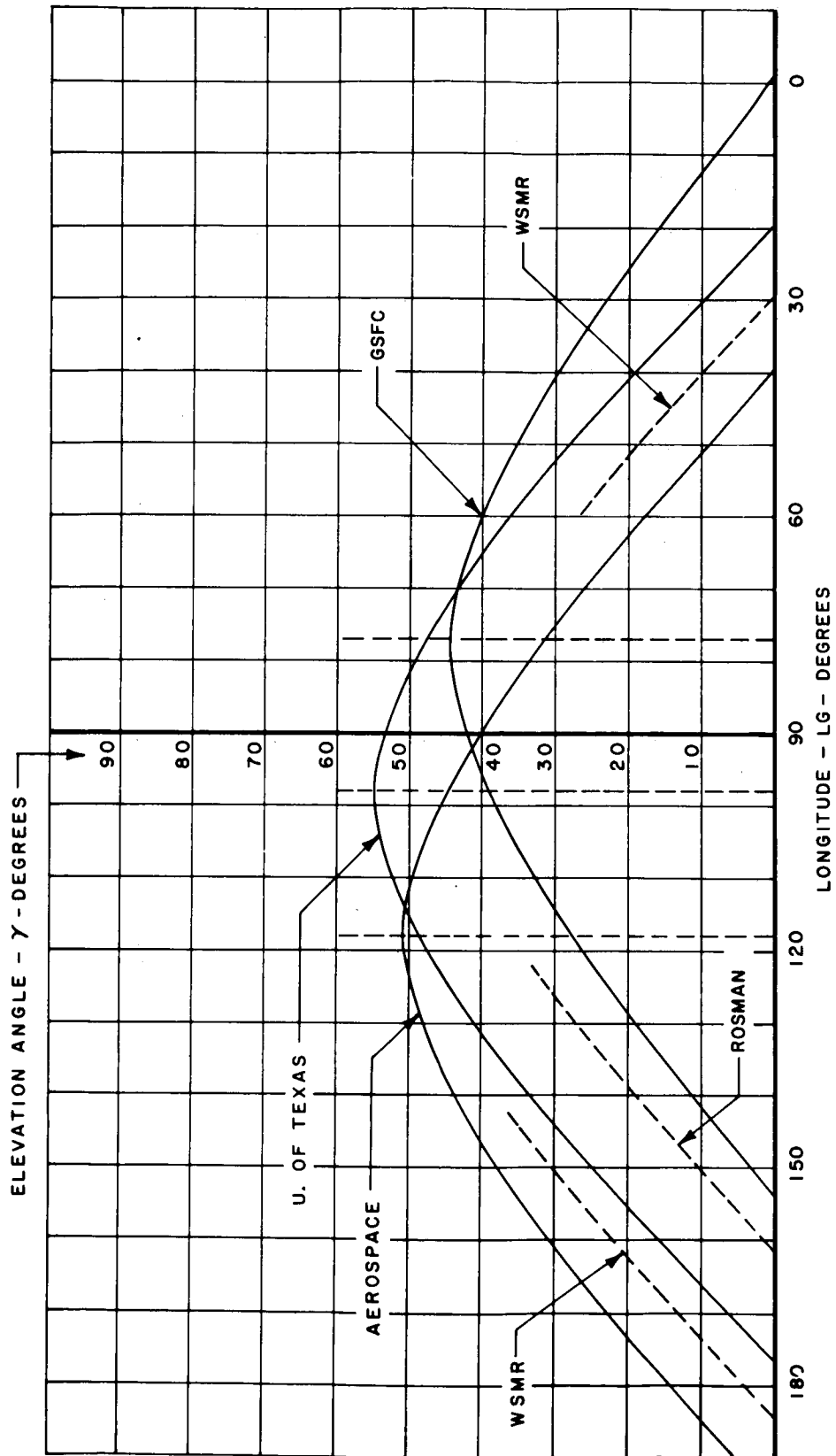


Figure 2-11. Elevation Angle vs Synchronous Satellite Longitude for the Millimeter Experimental Ground Stations

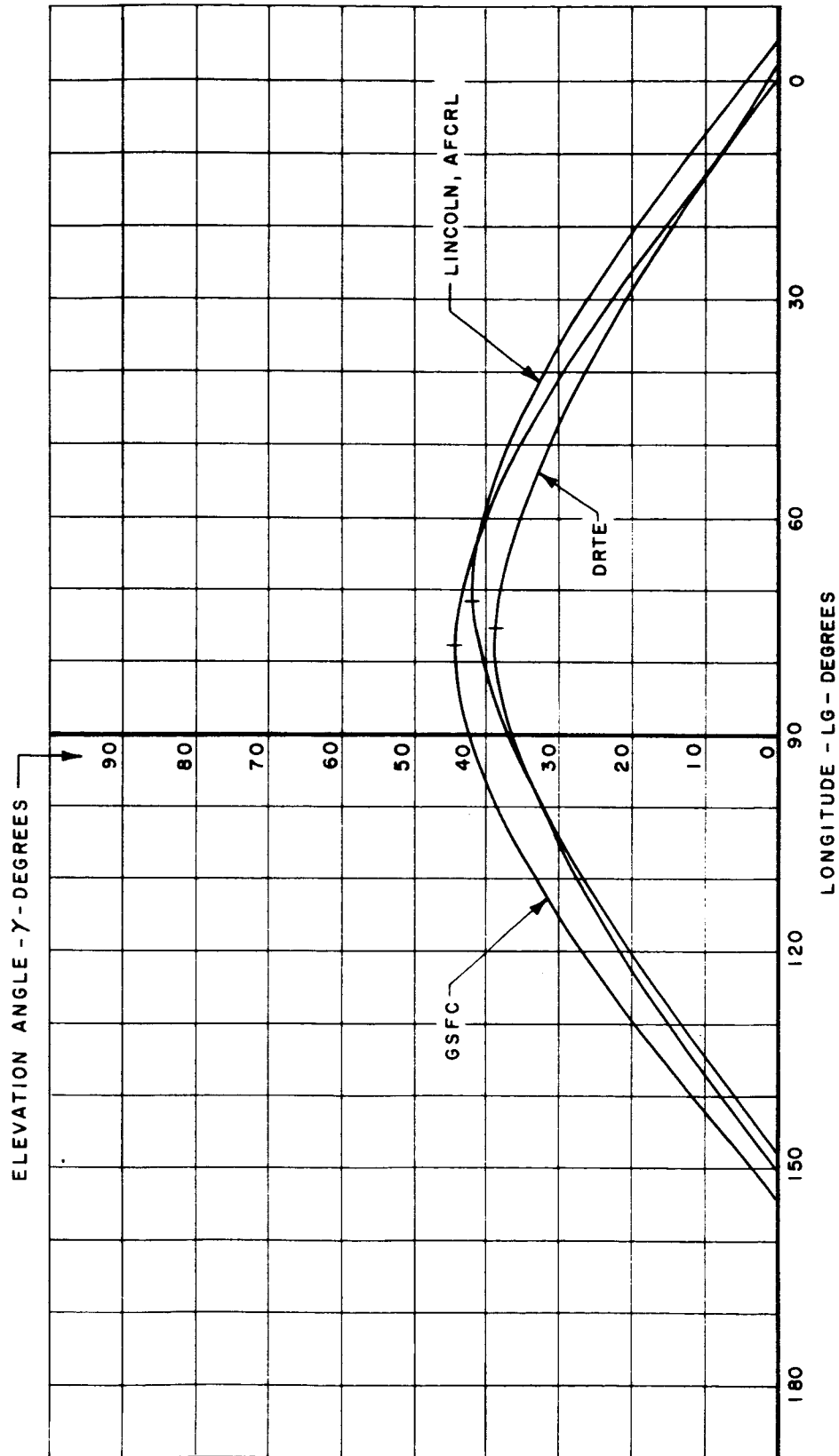


Figure 2-12. Elevation Angle vs Synchronous Satellite Longitude for the Millimeter Experimental Ground Stations

Establishment (DRTE), Lincoln Laboratory and Air Force Cambridge Research Labs (AFCRL). In addition, a transportable millimeter auxiliary antenna-receiver terminal located at either White Sands Missile Range (WSMR) or Rosman is considered as a gap filler to improve the elevation angle profile for the propagation experiments. Table 2-VI gives the possible points along the elevation profile for the satellite positions given in Table 2-V.

TABLE 2-V
ASSUMED POSITIONS OF ATS SYNCHRONOUS SATELLITES

<u>Position</u>	<u>Longitude</u>	<u>Symbol</u>	<u>Links</u>
Primary Atlantic	45° W	PA-45	Rosman-Europe and Rosman-Mojave
Secondary Atlantic	30° W	SA-30	Rosman-Europe
Primary Pacific	145° W	PP-145	Mojave-Canberra and Mojave-Rosman
Secondary Pacific	165° W	SP-165	Mojave-Canberra

TABLE 2-VI
ELEVATION ANGLE PROFILES FOR PROPAGATION EXPERIMENTS

<u>Position</u>	<u>Station</u>	<u>Elevation Angle</u>
PA-45	Aerospace	5°
	WSMR	15° *
	Univ. of Texas	24°
	DRTE	29°
	GSFC	33°
SA-30	Lincoln, AFCRL	35°
	Univ. of Texas	10°
	DRTE	21°
	GSFC	23°
	Lincoln, AFCRL	26°
PP-145	GSFC	7°
	Rosman	15° *
	Univ. of Texas	29°
	Aerospace	41°
SP-165	Univ. of Texas	10°
	WSMR	22° *
	Aerospace	31°

* Auxiliary Receiver

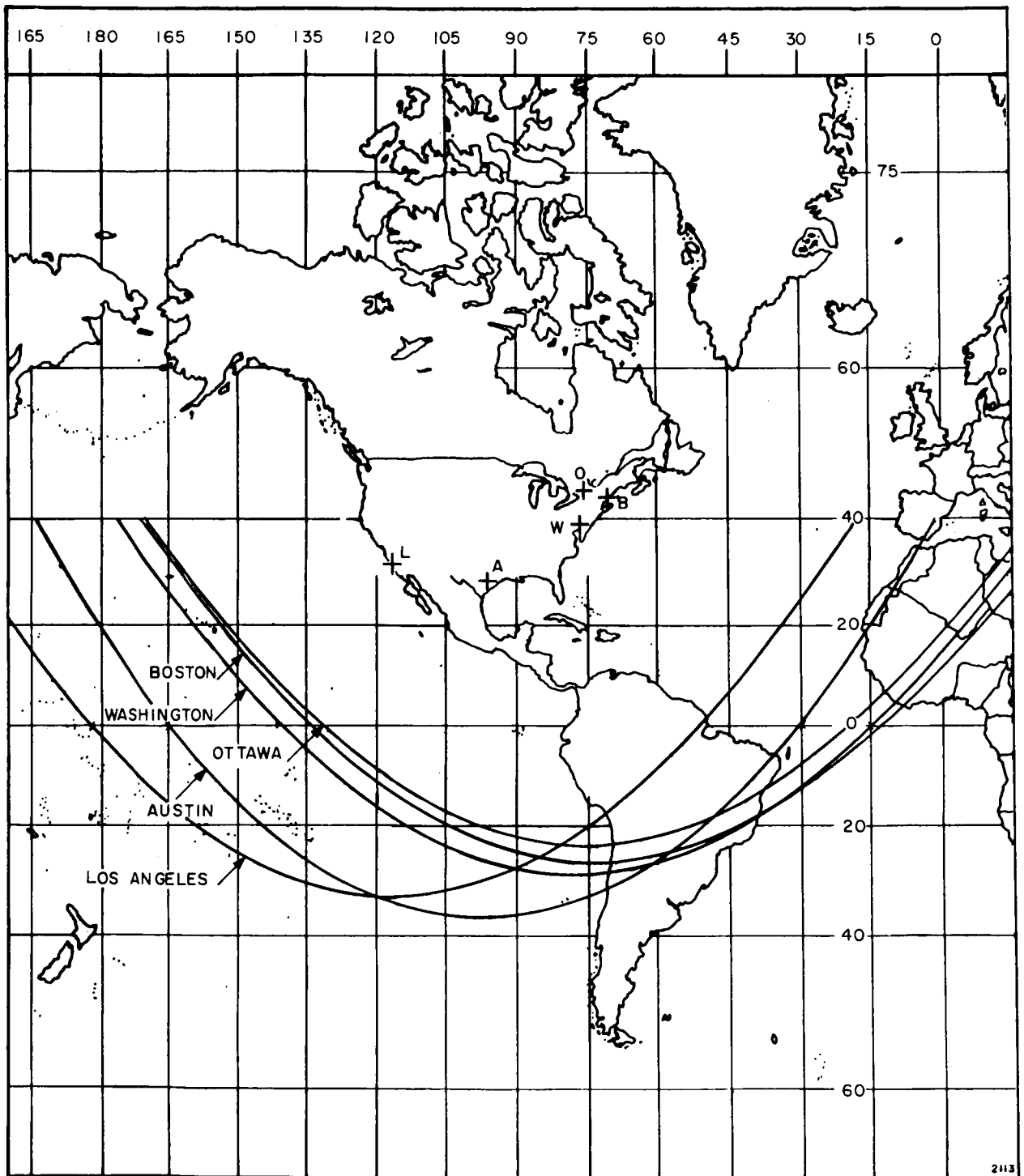
Some important conclusions can be drawn from Tables 2-V and 2-VI:

1. A synchronous satellite in the secondary Atlantic position of 30° West longitude provides a satisfactory combination of down-links with the ground stations indicated.
2. A synchronous satellite in the primary Atlantic position of 45° West longitude or in the secondary Pacific position of 165° West longitude provides a satisfactory combination of down-links with the ground stations indicated if a gap filler receiver is positioned near White Sands Missile Range.
3. A synchronous satellite in the primary Pacific position of 145° West longitude provides a satisfactory combination of down-links with the ground stations indicated only if a gap filler receiver is positioned at Rosman.
4. The AFCRL and Lincoln stations are of marginal value for both Pacific positions.

2.2.2 Medium Altitude (6000 nmi) Satellites

The medium altitude satellite is most desirable for the initial propagation experiments. The angular elevation rate of the medium altitude satellite is slow enough (no faster than 0.025 degrees per second at 6000 nmi) to permit ample viewing time per pass with sufficient data samples per degree of elevation. On the other hand, the elevation angular rate is fast enough to complete a full elevation profile before significant weather changes can occur. Elevation coverage from the horizon to 30 degrees can take place well within an hour on many of the orbital passes.

Figure 2-13 shows the zero degree elevation coverage contours for a 6000 nmi satellite for ground terminals located near Los Angeles, California; Austin, Texas; Washington, D. C.; Boston, Massachusetts and Ottawa, Canada. The Ottawa location has been included to accommodate Canada's Defense Research Telecommunication Establishment (DRTE) in any planning they might have for participation in this program. As the coverage diagrams



ZERO DEGREE ELEVATION COVERAGE
CONTOURS FOR A 6180 N. SATELLITE

Figure 2-13. Zero Degree Elevation Coverage Contours
for a 6000 nmi Satellite

indicate, the altitude of this satellite is sufficiently high to permit simultaneous observation by many ground stations for two hours or more.

A one-year viewing time profile was developed to: (1) estimate the number of satellite passes available to a ground station during any interval of time; (2) estimate the amount of viewing time per pass; and (3) estimate the total operational time on the satellite payload which is required to service all the ground stations during a given pass. The results of this profile show that the available viewing time is abundant, ranging from 35 passes (165-200 minutes per pass) every 13 days for Austin, Texas, to 31 passes (130-180 minutes per pass) every 13 days for Ottawa, Canada. For the same period of time, the maximum payload operational time ranges from 180-340 minutes for each of the 35 passes.

2.2.3 Inclined Synchronous Satellites

A synchronous altitude satellite which is inclined 30 degrees has an interesting application in the millimeter experiments. Its elevation angle relationship with respect to given point on the earth is variable, thereby offering a satisfactory elevation profile for each individual ground terminal. The inclined synchronous satellite does not offer the complete flexibility that is available with a medium altitude satellite but it is more flexible than the stationary satellite. Figures 2-14 and 2-15 are working charts, from which range of elevation angle for a given satellite longitude and ground station can be derived. Figure 2-14 gives approximate ground range on the surface of the earth in degrees of arc versus ground station latitude for various values of longitude difference between the ground station and the sub-orbital point of the satellite intersection with the equatorial plane. Figure 2-15 provides elevation angle versus differential longitude for various ground station latitudes and various satellite sub-orbital latitudes. Table 2-VII gives the approximate range of elevation angle for the various ground stations of interest.

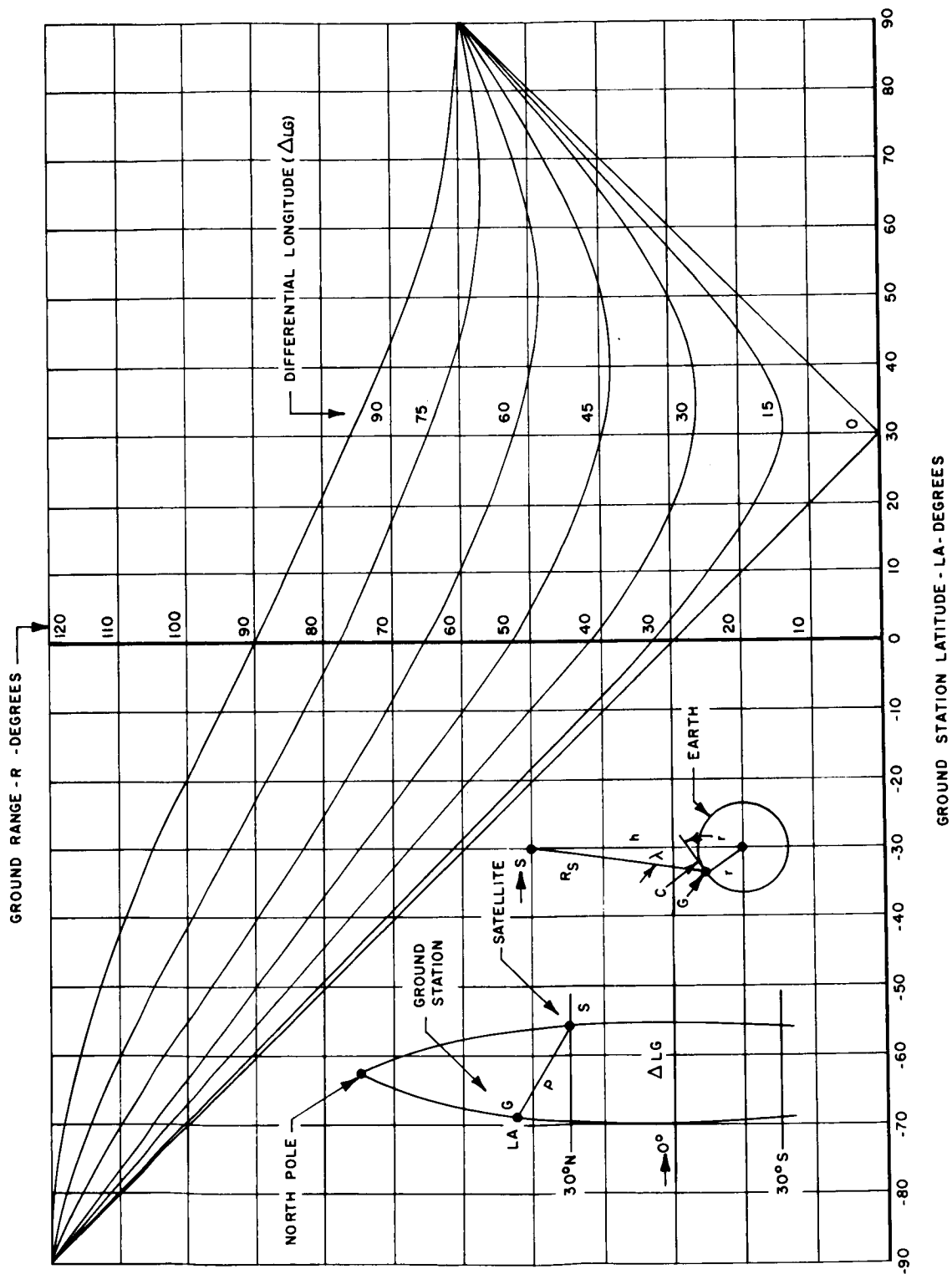


Figure 2-14. Ground Range vs Ground Station Latitude for an Inclined Synchronous Satellite over the 30th Parallel

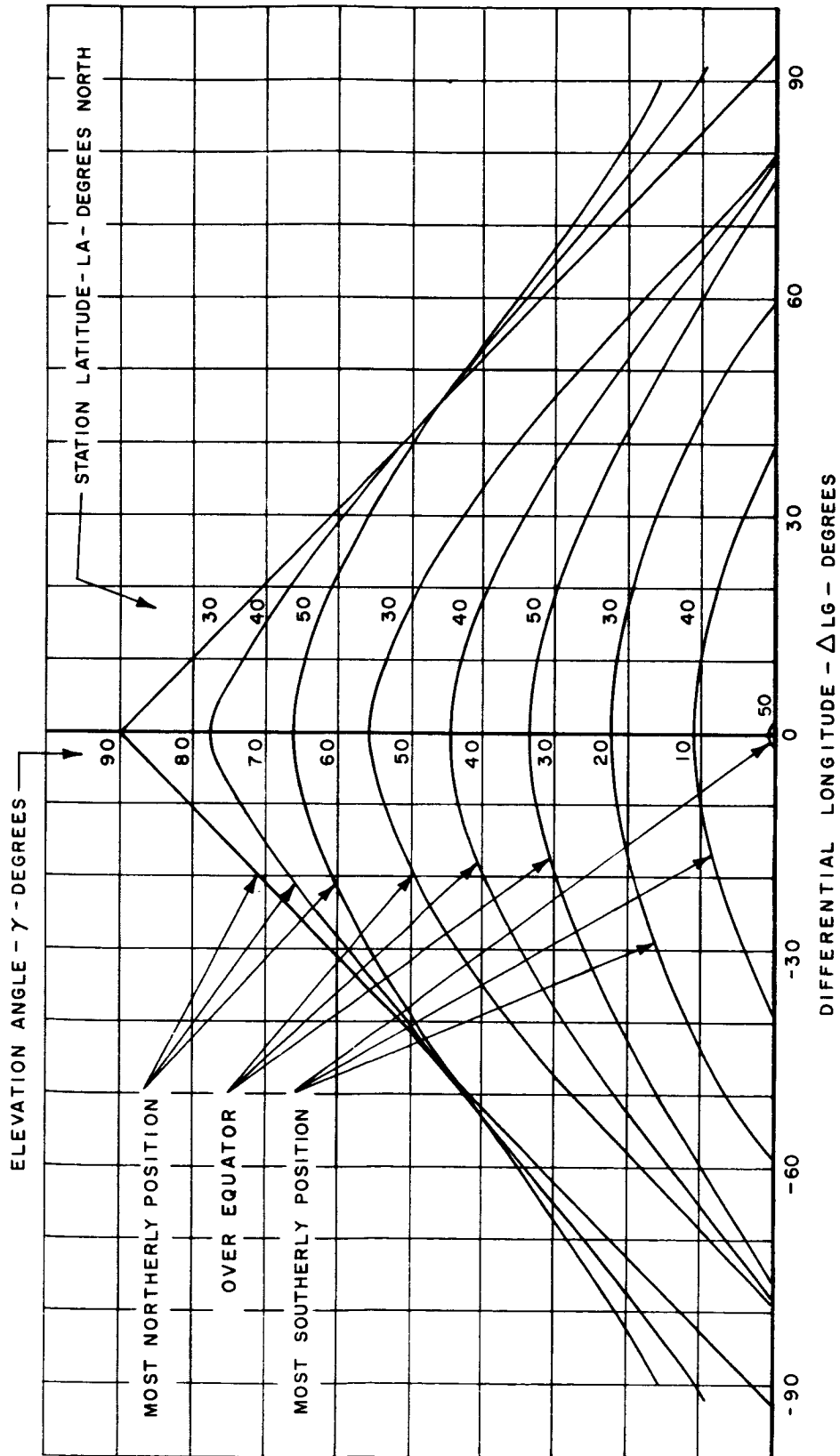


Figure 2-15. Elevation Angle vs Latitude and Longitude for Synchronous Satellites Inclined 300

TABLE 2-VII
ELEVATION ANGLE PROFILES FOR PROPAGATION EXPERIMENTS
WITH INCLINED SYNCHRONOUS ORBITS

<u>Station</u>	<u>Range in Elevation Angle (degrees)</u>			
	<u>PA-45</u>	<u>PA-30</u>	<u>PA-145</u>	<u>PA-165</u>
Aerospace	0-21	0-8	13-63	4-45
Univ. of Texas	5-39	0-24	8-44	0-25
GSFC	7-65	0-45	0-27	0-12
Lincoln, AFCRL	1-61	0-50	0-23	0-9
DRTE	0-58	0-46	0-27	0-13

2.3 Operational Analysis

Scheduling the measurement periods for the data collection program will be a major task. The propagation data collection schedule will not only have to be compatible with the other missions of the satellite but also compatible with the other missions of the experimental ground facilities.

The scheduling of spacecraft experiments centers primarily around the consumption of prime power aboard the spacecraft. Since the millimeter-wave payload is expected to consume about 80 watts of prime power, some capacity is available for the necessary command and telemetry channels, antenna control system and possibly some other experiments. It is understood that the ATS SASSE and SAGGE power supplies can continuously provide 142 watts and 130 watts, respectively. Solar cells serve as their primary source of energy. Satellite operation during the eclipse period is maintained by storage batteries which receive their charging energy from isolated sections of the solar panels. Propagating data collection can probably be arranged to exclude the periods of eclipse, if necessary. Scheduling activities for each of the experimental ground facilities should not be too difficult if these facilities are equipped with interchangeable RF heads, the proper antenna alignment equipment, a spacecraft simulator and well organized pre-test calibration and check-out procedures.

A typical work cycle which would be satisfactory for the propagation experiments would be to operate during a five day work week, ten to twelve times spaced seasonally during the year. A full work week every four or five weeks may be the most attractive arrangement from a manpower scheduling point of view. This several week period between tests also provides an opportunity for examining data and making changes in test procedure and ground equipment before the next test.

Each work week could consist of four data collection sessions, four to six hours duration for each, and appropriately spaced so that each station collects data during dawn and dusk and near noon and midnight. These sessions include pre-test and post-test data collection check-out and calibration with the spacecraft simulator which is located on the remote bore-sight facility.

During this data collection session, the spacecraft experiment packages would be first put into a programmed warm-up mode and then followed by cycles of data collection and standby with a prime power drain which is totally compatible with the spacecraft. The minimum ON period during each cycle is considered to be 30 minutes, providing that receiver signal acquisition can be accomplished rapidly. It is preferable, of course, during certain weather conditions, that the ON period be the full four to six hours. It is probably not necessary to statistically process all of the data collected in a four to six hour period, but it would be very beneficial to look for the occurrence of unusual propagation effects and if they occur, examine them in more detail.

No planning would be made with regard to weather since it is unpredictable and since work schedules must be established well in advance. Enough samples would be taken during the year which should result in a reasonable cross-section of the normal meteorological variables.

2.4 Test Waveforms

Three test waveforms, AM, PAM and PAM/FM, have been evaluated both from an analytical point of view and from a hardware implementation point of view in the First Quarterly Report. Based on the measurements made with these test waveforms, data on the characteristics of the channel can be determined from which the performance of the channel for various modulations can be inferred. In addition, basic correlative measurements are required to describe the condition of the atmosphere and explain why certain things are happening to the signals.

In order to determine the performance of a satellite-ground communication link at millimeter wave frequencies when various types of analog and digital modulations are used, it is necessary to know the characteristics of the link. Some of the pertinent characteristics which describe the channel are:

1. The multipath structure of the channel
2. The dispersion introduced by each of the multipaths
3. The time variations of gain and delay for each of the multipaths
4. The amplitude and phase characteristics as a function of frequency for the overall channel
5. The noise characteristics of the channel.

Knowledge of the above characteristics would give a fairly complete description of the channel. In particular, it would give the total coherence bandwidth, the selective fading and the amplitude fading of the channel. Other factors, not included in the above, which are also of interest, are the spatial decorrelation distance, the polarization diversity exhibited by the channel, and any angle diversity introduced by the channel. Knowledge of all of the above characteristics, as a function of meteorological conditions, location of the ground system and the elevation and velocity of the satellite, would provide a basis for determining the performance of the communications system using various types of modulations.

Ideal waveforms can be specified which give a measurement of the first four characteristics listed above. Such an ideal waveform would have an impulse-like characteristic which enables it to measure the scattering function of the channel. In actual practice, waveforms are used which, although not optimum, provide information on the channel characteristics that apply for determining the system performance for most modulations of interest. Three types of test waveforms that were considered are: an AM waveform with two sidebands, a PAM test waveform which is a time quantized pulse amplitude modulated waveform, and a PAM/FM test waveform, which involves modulating the FM carrier with a PAM waveform.

Where possible it would be desirable to design the system so that it could transmit as many of these waveforms as possible in a programmed manner. However, when the use of each of the presented waveforms is considered in terms of the implementation of the necessary hardware, within the confines of satellite and space environments, the most readily implemented of the three test waveforms is the AM waveform. It will fulfill the purposes of generating equally-spaced sideband energies which may be processed through receivers to determine the relative phase and amplitude stabilities of the two sidebands. Hence, it is felt that this approach is implementable for systems on a time schedule compatible with a one to two year flight hardware program. For time schedules of greater periods, that is, two to four years, implementation of the other waveforms can be considered.

2.4.1 AM Test Waveform

The AM test waveform lends itself readily to implementation in that it does allow the use of a stabilized millimeter source as the carrier through the use of an inguide shunt-mounted semi-conductor modulator.

The sideband energy is introduced onto the stable carrier. It is felt, at this time, that this particular approach is realistic and within the state-of-the-art, requiring a minimum amount of development work for implementation, when a reasonable transmitter power level is considered. This holds

for frequencies from 10 through 35 Gc. This shunt type of modulation does allow the introduction of modulating signals ranging from dc on through approximately 25 to 50 mc. The upper limiting capability of these shunt modulators is somewhat determined by the incident RF power which is being modulated. This is to say that the upper frequency limit of modulation is inversely proportional to the power being modulated. Above this frequency range, namely, from 8 mm to 3 mm, a major development program in the semi-conductor material and the type of modulation techniques would be required. This modulation approach can be implemented with approximately a 20 db on-off ratio which is equivalent to an approximate index of modulation of 80 percent. This modulation index would prove to be most adequate for the evaluation of the communication channel. The limiting factors in the generation of this modulation index are the engineering trade-offs between insertion loss I_L and isolation I_{so} , namely, the switching ratio $I_{so}:I_L$ of the modulator. Hence, if more than 80 percent modulation was required, this would be accompanied by a greater loss in carrier power due to I_L .

2.4.2 PAM Test Waveform

The second modulation to be considered is that of a PAM waveform. The implementation of the PAM Test Waveform is very similar to that discussed for the AM Test Waveform, in that an RF line modulation would be used. The major difference is that the modulation signals will now become a pulse train, and the output would be RF pulses which have a coherent stable characteristic. It is suggested that a 10 nanosecond pulse will be used with a one to two nanosecond rise time. This type of modulation can best be accomplished at a power level below 100 mw and at a wavelength below 8 mm. Since this technique does require the utilization of a duty factor, this approach of RF line modulation yields a reduction in average power which is proportional to the duty of the waveform generator. Therefore, it is felt that this modulated signal be followed by a coherent pulse amplifier such as a TWT, Pulse Klystron Amplifier, and/or other devices. This would allow for boosting the peak power output to obtain an average power level which would provide adequate signal-to-noise ratio in the channelized receiver.

This problem of generating peak power in coherent millimeter devices cannot be solved without a development in the RF source capability. This fact became quite evident during a survey of millimeter components.

The same results showed dramatically the limitations that are evident in today's millimeter source technology. Namely, the only devices capable of peak power equal to average power are found in the magnetron family and those are duty limited and provide only non-coherent signals, which would pose major problems in obtaining narrow-band predetection bandwidths.

2.4.3 PAM/FM Test Waveform

The pulse amplitude modulated FM test waveform can be implemented most readily through the utilization of a low power pulse amplitude FM signal generator followed by a final driver RF amplifier, such as TWT's and/or RF distributed amplifier techniques. Once again, the argument as presented in the preceding paragraph, as it relates to peak and average power devices, is applicable to this type of operation. Hence, the implementation of this system would be through the utilization of a low power FM oscillator followed by an RF line modulator whose output is fed directly to a high power transmitter amplifier device. Through the implementation of this technique, it is felt that this will more closely simulate an actual PAM/FM communication system, in that direct control of the PAM and direct control of the FM signals may be independent and may provide a coherent source for the purposes of implementing a channelized receiver.

2.5 Up-Links versus Down-Links

Down-links are most desirable when conducting propagation experiments. Up-links should be considered for propagation experiments only if the down-link transmitter proves to be a problem. The most important reason for wanting to use a down-link is that it requires less coordination and less modification on the part of the existing millimeter facilities. If properly instrumented with an automatic tracking system or a programmed

tracking system, these facilities can receive the test waveforms and make propagation measurements with little or no coordination with GSFC except to obtain satellite ephemeris data. Several stations can make measurements simultaneously without interfering with one another.

Furthermore, acquisition and tracking is much more difficult with an up-link because a closed loop is required to confirm that the transmitted signal is being properly received. A closed loop would require that each ground facility be equipped to receive a beacon signal or a telemetry signal from the satellite which indicates that the transmit beam is properly pointed.

One objection to the down-link is the power consumption of the space transmitter. However, a good receiver local oscillator consumes almost as much power and, since it must be on longer than the transmitter in order to accommodate each ground station individually, it is doubtful whether the satellite receiver really provides an advantage in prime power. The up-link just does not provide the necessary flexibility in scheduling propagation data collection with the other experiments being performed with the satellite. In addition, down-links are more desirable because simultaneous measurements with multiple feed antennas and dual reflector antennas are possible, thus providing information indicated in Table 2-III. Finally, down-links eliminate the need for on-board signal processing.

As mentioned in the summary, the recommended experiment consists of 35 and 16 Gc down-links and 94 Gc up-links. The 94 Gc up-link was recommended because of the development problems that would be associated with a long life 94 Gc satellite transmitter in the time scale assumed. The 94 Gc up-link is somewhat attractive because of the ground transmitter development presently underway for the Aerospace facility and because of the fact that the 94 Gc satellite receiver local oscillator signal can be derived from the 35 Gc transmitter output at little expense in weight and prime power.

3. SPACECRAFT EQUIPMENT DESIGN

This section of the report deals with the proposed implementation of space flight hardware which would be needed in the initial propagation measurements program outlined in the summary. The proposed program satisfies the basic measurements requirements and uses a basic measurement waveform which can be readily implemented. In view of the existing and planned experimental millimeter wave facilities, the proposed experiments would make the best use of all the available equipment capabilities and, therefore, provide the best propagation data for the funds and payload space expended.

It is proposed that the 35 Gc and 16 Gc satellite transmitters be utilized. Each transmits a single AM double-sideband waveform with a variable modulation frequency which is received by several ground stations simultaneously. In addition, it is proposed that a 94 Gc receiver be carried aboard the satellite in order to receive an AM double-sideband waveform from a transmitter such as the one being developed for the Aerospace facility.

At this point, it is desirable to restate a few of the many considerations which have led to the selection of this experiment. First and foremost, the availability of flight qualified hardware grossly limits the introduction of more sophisticated and/or higher frequency devices to be carried in the vehicle as transmitter sources, although it is well acknowledged that a transmitter source in the vehicle does present the most useful of all experimental approaches.

Secondly, as will be seen in Section 3.1, the 35 Gc and 16 Gc transmitter power capabilities will range from a minimum useful radiated RF power of 200 milliwatts up to approximately 10 watts of RF power. These factors may again be considered as trade-offs depending upon the time of

the experiment, namely, a schedule of development which can be allowed for generation of a useful experiment for a particular satellite payload.

As will be noted, tubes are available which possess the capability of providing a suitable RF source which has been missile and/or flight tested, hence will provide the greatest factor of confidence in the system.

A third major consideration in the selection of this experiment has been the availability of ground facilities and their ability to adequately interface with a communications experiment. It is most apparent that all sites presently available have been established and are presently utilizing radiometric systems as their main operational mode. In examining their capabilities, it is evident that, in order to achieve meaningful experimental data, a thorough site evaluation is necessary. This requires data on the facilities' operational capabilities at the frequencies at which the experiment is performed. The selection of a 35 Gc satellite transmitter was made primarily on the basis that all of the existing sites except Aerospace are presently performing at 35 Gc. Radiometric measurements have been made with these antenna facilities, either on extended targets or point sources, which have allowed them to perform sufficient antenna calibration and beam pattern measurements. Also, for the most part, all of these facilities have boresight facility measurements on their antenna and have established gain figures of antennas and pointing accuracy capabilities.

The selection of a 16 Gc satellite transmitter was made on the basis that it represents a logical point in the 10-100 Gc spectrum at which to perform propagation-communication experiments before entering the major area of atmospheric absorption.

Hence, for the above listed reasons, it was deemed most advisable that a 35 Gc and 16 Gc experiment be performed which allows the utilization of the University of Texas, Lincoln Laboratory and AFCRL facilities and could also include the recently developed Haystack facility as a possible receiver site for the evaluation of a large antenna aperture. Also, in

conjunction with the vehicles transmitter capabilities, and with the presently planned 94 Gc transmitter capability at the Aerospace Corporation, it will be shown that the ability to piggy-back a 94 Gc receiver on the 35 Gc transmitter in the satellite does not grossly penalize the weight and power consumption of the payload. It is proposed that this be accomplished through the utilization of a third harmonic mixer and an X-band IF technique which will allow the reception of 94 Gc signals. It is felt that this technique of utilizing a receiver in the spacecraft most readily interface with the Aerospace facility.

Aerospace is not planning to descend into the millimeter region below 94 Gc with their 15-foot antenna facility. Any plans for work at frequencies below 94 Gc would be associated with smaller six-foot reflector systems, such as that presently being prepared for use at 35 Gc and similar to those being suggested as auxiliary receivers. For this reason, and since they are presently instrumenting a one-hundred watt 94 Gc transmitter capability, the trade-offs for introducing a 94 Gc receiver within the spacecraft will yield a completely independent channel characterization capability to the experiment. It is also suggested that the Goddard Space Flight Center consider as part of its ground facility, a similar 94 Gc transmitter capability. This would provide an independent channel characterization capability totally under the control of NASA.

The 16 Gc satellite transmitter presently would interface with the Goddard Facility and the Canadian Station. The remaining facilities would have to be modified with receivers in order to participate at this frequency during the propagation experiments.

3.1 Spacecraft Equipment

The satellite transmitter and receiver block diagrams are shown in Figure 3-1. The two transmitters are considered to be the greatest power consuming devices aboard the satellite, and thus will receive prime emphasis.

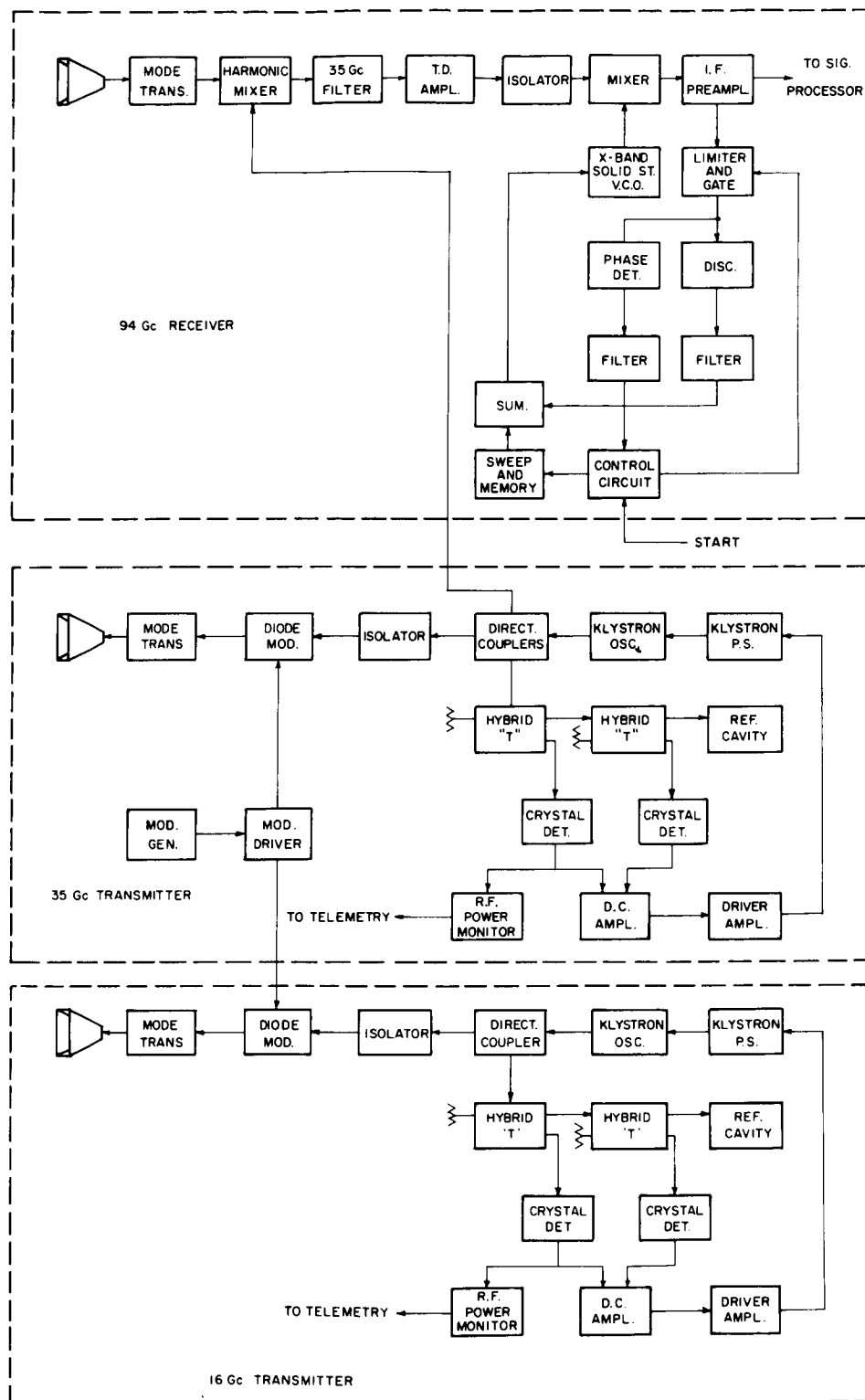


Figure 3-1. Satellite Transmitters and Receiver

3.1.1 35 Gc Satellite Transmitter

Although certain devices, such as the dual-cavity klystron designed by Dr. El Hefni of Bell Laboratories exhibit efficiencies up to 80 percent, these devices are still in the category of laboratory curios. Typical efficiencies of 0.1 to 1.0 percent for off-the-shelf items are more realistic. It should be noted that as the efficiency of the device is increased the prime power supplies decrease proportionately in size and weight. There are presently available two types of klystron oscillators capable of supplying 2 w and 200 mw respectively.

The efficiency of these two devices varies by almost an order of magnitude. This is due to the fact that as higher power outputs are attained, the standby power, such as filament power becomes less significant in the accumulative prime power required. This continues to be the case as greater RF power is generated.

The possibility of introducing a two-watt transmitter is within the state-of-the-art if one is willing to supply prime power in excess of 250 w. To supply the minimum useful output of 200 mw with present-day tubes, about 80 w of prime power must be supplied.

For this report the design of a 200 mw transmitter is presented because of the specified prime power restrictions and because it possibly represents the minimum useful experiment. Higher power designs will be discussed in subsequent reports. Referring to the 35 Gc transmitter in the block diagram of Figure 3-1, the total losses in the various coupling elements have been estimated conservatively to be a maximum of 3 db. Thus, the source must be capable of delivering a minimum of 400 mw of microwave power. It is further desirable to employ as the transmitter a device which has been derated as far as its power output is concerned, and ruggedized for missile applications.

One possibility is the I. T. T. F-2900 series Klystron. This klystron has been derated from an output of about 1 w to 400 mw. It is felt that no

serious problem exists in operating this device at 400 mw output power. Another possible device is the Varian VA-283 reflex klystron with an output power of 400 mw. This tube has been designed for extreme environments in airborne applications.

The prime power required for a selected VA-283 or F-2900 is 77 w. The transmitting tube will be stabilized in frequency utilizing an AFC loop. The sampled power is derived from a directional coupler with a coupling coefficient of about 20 db and an insertion loss not exceeding 0.5 db. The transmitted power, meanwhile, is applied to the input of a second directional coupler. Here, approximately 2 to 4 mw is coupled out and applied as the local oscillator drive to the 94 Gc receiver harmonic mixer. The output of this directional coupler is fed to a semiconductor AM shunt modulator. The insertion loss of the modulator is estimated at a maximum of 1.5 db.

The RF carrier is modulated at three independent modulation frequencies, i.e., 10 kc, 10 mc, and 50 mc. The change in modulation frequency is performed in a step manner and need not be done excessively fast as the propagation path of a 6000 nmi satellite will not change at a fast rate. The modulating signals are derived from the spacecraft reference and divided down to the proper frequencies. These frequencies are selectable either through a ground command or a simple, slow commutating switch aboard the satellite.

The modulator itself consists very simply of a varactor diode located in a shunt configuration in a $\pi/4$ length of waveguide. One side of the diode is at DC ground, while the other side is attached to a TNC connector center conductor via an RF bypass network. The drive power required is quite small, certainly below 100 mw. Thus, the modulator driver need not be very elaborate. A transistor buffer amplifier followed by an emitter follower ought to suffice. The modulated RF is now applied to the antenna through a short length of waveguide. The antenna is discussed in Section 3.1.4.

Table 3-I is a tabulation of the weight, volume, and power consumed by the 35 Gc transmitter module. The weight of the module is well below the 25 lb limitation and according to the total volume the transmitter can easily be packaged into the nominal 18 x 11 x 8 in. experiment package. If the total peak power drain should happen to be limited to 25 w instead of 80 w, batteries would have to be used as discussed in Section 3.1.4.

TABLE 3-I
35 Gc TRANSMITTER VOLUME, WEIGHT and POWER

Item	Weight (oz)	Size (in.)	Prime Power Required (w)	Remarks
Diode Mod.	2.	2x1x1		
Modulator Driver	4.	2x2x3	1.0	
Modulation Gen.	2.	1x1x2	0.2	
Directional Coupler	5.	2x2x1		
Isolator	3.	2x1x1		
Klystron (400 mw)	7.	3x2x2	56.0	ITT or Varian Selected Tube
Klystron Power Supply	64.	3x3x10	21.0	
Hybrid 'T'	4.	3x2x2		2 required
Cavity	8.	3x3x3		
Crystal Det.	2.	1x1x3		2 required
D. C. Amplifier	4.	2x2x3	1.0	
Driver Amplifier	4.	2x2x3	1.0	
Program Control	4.	2x2x3	0.5	
Waveguide	12.	2x2x12		
Connectors	16.	1x1x8		
Miscellaneous	16.	3x6x6		Coax cable and wire
TOTALS:	9 lbs. 13 oz.	366 cu. in.	80.7 w	

3.1.2 16 Gc Satellite Transmitter

As in the 35 Gc transmitter discussion, the 200 mw transmitted power case is presented because of the prime power restrictions. Here also the transmission losses in the transmitter system have been estimated at 3 db maximum and the source must, therefore, be capable of 400 mw of RF power in order to deliver 200 mw to the antenna system. The same

qualities of a derated, rugged, reliable device are also desirable as in the 35 Gc case.

A typical device under consideration is a selected Sperry type SOU-403 two-cavity klystron. This device is capable of 1w power output; but would be operated in a derated manner to improve reliability and to reduce power consumption. The prime power required for operation of a selected klystron would be about 72 w, which includes power supply conversion losses.

The transmitting tube will be stabilized in frequency by means of an AFC loop as shown in Figure 3-1. The operation of the loop is essentially the same as the one used in the 35 Gc transmitters and is described in the preceding section.

The RF carrier will be modulated in the same manner as the 35 Gc transmitter using the same type of diode modulator. The 16 Gc antenna is discussed in Section 3.1.4.

Table 3-II is a tabulation of the weight, volume and power consumption expected in implementing the 16 Gc transmitter module. The weight and volume of the module is the same as that of the 35 Gc module. As discussed in Section 3.1.4, batteries could be used to lower the peak power drain to 25 w.

3.1.3 94 Gc Satellite Receiver

As previously described in this section, the proposed satellite receiver will make use of a portion of the on-board generated RF energy from the unmodulated 35 Gc transmitter carrier. Through the implementation of this technique, the receiver's overall prime power consumption is drastically reduced. As an example, it would require approximately 60 to 80 w prime power to generate the necessary local oscillator signal for the first converter. However, in the proposed implementation, the satellite 94 Gc receiver utilizes the previously generated 35 Gc signal as its first

converter signal, and through the use of a third harmonic converter receiver operation is feasible at the expense of 6 w or less. The proposed receiver and its interface with the transmitter is shown in Figure 3-1.

TABLE 3-II
16 Gc TRANSMITTER VOLUME, WEIGHT and POWER

Item	Weight (oz)	Size (in.)	Prime Power Required (w)	Remarks
Diode Mod.	2.	2x1x1		
Modulator Driver	4.	2x2x3	1.0	
Modulation Gen.	2.	1x1x2	0.2	
Direct. Coupler	5.	2x2x1		
Isolator	3.	2x1x1		
Klystron (400 mw)	7.	3x2x2	35.0	Selected Sperry Type SOU-408 2 Cavity
Cavity	8.	3x3x3		
Hybrid 'T's	4.	1x1x1/2		2 required
Crystal Det.	2.	1x1x3		2 required
D. C. Amplifier	4.	2x2x3	1.0	
Driver Amplifier	4.	2x2x3	1.0	
Klystron Power Supply	64.	3x3x10	15.0	
Waveguide	16.	2x2x12		
Connectors	16.	1x1x8		
Miscellaneous	16.	3x6x6		Coax cable
TOTALS:	9 lbs. 13 oz.	343 cu. in.	53.2 w	

Once the 94 Gc signal has been received by the antenna, it is fed to the harmonic mixer where it is converted into the first IF. This first converter derives its local oscillator drive from the 35 Gc transmitter by means of a directional coupler. The third harmonic is generated in the nonlinear mixer diode and is used as the down converting signal in order to derive the X-band IF signal. It should be noted that this technique is not beyond the present state-of-the-art, considering the millimeter and submillimeter work being done by many in the field and, in particular, the capabilities of Raytheon's Santa Barbara Operation to utilize their wafer diodes as harmonic mixer elements for receiving systems in the millimeter and submillimeter regions. The X-band IF system consists of a tunnel diode amplifier which requires

minimum power, yet provides adequate amplification to minimize the effects of the second stage noise figure. Considering that both of these devices represent state-of-the-art technology, this approach becomes quite practical.

The first IF is now followed by the second mixer which converts the X-band signal to a second intermediate frequency at approximately 200 mc with an instantaneous bandwidth of approximately 100 mc. The output of this IF is then fed directly to a triplexing device which, through high pass, low pass, and bandpass filtering, allows the selection of the carrier and its two associated sidebands. At this point the carrier filter output is utilized for closing the loop of the phase locked AFC system. This is accomplished by means of tuned narrow band amplifiers and limiters in order to provide the error signal for the phase comparator which drives the VCO. This VCO is a solid state, X-band oscillator which is tuned to the proper frequency in order to correct for doppler and other frequency shifts inherent in the communications channel. This loop will be provided with an automatic sweep acquisition circuit which sweeps the VCO until a lock signal is derived from the phase comparator, and will also contain an override signal to prevent the VCO from locking onto one of the sidebands associated with the carrier. The following sections will describe in more detail how these two signals, namely, the sweep and lock-on override signal, are derived from the signal processor.

Table 3-III provides a reasonable weight, size, and power estimate of this particular receiver system. As can be seen from the tabulation, the totals for the incorporation of this receiver within the 35 Gc transmitter burdens the prime power source by a very small amount. The combined weight and volume of the 35 Gc transmitter/94 Gc receiver package is still within the 25 lb limitation and should fit into the nominal 18x11x8 in. experiment package. The use of batteries for the combined package is discussed in Section 3.1.4.

TABLE 3-III
94 Gc RECEIVER VOLUME, WEIGHT and POWER

Item	Weight (oz)	Size (in.)	Prime Power Required (w)	Remarks
Harmonic Mixer	6.	4x2x2		
Tunnel Diode Ampl.	6.	3x3x2	0.1	
Mixer Preamplifier	13.	6x3x2	0.5	
X-band Solid State Source	9.	3x3x3	3.4	
Band Pass Ampl. Mixer	2.	2x1x1	0.2	Parts only will build - 2 required
Video Amp. Σ	8.	3x3x2	0.2	Parts only will build - 2 required
Second Mixer				Parts only will build - 2 required
B. P. Ampl., Det. and Integ.	5.	4x1x1	0.1	Parts only will build - 2 required
3 Mixers & 3 Filters	4.	3x3x1	0.1	Parts only will build
Synth., Gates, F. D. C.	6.	3x3x2	0.5	Parts only will build
$\emptyset$ Det., Disc., Σ and Filters	5.	3x2x1	0.5	Parts only will build - 2 required
Limiter, Integ.	3.	3x1x1	0.5	Parts only will build - 2 required
$\emptyset$ shift, $\emptyset$ Det.				Parts only will build
Limiter & Gate	4.	2x2x1	0.4	
Waveguide	8.	2x2x12		
Connectors	16.	1x1x8		
Miscellaneous	16.	3x6x6		Coax and wire
TOTALS:	7 lbs. 8 oz.	325 cu. in.	7.5 w	

3.1.4 Spacecraft Interfaces

This section of the report deals with the critical spacecraft interfaces presently seen by study. The primary interface which is considered to be of paramount importance in determination of the feasibility and reliability of the experiments is that of the antenna with the spacecraft structure and the stabilization system. In order to make propagation measurements, 27 db (90°x60° beam) antennas are required at each operating frequency which are pointed at the Continental United States. Linearly polarized satellite antennas could be used if polarization adjustments are made at the ground terminals to maximize signal strength.

It should be noted that two basic types of spacecraft are presently under consideration, first, the gravity gradient stabilized spacecraft which lends itself readily to a simple and reliable antenna and feed system; and second, the spin stabilized spacecraft which would require a mechanically despun antenna system. The alternative to using a despun antenna would be to use a simple feed and allow the spinning aircraft to generate a sweeping antenna beam pattern across the ground terminals. This approach it is felt, is not very desirable, although it would yield some data at a reduced data rate. The primary objection to this approach would be the stringent requirements imposed upon the knowledge of the entire antenna system and its overall pointing accuracy such that antenna beam shape may be separated from those fading effects caused by the atmosphere. Therefore, it is proposed that the initial set of experiments utilize a reliable antenna system which would allow direct interpretation of the received data without the necessity for having to compensate for spacecraft orientation and spacecraft spin rates in the data processing.

It is recognized by the study that the spacecraft's antenna is of paramount importance for the future utilization of millimeter waves in communication systems. It is therefore felt imperative that the present development program for mechanically despun satellite antenna systems be expanded to include operation in the millimeter region.

One area of prime concern, other than the mechanical antenna interface, would be that of the prime power duty cycle of the experiment and its compatibility with the other experiments being performed aboard the spacecraft. It is hopeful that prime power in the order of 80 w can be supplied for periods up to six hours without resorting to any secondary battery reservoir system. However, if the total power drain for the experiment is limited to 25 w and the weight is limited to 25 lb, then the following battery capacities and weights could be used. Calculations are based on silver cadmium batteries being used and discharged to two-thirds of their initial charge. These batteries are stated to combine the best features of silver-zinc and nickel-cadmium types to give high capacity and long life.

35 Gc Transmitter at 200 mw Power Level

Peak Power Drain -- 80 w

Weight of Electronics -- 10 lb

A battery capacity of 165 watt-hours is required to allow a one-third discharge in one hour. This is based upon the fact that although 80 w is being drained from the battery, 25 w are being recharged and the difference is 55 w of discharge, which is one-third of 165. The 165 watt-hour battery would weigh 11.0 lb and would recharge in 2.2 hours at the 25 w charging rate, resulting in slightly less than one-third duty cycle.

16 Gc Transmitter at 200 mw Power Level

Peak Power Drain -- 54 w

Weight of Electronics -- 10 lb

Using the same conditions as stated for the 35 Gc transmitter case, the net drain will be 29 w requiring 90 watt-hours of battery capacity for one hour of drain at a weight of 6 lb, resulting in a total weight of 16 lb for the transmitter.

The battery could be recharged in 1.16 hours at the 25 watt-hour rate, resulting in almost a 50 percent duty cycle.

35 Gc Transmitter and 94 Gc Receiver

Peak Power Drain - 87.5 w

Weight of Electronics - 17.5 lb

The net drain in this case would be 62.5 w and would result in 6-1/4 lb of batteries to supply a 94 watt-hour capacity required for one-half hour of operation. The total weight would then be 23-3/4 lb for the 35 Gc transmitter-94 Gc Receiver combination. The recharge time would be 1-1/4 hours.

The experiment package vehicle would be required to interface directly with the command and control subsystem on-board the spacecraft and would also require a number of telemetry channels for purposes of translating

on-board equipment status data and 94 Gc propagation data to the ground control station. During the operation of the experiment when utilizing microwave tube type of devices it is expected that programmed warm-up sessions would be required for reliable operation of the experiment. On-board timers with a minimal amount of control circuitry would be required to implement such a programmed warm-up and stand-by mode of operation.

4. GROUND EQUIPMENT DESIGN

The design philosophy, used for the ground based equipment at the GSFC site, includes a combination of several technological approaches in order to determine the optimum design. A thorough knowledge of the advantages and shortcomings inherent in each choice must be made available to the design. It is felt that this maximum utilization of technology will provide the program with a wealth of knowledge which would prove invaluable in the final selection of millimeter satellite communication system hardware.

4.1 Signal Sources

The signal sources which are used as transmitters to provide boresight signals for the purpose of generating antenna patterns and boresight accuracy measurements on the ground-based facility are shown in the block diagram of Figure 4-1. This equipment will also provide the GSFC facility with AM and FM capabilities in a ground-to-ground experimental communications link which would allow development of millimeter technology applicable to spacecraft systems and ground-based systems. In addition, these signal sources could eventually interface with higher power amplifier devices. Hence, these sources with their output of approximately one watt could then drive a 100 w transmitter or a 1000 w transmitter as would be required in a large, high data-rate space-earth communications system. The system would possess the capability of a wide deviation FM system and in addition would possess capability of pulse modulation and AM modulation.

This approach, it is felt, is not the most economical approach that could be presented, yet it is felt that the versatility and the over-all growth potential as presented in the block diagram of Figure 4-1 will represent the instrumentation of a future millimeter ground facility capable of performing many tasks envisioned by the present study. This would include the capability

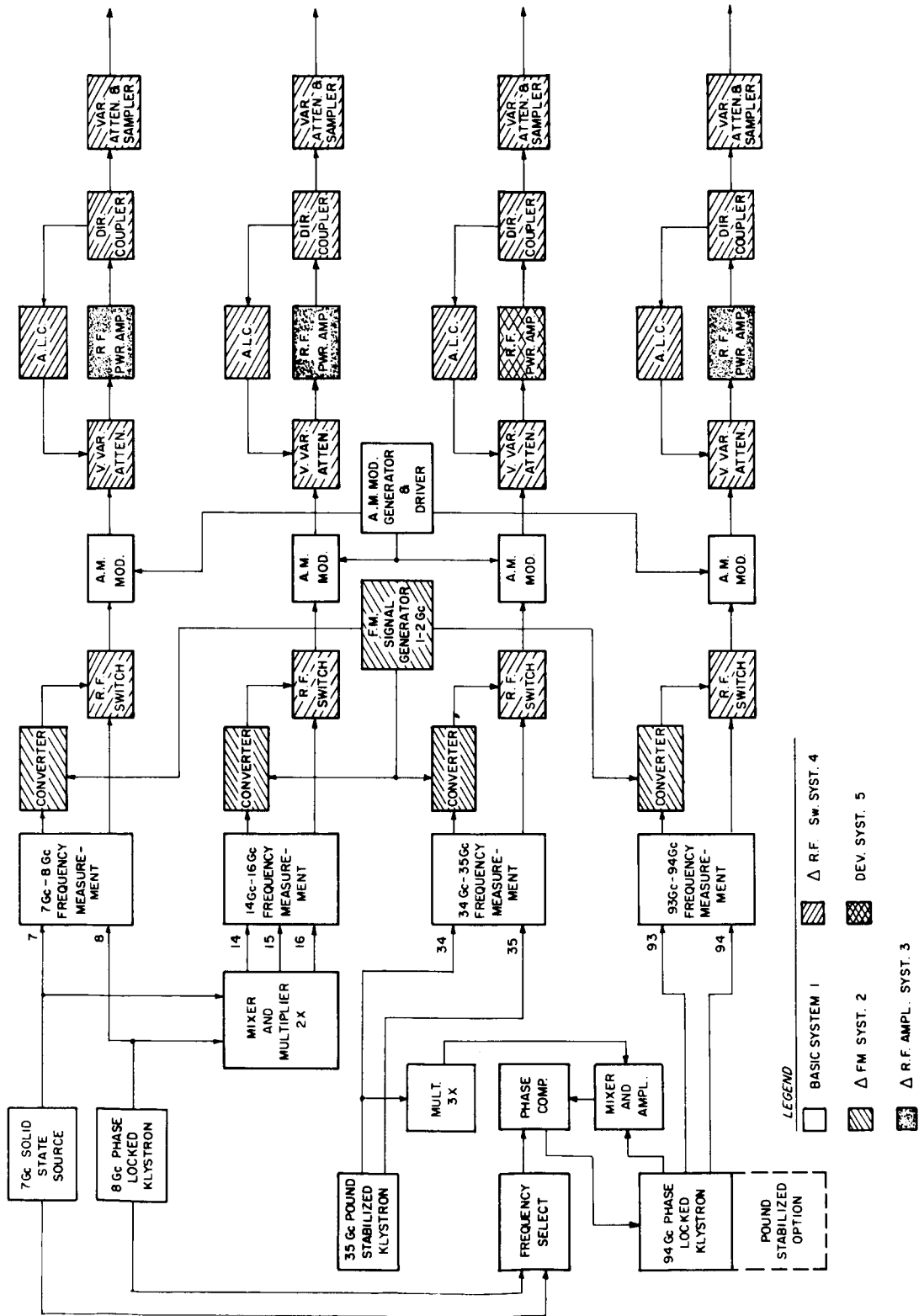


Figure 4-1. Signal Sources for GSFC Ground Facility

of AM, pulse amplitude modulation and FM /pulse amplitude modulation. In addition, variable indices of modulation for FM variable bandwidth capabilities would be inherent in the system.

4.1.1 Frequency Sources

On the extreme left-hand side of the block diagram are located the stabilized millimeter and centimeter RF sources. These sources employ interconnections and hybrids to generate the necessary combination of frequencies. This area of the system in particular has been approached in such a way as to make maximum coverage of electronics technology for the purpose of proving the feasibility of hardware implementation techniques. As an example, it is proposed to utilize 7 Gc solid state multiplier techniques to provide a coherent 7 Gc signal derived from a low frequency stable oscillator.

This area of the system is complemented by the addition of an 8 Gc phase locked klystron technique which will incorporate a similar master oscillator clock and will allow the introduction, at some later date, of frequency (synthesizer) techniques for the purposes of providing selectable frequency locks over small frequency increments such as 100 cycles at 8 Gc.

These primary sources at 7 and 8 Gc can be combined by way of solid state mixing and/or multiplication to derive signals in the 14 to 16 Gc frequency band. This mixer and multiplier combination of devices will allow a fixed tuned 7 Gc solid state multiplier to provide a 14 Gc signal when the multiplier path is utilized. This technique will, therefore, generate a totally solid-state approach to the generation of a stable 14 Gc signal. Through the use of a mixer the 7 Gc and the 8 Gc signals would produce a 15 Gc signal with a limited tuneability about this frequency. The 8 Gc stable signal fed into a times two multiplier would generate a 16 Gc signal.

A Pound Stabilized Klystron approach has been selected for use in the 35 to 36 Gc range. This technique has been used in many of the microwave regions and would require only extension of high-Q cavity capabilities to

provide a high performance stabilized 35 or 36 Gc RF source. Other frequencies of interest in the transmitter system may also be generated via this technique by incorporating interchangeability of reference cavities in the system design. This would provide more versatility in the equipment utilization.

The 94 Gc frequency would be generated two ways. The first way would be to phase lock a klystron and the second would be pound stabilization of a klystron. The pound technique should be attempted although difficulty is expected in the generation of a high Q cavity for operation of this frequency. Problems associated with this technique might well be the maintaining a high Q in a corrosive atmosphere. It would be advisable to explore the phase lock technique and possible use a closed atmosphere waveguide approach to maintain the Q of the cavity.

The actual technique to be utilized with the phase lock klystron, which is shown on the block diagram, utilizes a times 3 multiplier from the 34 or 35 Gc source and provides a signal to the mixer amplifier combination allowing phase locking to a reference frequency of 7 or 8 Gc. This technique would then make use of the all solid state 7 Gc device in addition to the pound stabilized klystron at 35 Gc as a referencing signal to close a 94 Gc klystron loop.

4.1.2 Frequency Measurements

The next step in the transmitter process involves frequency measurements. This is represented by the large blocks shown in the diagram of Figure 4-1. Basically, this consists of coupler sections which allow the sampling of the RF signal. Part of the sampled energy is used to measure the frequency by using resonant cavity measurement techniques. In addition, some of the energy would be available for the purpose of spectrum analysis which would allow the direct measurement of the spurious components and the frequency stability of each of the sources and thereby provide an evaluation in this respect of the different techniques employed.

4.1.3 FM Modulators

As previously noted, the primary frequencies in question are: 8, 15, 35 and 94 Gc. The reasons for the generation of frequencies at 7, 14, 34, 36 and 93 Gc are to allow for the introduction of the FM signal generator by conversion techniques to be utilized for the transmitter capabilities. This implementation it is felt, can be best accomplished through the employment of voltage tunable magnetrons which are capable of octave bandwidths; and then via conversion technique to be introduced on a suitable carrier source. It is proposed that this conversion of the FM signal on to a stable carrier would be performed at a reasonable power level (i.e., 10-100 mw of power at each of the frequencies would be required for the converter to work in an efficient mode). It is felt that the minimum problems of conversion and linearity of modulation would be encountered at power levels in this region. Hence, the required output from each of the suitable sources would be in this order and the required signal from the FM generator operating in the 1-2 Gc region would only be in the order of 100 mw. This, then, is followed via switching techniques by an AM modulator section which would allow for pulse modulation of the FM waveform and/or gating of the transmitter functions.

4.1.4 AM Modulators

Amplitude modulation will be accomplished by using a shunt modulator. This shunt modulator will be used to generate AM sidebands up to approximately 50 mc on the RF carriers. This AM modulator then directly interfaces with a voltage variable attenuator, preferably the ferrite unidirectional type of device, which will provide for proper matching and interface into a RF power amplifier section.

4.1.5 Power Amplifiers

This RF power amplifier section would be of the broadband type and would allow for boosting of the signal from 1-10 mw up to 1-2 w of RF power. This technique, it is felt, is readily implemented in the areas of 8 and 16 Gc; in the areas of 35 Gc, some difficulty in finding a RF power amplifier at the 1-2 w level is encountered. Although it is not beyond the state-of-the-art

it is primarily a problem of developing a particular tube which supplies the 1-2 w power level. As shown in the survey of millimeter RF sources, there is a pronounced gap in the availability of RF amplifiers in the 35 Gc area. Although amplifiers are available that are capable of a kilowatt of CW power at 35 Gc, there are none between that level and a few milliwatts. At 94 Gc, there are amplifiers available which are considered almost state-of-the-art which incorporate distributed interaction or TWT techniques.

4.1.6 Power Output Control

The final interfacing components with the proposed antenna system would consist of a variable attenuator and power sampling coupler. The purpose of the attenuator would be to allow the variation of final transmitter power output without the variation of the transmitter chain power levels. To attempt large power variations by other means may result in changes in the transfer characteristics of the amplifier chain. An ALC (automatic level control) loop will be used to maintain a constant power output from the amplifier system. This loop, it is felt, is readily available and would provide the transmitter facilities with stable RF output power levels, which are generally required for the work on antenna pattern measurements and receiver calibration and sensitivity checks.

4.2 Main Receivers

The main receiver system for the GSFC facility, as shown in the block diagram of Figure 4-2 represents the current thoughts on the present and the potential capabilities of the ground-based facility that would be required in order to operate with maximum capabilities in the total millimeter spectrum.

The block diagram has been divided into the four major sections: An RF head and three receiver IF sections, to facilitate the following of signal paths and function clarification. The approach has been to maintain as much equipment as possible in a common useage status relative to all changes in frequency associated with the millimeter experiments.

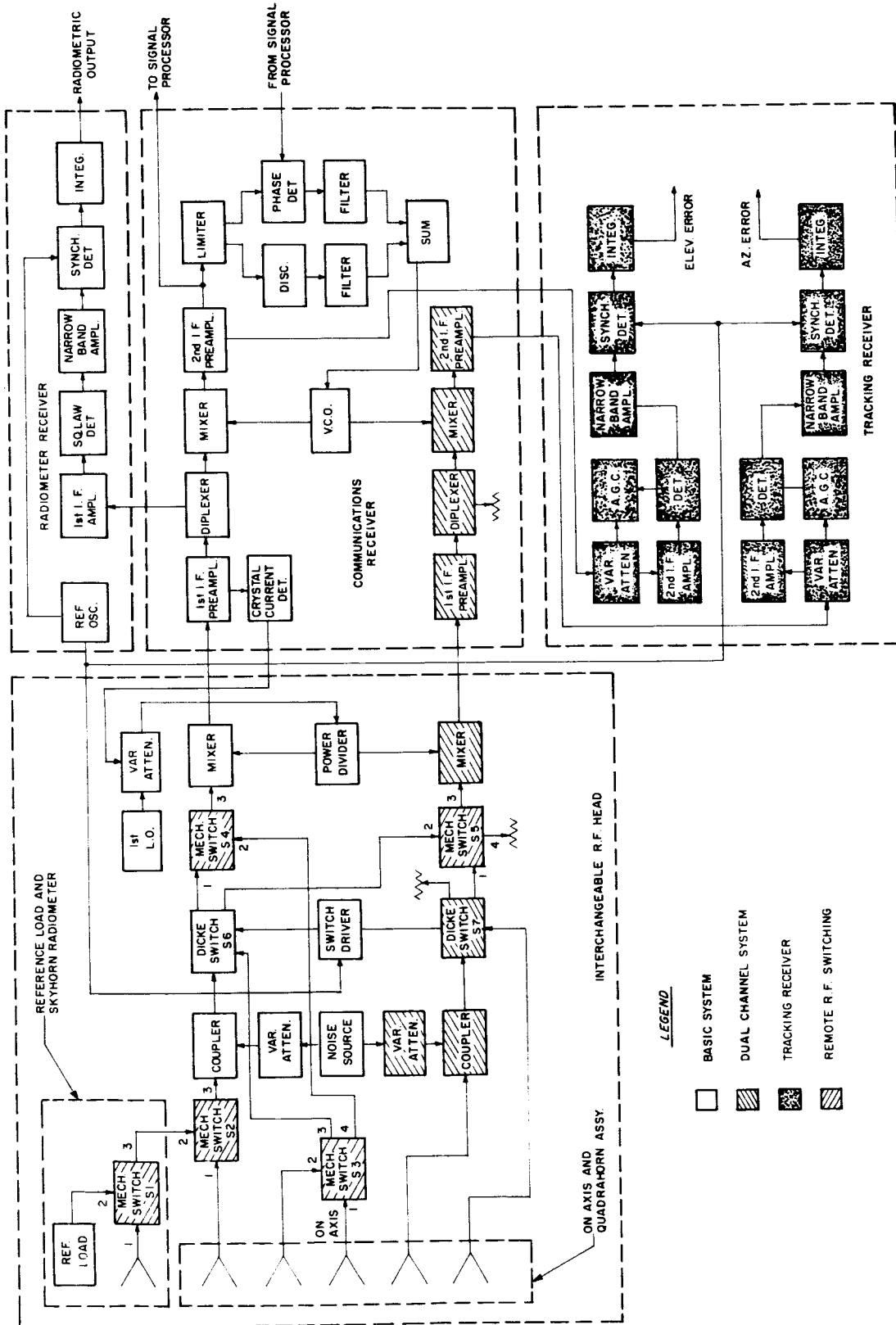


Figure 4-2. Ground Receiver System

Here again, the versatility in the overall receiver system provides for potential growth with the least obsolescence of initial equipment. As understood, the initial procurement of the communications and radiometric receiver would allow for a one-axis tracking system and the addition of the second receiver channel as shown on the block diagram would enable a complete tracking system to be implemented at some future date.

Duplications of equipment functions have been minimized and techniques have been employed so that these units share their function wherever possible between all channels of the receiving system. As previously stated, this overall approach is not the most economical, but it does provide for the most desirable potential growth as indicated by the present study.

The radiometric systems required for the performance in this operation are not deemed to be the primary objective of the facility, hence optimum radiometric sensitivities are not of paramount concern. It is felt that the radiometric system need only provide indications of gross effects in the absorption and background temperatures as observed by the ground installation. Although this could be accomplished by a narrow band radiometric system optimized for receiver sensitivity with a corresponding savings in initial investment, the equipment would become obsolete in the aspect of broadband capabilities in the communication function.

4.2.1 Interchangeable RF Receivers

The first part of the block diagram as shown on the left-hand side shows the RF feed interface arrangement of each interchangeable RF head with the ground terminal antenna system which includes a 15 foot millimeter dish. A five horn cluster feed would be used with one horn mounted on axis and the other four providing a quadrahorn, 2 or 3 db cross-over beam pattern. In addition to these primary antennas, a radiometer reference standard gain horn and a reference load would be provided for the radiometric operations. These primary feeds and reference components may be interfaced in the system by means of a rather complex switching technique. The complexity results from the multimode operational capability of the receiver system.

Mechanical switches located at points in the RF head section as shown on the block diagram of the receiver could be used for the purpose of rapid changeover between modes of operation. As an alternate approach, the input RF section of the receiver may be implemented in such a manner as to enable mode changeover by replacing certain sections of waveguide and/or bends at discrete points in the package.

In the case of mechanical switches, the changeover is much faster, but the initial cost is considerably higher whereas the second approach will cost less, but will require more time to make a mode change.

Frequency changeover is accomplished by removing the entire front end section and replacing it with another module operating at a different frequency. This modular arrangement is similar to the technique employed in some types of microwave test equipment. Each frequency head will be packaged to mate into the remaining sections of the receiver by means of two of three waveguide joints and power, and signal connectors. This would allow changeover to a new frequency of operation to be accomplished in a relatively short time.

4.2.2 IF Receivers

The input RF section is then followed by the receiver IF sections. The RF and IF sections interface by means of a diplexer operating at a high frequency and at this point the receiver divides into three IF sections - the radiometric IF receiver, the communication IF receiver, and the tracking IF receiver. Parts of the communications receiver serve a dual function in that they are also used in the tracking mode of operation. Tracking is accomplished by lobe switching and error signals will be provided for use in closed loop servo operation of the antenna facility.

The outputs of the diplexer in the upper channel as shown on the block diagram are fed to two sections. One output is fed to the radiometric receiver section which is tuned to a different frequency relative to the second output of this diplexer. The remaining components of the radiometric receiver process the signal to complete the Dicke type radiometer measurements.

The second output from the upper diplexer is fed to a mixer preamplifier. The reference signal for this mixer and the lower channel mixer is obtained from a VCO. The output of the second IF preamplifier goes to a carrier lock loop the output of which controls the VCO and causes the receiver to lock on the carrier. The output of this preamplifier is also fed to the tracking receiver where it is processed along with the lower channel signal, and generates the azimuth and the elevation error signals that would be required in order to angle track.

This implementation would allow this system to provide radiometric signal processing in addition to providing an adequate signal bandwidth simultaneously, and within the same bandwidth as proposed in this receiving system. This system also provides very large predetection first IF bandwidth (500-700 mc) which inherently provides the system with longevity of usefulness in the areas of high data rate communications systems.

The radiometric system utilizes the following technique. The front end of the receiver is alternately switched between the received signal and a reference load, or standard gain horn at a prescribed rate. By using a synchronous detector operating at the same rate, there is then provided a proportional output which is indicative of the relative signal and reference port temperatures. This would result in a true band integrating radiometer measurement when utilized either as a reference sky horn system, or a reference load system. The tracking mode uses loop beam switches to derive the error signal and thus would be proportional to the temperature differences. The measurement of the absolute temperature of the two beams would be accomplished by the pre-calibration of the receiver and the establishment of a primary baseline prior to the tracking of satellites and/or sources. It is felt that this technique is readily implementable and would prove useful and valuable in the reduction of data during the real time evaluation of communications characteristics.

This basic radiometric lobe switch-track technique is proposed to be used at all frequencies since it does circumvent the problems associated with

a phase sensitive monopulse system, and is readily implemented at all frequencies of interest in the millimeter spectrum. The requirements for gain and phase stable receivers are not nearly as stringent as those required for a monopulse system.

4.2.3 Receiver Operational Mode Switching

As stated in a previous section, mechanical switching has been included in the system to enable operating personnel to make rapid mode of operation changes. It is the aim of this section to describe the signal path flow as the receiver modes vary. These switches are shown on the block diagram as S_1 to S_7 inclusively. The nomenclature of these switches is as follows:

Switch Number	Nomenclature
S_1	Radiometric Reference Switch
S_2 and S_3	Track or Radiometer Selector Switches
S_4	Communications or Track Selector Switch
S_5	Dual Channel Single Axis Selector Switch
S_6 and S_7	Dicke Radiometer Reference Switches and Lobe Switch Tracking Reference Switches

The receiver operational modes are as follows:

Radiometric Modes

- a) Sky Reference
- b) Reference Load
- c) Lobe Switching

Communication Modes

- a) Single Channel
- b) Dual Channel

Tracking Modes

- a) Radiometric Lobe Switching
- b) Communications Lobe Switching

The switch positions as a function of operational mode are shown in Table 4-1.

4.3 Ground Transmitter (94 Gc)

This section deals with the requirements and capabilities of the ground transmitter operating at 94 Gc which would interface with the satellite receiver described in Section 3.1.3. As indicated in Section 5, the signal power analysis is based on a 10 w transmitter as the minimum capability. However, serious consideration should be given to a 100 w capability.

This transmitter can take the form of a low power driver such as klystron or distributed interaction klystron devices which can be amplitude modulated via a shunt modulation technique, as previously described in Section 3.1. This, then would be followed by a final driver amplifier which would transmit 10 to 100 w of RF power. This final driver amplifier could readily take the form of the presently developed Hughes TWT type of coherent millimeter amplifier.

This type of operation would prove to be most efficient in that the final driver stages may be operated in a saturated mode to optimize the power output of the last driver stage and minimize amplitude fluctuations due to the previously introduced AM technique. Hence, it is felt that this general philosophy would lend itself readily to solving the problems of generating high levels of millimeter power for ground based installations. Further detail on this particular approach would, by necessity, require a more detailed investigation into the actual operating characteristics of the final driver stages and its associated hardware.

This information, it is felt, will be available within the near future, due to the actual experience of the Hughes and Aerospace test and evaluation programs on these high power millimeter transmitter sources. Therefore, it is proposed that a continuing exchange of information with these two groups be such that the latest and most up to date information with regard to these devices is introduced into the final design document of this study.

TABLE 4-1. OPERATIONAL MODES AND SWITCH POSITIONS

Radiometric				Communications		Tracking	
Switch Number	Reference Sky	Reference Load	Lobe Switch	Single Channel	Dual Channel	Radiometric Lobe Switch	Communications Lobe Switch
S ₁	1-3	2-3	Not Used	Not Used			
S ₂	2-3	2-3	1-3			1-3	1-3
S ₃	1-3	1-3	2-3	1-4		2-3	2-3
S ₄	1-3	1-3	1-3	2-3		1-3	1-3
S ₅					2-3	1-3	1-3
S ₆ & S ₇	Dicke	Dicke	Dicke	Not Used	Modulation	Lobe Modulation	Lobe Modulation

4.4 Auxiliary Ground Terminals

As indicated in the introduction to this report and as further outlined in Section 2.1, when forced with implementation of a propagation experiment aboard a synchronous stationary satellite, the availability of an auxiliary transportable ground terminal which would perform as a gap filler in the elevation profile examination of the medium would prove to be a most useful and versatile piece of equipment from the experimenter's point of view.

Further use of this auxiliary station could be made by co-locating it with one of the larger fixed installations for a period of time to determine multipathing effects as a function of beam size. The availability of two of these auxiliary stations in a dual reflector variable baseline configuration would provide useful estimates on spatial decorrelation of amplitude fading.

As indicated in Section 2.1, this device need only determine flat frequency fading by providing amplitude data on the received carrier at the particular elevation angles prescribed. It is not deemed necessary that this particular auxiliary terminal possess the overall ground terminal capabilities as prescribed for the existing large antenna facilities. This terminal would be outfitted utilizing a transportable antenna and pedestal system which would allow for adequate positioning accuracy on a fixed satellite. The antenna system would consist of a parabolic reflector and, for purposes of transportability, a diameter of 10 ft would be considered a reasonable trade-off.

When considering adequate signal levels, for measuring amplitude fading, a 10 ft antenna appears to be sufficient. This antenna system would then be attached to a simple accurate hand positioned mount system which would allow for the handling and positioning of the antenna in a reasonable mechanical environment. The output of the antenna's feed system would interface directly with the conventional receiver front ends described in Section 4.2.1 and the signal processing required at the site would be simple amplitude detection and recording capabilities which will be described in Section 5.1. Once again it should be emphasized that phase coherent measurements need not be attempted at the auxiliary sites. It is felt that if phase coherence measurements of the signal is performed by a larger facility at an elevation angle

less than the one in which the auxiliary site is located, then measurements at the auxiliary site would not be absolutely necessary. Hence, the primary function of the auxiliary terminal would be to supply a ground terminal which may be readily transportable to varying locations to establish statistical fading information on the signal under varying weather model conditions and also to provide a tool at the presently existing research ground terminals to perform variable aperture and spatial amplitude decorrelation measurements. One or more auxiliary receivers would allow greater versatility in the experiment program by maximizing the data output for a given payload within the spacecraft.

The design philosophy of the auxiliary ground terminal antenna system is based on the requirement that the antenna system must be easily transported from one location to another where the distance between the two sites could be several feet or it could be several hundred miles. A moderate amount of setup and tear down time would be required by a crew of two to three persons without the use of elaborate cranes or machinery. One consideration in this regard is to mount the antenna system on a flat bed trailer. Also a compartment must be provided on the back of the dish assembly to be utilized for the mounting of the antenna feed and RF receiver components. This RF package would be readily interchangeable for operation at 16 Gc and 35 Gc.

Three antenna sizes have been investigated which are 6, 8 and 10 ft parabolic type reflectors. The surface tolerance required of the reflector at 35 Gc is 0.02 in. The approach used by one manufacturer is to utilize spun aluminum fabrication techniques. Attaining this close tolerance increases the cost considerably since the normal runout of surface tolerance for a 10 ft dish utilizing this technique is $\pm 3/32$ in. or about 0.09 in. The weight breakdown for the three basic dish sizes is as follows:

<u>Size</u>	<u>Weight</u>
6 ft	105 lb
8 ft	125 lb
10 ft	240 lb

The above weight includes a mounting plate on the back of the dish. The feed system would add about 50 lb to the weight for a total of 290-300 lb in the case of the 10 ft antenna. This is the weight to be supported by the pedestal.

A hand crank elevation over azimuth pedestal with a three foot standoff, capable of handling the wind loads associated with the 10 ft dish in 30 mph winds, would weigh about 500 lb. This pedestal would have 0.1 deg pointing accuracy in azimuth and 0.15 deg for elevation. The pedestal and antenna would be capable of surviving 100 mph winds in the stow position with the antenna pointing at the zenith.

A light duty single axle flat bed trailer with the required rigidity and support jacks supplied would cost approximately 4000 dollars. This would greatly aid the mobility feature required of the system. Due to clearance problems and to prevent damage, the feed system and the antenna would be detached from the pedestal during the transporting phase. Containers could be built on to the trailer to house and protect the detached subassemblies while moving from site to site.

During the design phase there would be required about one man-month of integration setup and testing time. The total material cost if the trailer is utilized, would be about 16 K dollars for the antenna system.

4.5 Equipment Performance Specifications

To complete this section on ground equipment design, preliminary specifications are given to show equipment performance desired. The specific frequencies at which the equipment most operate have been selected from the presently designated ground-spacecraft communications and space research bands in accordance with the ITU October 1963 Extraordinary Administrative

Radio Conference (EARC) standards. The specific frequencies at which the RF equipment should operate are:

<u>Nominal Frequency</u>	<u>Actual Band</u>
8 Gc	8.40 - 8.50 Gc
16 Gc	15.25 - 15.35 Gc
35 Gc	34.2 - 35.2 Gc
94 Gc	93.0 - 95.0 Gc

The operating environment for all equipment is considered to be laboratory conditions with temperature variance of $+65^{\circ}\text{F}$ to $+85^{\circ}\text{F}$. The equipment should be assembled with good commercial practices to withstand normal handling. Shock sensitive items shall be adequately protected. All high voltage components shall be properly shielded. Any necessary cooling of components shall be self-contained. In non-operating conditions the equipment should be capable of surviving $+10^{\circ}\text{F}$ to 120°F .

4.5.1 Preliminary Specification for Signal Sources

4.5.1.1 General

The signal sources must provide boresight signals for antenna alignment and beam pattern measurements and also AM and FM modulated signals for communication experiments. The equipment design shall be based on the concept of interchangeable RF heads and a common power supply, master oscillator and modulating signal generator.

4.5.1.2 Frequency Specifications

The frequency stability of each RF source shall be determined by direct frequency measurement with master clock standards and frequency translation techniques. The long and short term stabilities of each frequency are as follows.

<u>Frequency Band (Gc)</u>	<u>Long Term (1 day)</u>	<u>Short Term (0.1 sec)</u>
8	1×10^6	1×10^7
16	1×10^6	1×10^8
35	1×10^6	1×10^9 design goal
94	1×10^6	1×10^9 design goal

The spectral purity of each RF sources is considered to be of prime importance. Under CW operation the spurious signals shall not exceed the following values:

<u>Frequency Band (Gc)</u>	<u>Spurious AM below Carrier into 100 cps bw (10 kc-100 kc)</u>	<u>Spurious FM below carrier in 100 cps bw (1 kc - 100 kc)</u>
8	110 db	1.5 cps rms
16	110 db	2.0 cps rms
35	100 db design goal	4.0 cps rms design goal
94	90 db design goal	10.0 cps rms design goal

4.5.1.3 Power Output

The minimum power output at each frequency shall be at least one watt. The output level shall be controlled by a manually variable attenuator.

Output power stability shall be accomplished through Automatic Level Control (ALC) circuits which maintain the following short and long term stability for each frequency.

<u>Frequency</u>	<u>Long Term (8 hrs)</u>	<u>Short Term (1 min.)</u>
8	± 1.0 db	± 0.5 db
16	± 1.0 db	± 0.5 db
35	± 1.0 db	± 0.5 db
94	± 1.5 db	± 0.7 db

4.5.1.4 Modulation Capabilities

The transmitter system shall be capable of transmitting AM double sideband signals with modulation frequency variable from dc to 50 mc. The modulation shall be variable from 0 to 80 percent. In addition, an FM modulation capability shall be provided with a variable bandwidth from 1 mc to 50 mc with 1 mc to 100 mc as a design goal. The index of modulation shall be variable from 1.0 to 4.0.

4.5.2 Preliminary Specification for Main Receivers

4.5.2.1 General

The receiver system performs a dual function in the main antenna facility. At each of the specified frequencies it shall be capable of receiving communication signals and shall be capable of making correlative radiometric measurements. It shall be capable of being modified to perform an automatic tracking function on the incoming communication signals. The receiver shall be designed such that change in frequency of operation can be accomplished through the use of interchangeable RF heads which interface with common communication and radiometric receiver packages. The signal measurements, using a phase lock type of communication receiver are made simultaneously with the radiometric measurements, using a band integrating type of radio-meter. The communication receiver is followed by a signal processing equipment to provide amplitude, phase and frequency measurements on the modulation specified in Section 4.5.1.

4.5.2.2 Communication Receiver

The communication receiver shall have an RF pre-detection bandwidth of at least 100 mc and a capability of introducing pre-detection bandwidth reduction through the use of selectable filter networks in order to optimize signal-to-noise ratio to the signal processor section.

The first local oscillator should be operated as a phase lock (carrier) system and/or a clock reference system. The phase lock loop bandwidth shall be optimized for the combined stabilities at the transmitter and receiver local oscillator.

The noise figure at each of the specified operating frequencies shall be as follows:

<u>Frequency Band (GC)</u>	<u>Noise Figure (db)</u>
8	9.5
16	11.0
35	14.0
94	19.0

The signal processor section must be capable of providing phase and amplitude measured on the AM sidebands over the full modulation capability of the signal sources as specified in Section 4.5.1. In addition, the signal processor will incorporate an FM discriminator capable of detecting the impressed modulation. This device shall have selectable pre-detection bandwidth filters and a variable discriminator slope. In addition, attention should be given to the possible introduction of PAM and PAM/FM demodulation equipments.

4.5.2.3 Radiometer Receiver

The output of the radiometer receiver shall have selectable post-detection integration time constant variable from 0.1 sec. to 10.0 sec. and should be capable of driving a conventional strip chart recorder.

The system should have noise tube calibration, a reference load and a reference horn. It shall be capable of being used for lobe switching radiometry.

The radiometer sensitivity at each of the specified frequency bands shall be as follows:

<u>Frequency Band (Gc)</u>	<u>Differential Temperature Sensitivity (°Kelvin)</u>	<u>Integration Time (1.0 sec)</u>
8	0.4	1.0
16	0.8	1.0
35	1.0	1.0
94	1.5	1.0

4.5.3 Preliminary Specification for Spacecraft Simulator*

4.5.3.1 General

A spacecraft simulator shall be provided which performs the same functions as those provided by the spacecraft payload. This unit will be located at a remote boresite location and used for pre-test and post-test calibration and check-out of the equipment in the main facility.

4.5.3.2 Frequencies of Operation

This equipment shall be capable of transmitting signals at 16 Gc and 35 Gc and shall be capable of receiving 94 Gc signals.

The frequency stability of each RF source shall be determined by direct frequency measurement with master clock standards and frequency translation techniques. The long and short term stabilities of each frequency are as follows:

<u>Frequency Band (Gc)</u>	<u>Long Term (1 day)</u>	<u>Short Term (0.1 sec)</u>
15	1×10^6	1×10^8
35	1×10^6	1×10^9 design goal
94	1×10^6	1×10^9 design goal

* The engineering model of the space flight hardware can be used as one of the simulators. These simulators may, or may not, have 94 Gc Receivers depending upon the facility with which they operate.

The spectral purity of each RF source is considered to be of prime importance. Under CW operation the spurious signals shall not exceed the following values:

<u>Frequency Band (Gc)</u>	<u>Spurious AM below carrier into 100 cps bw (10 kc-100 kc)</u>	<u>Spurious FM below carrier in 100 cps bw (1 kc-100 kc)</u>
15	110 db	2.0 cps rms
35	100 db design goal	4.0 cps rms design goal
94	90 db design goal	10.0 cps rms design goal

4.5.3.3 Transmitter Power Output

The minimum power output at each frequency shall be at least one watt. The output level shall be controlled by a manually variable attenuator.

Output power stability shall be accomplished through Automatic Level Control (ALC) circuits which maintain the following short and long term stability for each frequency.

<u>Frequency (Gc)</u>	<u>Long Term (8 hrs.)</u>	<u>Short Term (1 min.)</u>
15	± 1.0 db	± 0.5 db
35	± 1.0 db	± 0.5 db
94	± 1.5 db	± 0.7 db

4.5.3.4 Modulation Capabilities

The simulator shall be capable of receiving and transmitting CW and AM double sideband signals with modulation frequency variable from dc to 50 mc. The modulation shall be variable from 0 to 80 percent.

4.5.3.5 Communication Receiver

The 94 Gc receiver second local oscillator shall operate as a phase lock (carrier) system.

The 94 Gc receiver signal processor shall perform amplitude measurements on the carrier and relative amplitude and relative phase measurements between the two AM sidebands.

4.5.4 Preliminary Specification for Auxiliary Receiver

4.5.4.1 General

The auxiliary receiver system shall be capable of receiving communication signals and shall be capable of making correlative radiometric measurements. The receiver shall be designed such that change in frequency of operation can be accomplished through the use of interchangeable RF heads which interface with common communication and radiometric receiver packages. The signal measurements, using a phase lock type of communication receiver are made simultaneously with the radiometric measurements, using a band integrating type of radiometer. The communication receiver is followed by signal processing equipment to provide amplitude, phase and frequency measurements on the modulation specified in Section 4.5.1. This system shall include an antenna-pedestal subsystem which is capable of being pointed at a synchronous stationary satellite for the purposes of receiving communication signals. This auxiliary system shall be capable of being transported by and operated on a flatbed trailer.

4.5.4.2 Communication Receiver

The communication receiver shall have an RF pre-detection bandwidth of at least 100 mc and a capability of introducing pre-detection bandwidth reduction through the use of selectable filter networks in order to optimize signal-to-noise ratio to the signal processor section.

The first local oscillator should be operated as a phase lock (carrier) system and/or a clock reference system. The phase lock loop bandwidth shall be optimized for the combined stabilities at the transmitter and receiver local oscillator.

The noise figure at each of the specified operating frequencies shall be as follows:

<u>Frequency Band (Gc)</u>	<u>Noise Figure (db)</u>
16	11.0
35	14.0

The signal processor shall be capable of providing amplitude measurements on a CW carrier and shall be capable of being modified to provide relative amplitude and relative phase measurements between two AM sidebands.

4.5.4.3 Radiometer Receiver

The output of the radiometer receiver shall have selectable post-detection integration time constant variable from 0.1 sec. to 10.0 sec. and should be capable of driving a conventional strip chart recorder.

The system should have noise tube calibration, a reference load and a reference horn. It shall be capable of being used for lobe switching radiometry.

The radiometer sensitivity at each of the specified frequency bands shall be as follows:

<u>Frequency Band (Gc)</u>	<u>Differential Temperature Sensitivity (°Kelvin)</u>	<u>Integration Time (1.0 sec)</u>
16	0.8	1.0
35	1.0	1.0

4.5.4.4 Antenna-Pedestal System

The antenna-pedestal system shall be Cassegrain capable of operating at frequencies of 16 Gc and 35 Gc with interchangeable RF receiver heads and feed systems.

The parabolic reflector shall be 10 ft in diameter.

The surface tolerances of the parabolic reflector shall be 0.02 in. rms.

The gain of the antenna shall be 51 db at 16 Gc and 58 db at 35 Gc.

The beamwidth of the antenna at the half power point shall be 0.17 deg at 16 Gc and 0.08 deg at 35 Gc.

The sidelobes of the antenna shall be -20 db with respect to the main beam at frequencies of 16 Gc and 35 Gc.

The pedestal shall be designed for manual operation and shall be capable of indicating the position of the antenna within ± 0.1 deg in azimuth and ± 0.15 deg in elevation. The pedestal design shall allow the antenna to be pointed in any direction within 0 to 360 deg in azimuth and -2 to 90 deg in elevation. Optical instrumentation shall be provided for boresighting purposes.

The antenna-pedestal system shall be capable of being manually operated in 30 mph winds. It shall be capable of surviving 100 mph winds in a stowed position.

A receiver compartment shall be provided in the antenna support structure behind the reflector and shall be capable of housing an interchangeable RF receiver head. The RF receiver head shall be connected by ordinary cable to the IF receivers which are remote from the pedestal.

The antenna-pedestal system shall be operated from a flat bed trailer for purposes of transportability from one location to another with a moderate amount of set-up and tear down time.

5. SIGNAL PROCESSING

This section describes the signal processors which are used to transfer the phase and amplitude information contained in the received signals to analog storage on tape. A signal flow analysis is also given which describes the energy spectrum at all points in the communication channel from the transmitter modulator to the phase and amplitude detectors in the signal processor. A signal level analysis is also given which shows the signal-to-noise ratios at major points in the receivers and signal processors. This signal level analysis is related to elevation angle of the ground terminal line-of-sight with the satellite and the weather models established. Finally, using the links established in Section 2.2 "Orbital Analysis", which are based on assumed positions of the Synchronous ATS satellites, an evaluation is made on their value in the propagation data collection program.

5.1 Signal Processor Configuration

Before signal flow and signal level analyses are presented, the block diagrams for the satellite and ground signal processors in Figures 5-1 and 5-2 are discussed. The two signal processor configurations to be implemented for this experiment, one for the 94 Gc receiver in the satellite, and a second more sophisticated configuration to be used for all frequencies at the ground stations, are compatible with the amplitude modulated test waveform with modulation frequencies of approximately 5 kc, 10 mc and 50 mc.

The signal processor interfaces directly with the phase-locked receiver in the IF communications receivers which were illustrated in Figures 3-1 and 4-1 of Sections 3 and 4. The phase-locked receiver translates the received energy spectrum down to the second IF frequency of 66 mc and removes the effects of doppler and any transmitter and receiver frequency source instability that are associated with the carrier frequency.

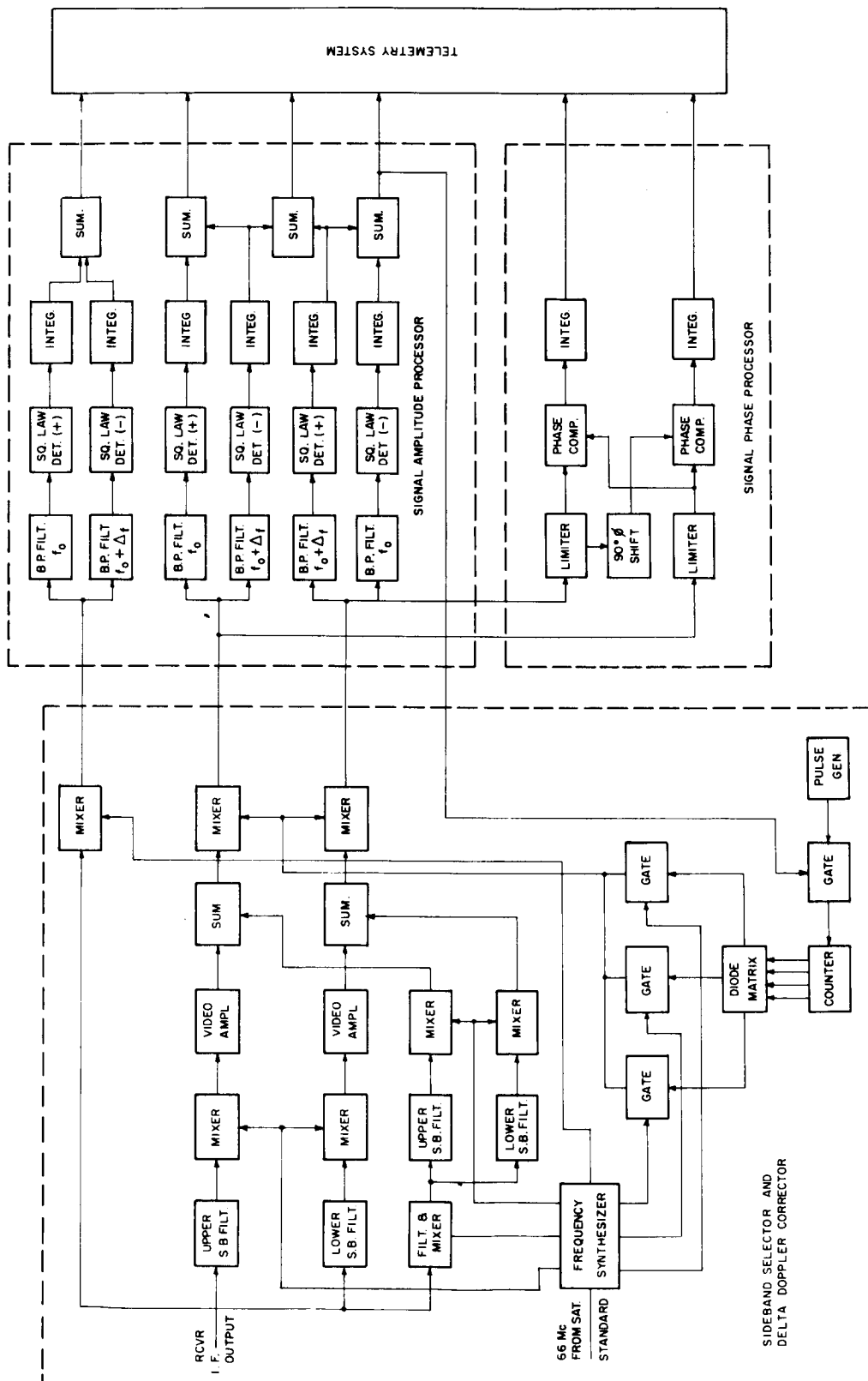


Figure 5-1. Satellite Signal Processor

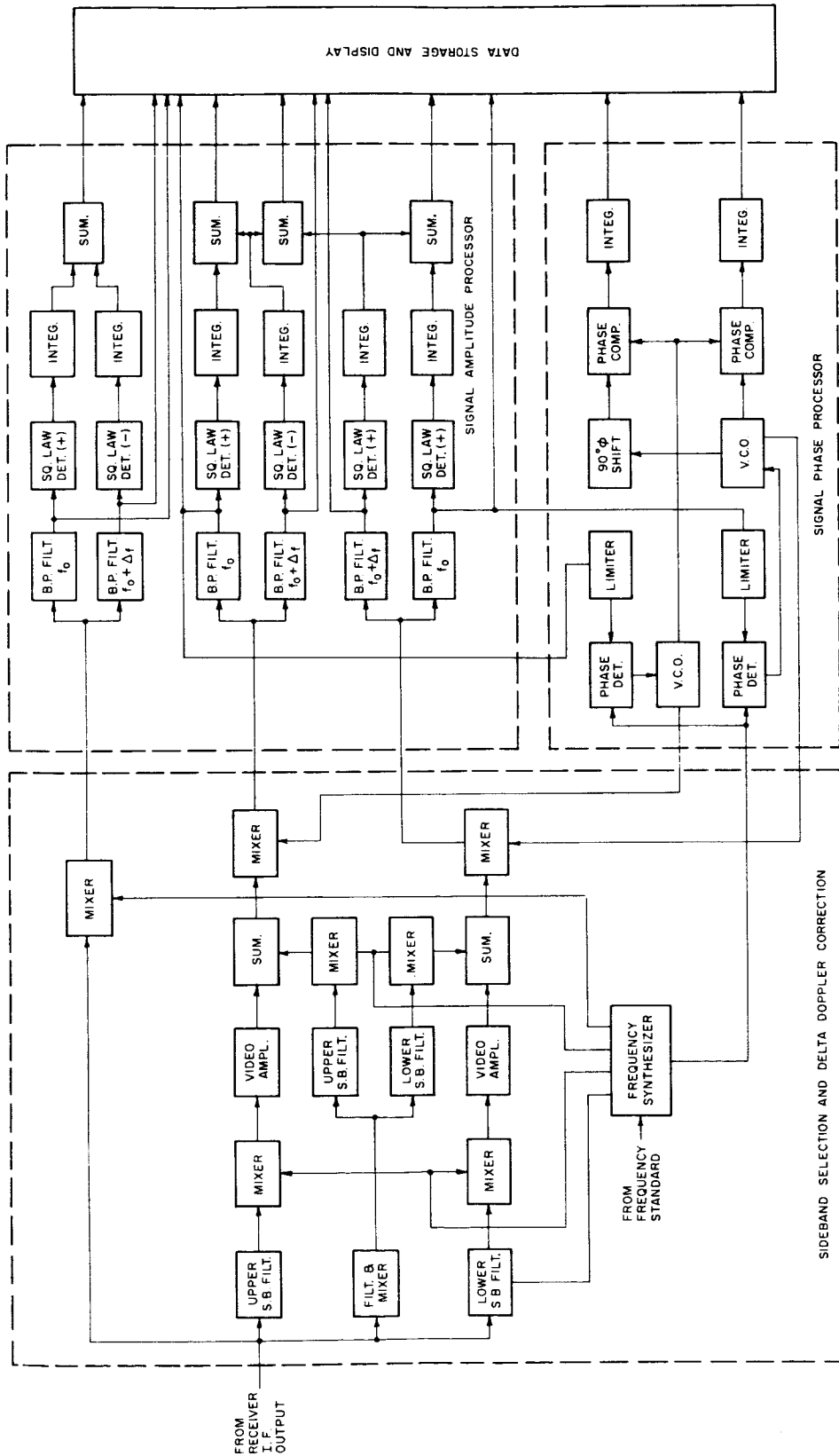


Figure 5-2. Ground Signal Processor

5.1.1 Sideband Selection and Delta Doppler Correction

The energy in the received signal spectrum which is centered at 66 mc is separated into three distinct channels. The first of these channels, the upper sideband channel, begins with the upper sideband energy being amplified while all other energy is attenuated by the upper sideband filters. This energy is then transferred to a mixer in which the local oscillator is at 66 mc and the output, which is the lower conversion product, is selected by the video amplifier. This lower conversion product is the modulation frequency plus the delta doppler and any phase shift due to the communication channel. This energy due to the upper sideband is transferred through a summation network to a second mixer, the function of which is to translate this energy to a convenient frequency (10.7 mc) for predetection filtering and signal phase and amplitude processing.

The second channel, the lower sideband channel, performs the same processing as the first channel and translates the energy in the lower sideband to 10.7 mc. The third and last channel consists of a single mixer which translates the 66 mc carrier directly to 10.7 mc for additional processing.

This sideband selection and delta doppler correction process is readily implemented when the modulation frequency is 10 mc or 50 mc, however, for the case of the 5 kc modulation frequency, the received signal at 66 mc must be translated to a much lower frequency, namely, 6.6 mc, to perform the desired sideband separation. The sidebands are each translated to a center frequency equal to the modulation frequency and then inserted back into the higher modulation frequency channels through the summation networks.

In the ground receiver signal processors, the second mixer which translates each sideband to 10.7 mc is part of a phase locked loop which contains a voltage controlled oscillator narrowed to 500 cps since the phase-locked loops cancel the delta doppler and any modulation frequency errors. All frequencies required for the translating functions are derived from the 66 mc frequency standard in the ground receiver. The fixed modulation frequencies

(5 kc, 10 mc and 50 mc) dictates the values of the three frequencies required for the final translation to 10.7 mc. These three frequencies are applied manually to the second mixers in sequence and, in the event a signal appears at the output of the signal amplitude processor, the sequence is halted since the correct local oscillator frequency is selected. In the satellite receiver, these three frequencies are applied automatically.

5.1.2 Signal Amplitude Processing

The signal amplitude processor generates four data outputs which are directly proportional to the carrier power, the upper sideband power, the lower sideband power, and the differential gain of the upper and lower sideband channels.

The energy in the carrier channel is band limited and detected with a square law device, thus generating an output proportional to the input power. At low values of signal-to-noise ratio, the detected output, due to the noise power, would be in the same order of magnitude as the portion of the output due to the signal power. This DC voltage at the output of the detector, due to the input noise power, is eliminated by summing the same noise power at a frequency displaced from the signal which is provided by another square law detector with opposite polarity output. This configuration is the same for both the upper and lower sideband outputs. An additional summation network is utilized to monitor the differential gain in the two channels. All five outputs are fed directly to the analog recording system.

5.1.3 Signal Phase Processing

In the ground receivers, phase must be determined by comparing the outputs of the voltage controlled oscillators since all frequency and phase variations are removed from the signal channel in this phase-locked loop. The two VCO signals are compared in in-phase and quadrature phase detectors which provide voltage outputs which represent 0 to 360 deg of phase rotation. The output of the phase comparator is integrated and buffer amplified such that direct interfacing with the analog recording system is provided.

In the satellite receiver, the signals are received and processed through tuned hard limiter circuits which provide in-phase and quadrature signals for processing through dual phase comparators. This provides an output from 0 to 360 deg of phase information. The output of the phase comparator is integrated and buffer amplified such that direct interfacing with the telemetry link is provided for the spacecraft.

5.1.4 Analog Data Storage and Presentation

The analog recording system in the ground terminal includes a tape recorder which stores the data for non-real time analog to digital conversion and digital computation. An analog strip line recorder is also provided to present the data in real time for purposes of monitoring, calibration and early interpretation of the raw data.

In addition to recording post detection signals which represent signal power and relative phase, the outputs of predetection filters would be translated to a frequency much lower than the 10.7 mc and stored on the same tape recorder.

5.2 Signal Flow Analysis

The signal flow analysis will describe the energy spectrum at all points in the communication channel in which a change in the energy spectrum takes place. The satellite-to-ground channel will be analyzed in detail and then the ground-to-satellite channel will be discussed in terms of its significant differences.

5.2.1 Satellite to Ground

The communication channel is considered to include the propagating medium and all circuitry located in the transmission line, from the generation of the test waveform in the satellite transmitter to the output of the signal processor in the ground receivers.

The total power contained in an amplitude modulated waveform is the sum of the powers in the carrier, and all its sidebands. Conventional amplitude modulation techniques, in which active modulators are utilized, produce constant carrier power output, while the sideband power is a function of the modulation index. This additional power required for the sidebands was generated by the active modulator.

The modulators to be used in the transmitters will be of the passive type, and as such, are incapable of adding power. This type of device generates the amplitude waveform by varying the insertion loss of the carrier at the modulation frequency, thus a portion of the CW power is absorbed by the modulator.

An expression may be generated to describe the time function of the transmitted waveform, generated by a system with a passive modulator. The general voltage time function of an amplitude modulated waveform generated with an active modulator is expressed as:

$$e(t) = E_t \left[\sin \omega_o t + \frac{m}{2} \cos (\omega_o - \omega_m)t - \frac{m}{2} \cos (\omega_o + \omega_m)t \right] \quad (5-1)$$

where:

$e(t)$ = instantaneous amplitude of the transmitted signal

E_t = peak amplitude of the transmitted signal

m = modulation index

$\frac{\omega_o}{2\pi}$ = carrier frequency

$\frac{\omega_m}{2\pi}$ = modulation frequency

The voltage time functions of the waveforms resulting from both active and passive modulation techniques are described in Figure 5-3. The modulation index is defined as:

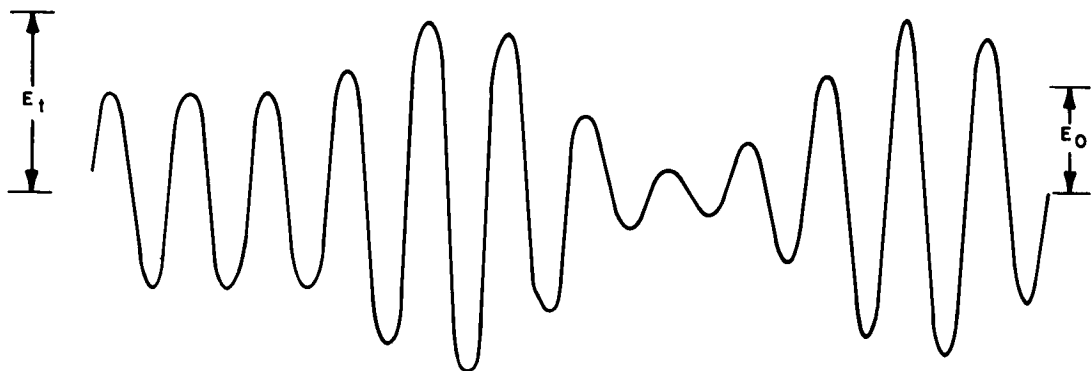
$$m = \frac{E_t - E_o}{E_o} \quad (5-2)$$

where:

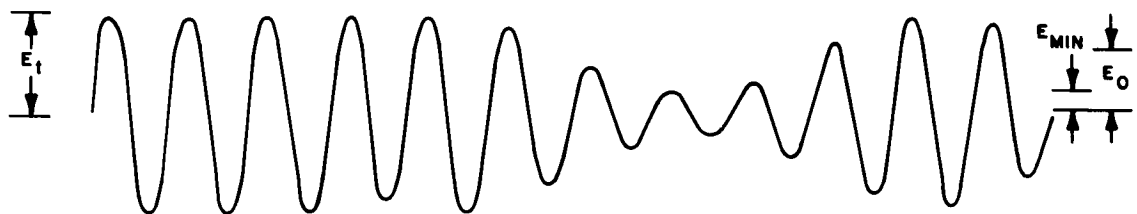
E_o = average envelope amplitude

The average envelope amplitude, assuming sine wave modulation may be defined as:

$$E_o = \frac{E_t + E_{\text{Min}}}{2} \quad (5-3)$$



A. AMPLITUDE MODULATED WAVEFORM GENERATED WITH ACTIVE MODULATOR



B. AMPLITUDE MODULATED WAVEFORM GENERATED WITH PASSIVE MODULATOR

Figure 5-3. Amplitude Modulated Waveforms

The voltage time function of the modulated waveform generated by a system utilizing a passive modulator is defined in terms of the above expression as:

$$e(t) = E_t \left[\frac{1}{1+m} \sin \omega_o t + \frac{m}{2} \cdot \frac{1}{1+m} \cos (\omega_o - \omega_m)t - \frac{m}{2} \cdot \frac{1}{1+m} \cos (\omega_o + \omega_m)t \right] \quad (5-4)$$

The degradation in the power of the carrier and one sideband, with respect to the carrier power at the modulator input are plotted in Figure 5-4. With a modulation index of 1.0, the power in the modulated carrier is 6 db below the unmodulated carrier power, and the power in each sideband is 12 db below the unmodulated carrier power.

To relate the signal represented by Equation (5-4) to the frequencies generated by the reference oscillator in the ground station the voltage time function is rewritten as:

$$e(t) = E_t \left[\frac{1}{1+m} \sin \{ (\omega_o + \Delta\omega_o)t + \phi_o \} + \frac{m}{2} \cdot \frac{1}{1+m} \cos \{ (\omega_o + \Delta\omega_o)t - (\omega_m + \Delta\omega_m)t + \phi_o - \phi_m \} - \frac{m}{2} \cdot \frac{1}{1+m} \cos \{ (\omega_o + \Delta\omega_o)t + (\omega_m + \Delta\omega_m)t + \phi_o + \phi_m \} \right] \quad (5-5)$$

$$\frac{\Delta\omega_o}{2\pi} = \text{carrier frequency error}$$

$$\frac{\Delta\omega_m}{2\pi} = \text{modulation frequency error}$$

$$\phi_o = \text{carrier phase relative to ground reference}$$

$$\phi_m = \text{modulation phase relative to ground reference}$$

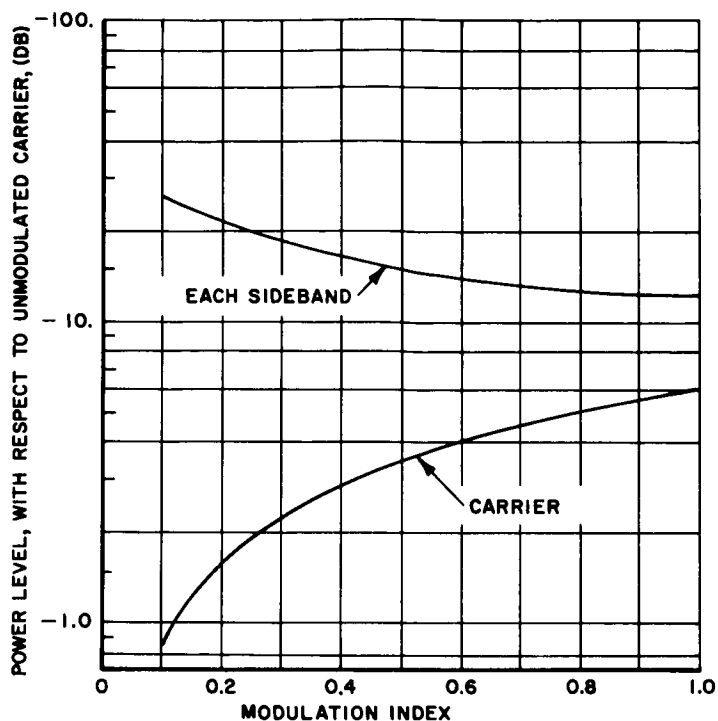


Figure 5-4. Sideband and Carrier Power vs Modulation Index

The power radiated in any given direction is defined as the product of the power at the antenna input and the gain of the antenna in that direction.

$$P_t(\theta) = P_j G(\alpha) \quad (5-6)$$

where:

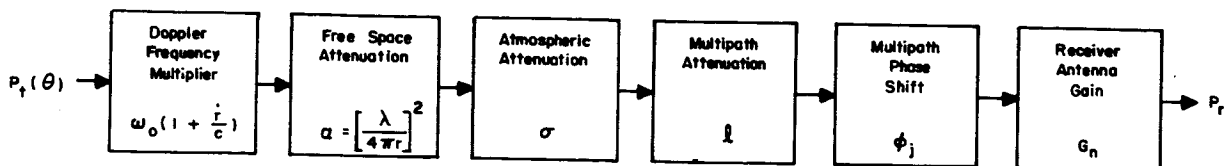
$P_t(\theta)$ = radiated power

P_j = power at input to antenna

$G(\alpha)$ = antenna gain as a function of angle α which is the satellite to ground line-of-site zenith angle at the satellite.

It has been assumed that the antenna gain is constant in the azimuth plane and it is expected that the angular uncertainty of the antenna beam axis with respect to the local satellite vertical is negligible.

The transmitted power spectrum will be altered in power, frequency, and phase by the intervening medium, slant range and relative velocity of the spacecraft. These characteristics are defined in the following diagram.



where:

r = slant range

$\dot{r}$ = radial range rate

c = velocity of light

λ = wavelength

$$e_r = e_{ro} - e_{ru} + e_{rl} = \text{received signal} \quad (5-7)$$

$$e_{ro} = \sqrt{\alpha \sigma l_o G_r} \frac{1}{1+m} E_t \sin \left[(\omega_o + \Delta \omega_o) t + \phi_o \right] \left(1 + \frac{\dot{r}}{c} \right) \quad (5-8)$$

$$e_{ru} = \sqrt{\alpha \sigma l_u G_r} \frac{m}{2(1+m)} E_t \cos \left\{ \left[(\omega_o + \Delta \omega_o) + (\omega_m + \Delta \omega_m) \right] t + \phi_o + \phi_m + \phi_\mu \right\} \left(1 + \frac{\dot{r}}{c} \right) \quad (5-9)$$

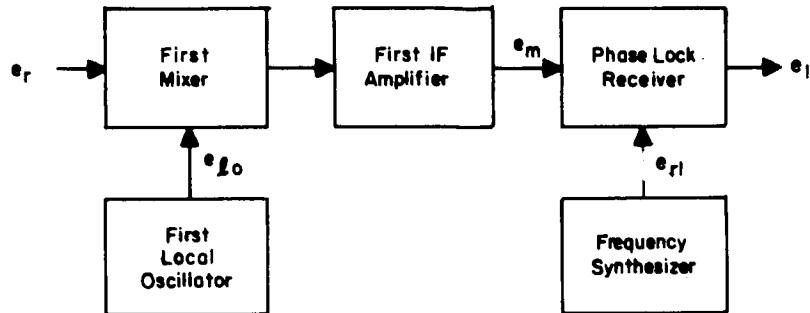
$$e_{rl} = \sqrt{\alpha \sigma l_e G_r} \frac{m}{2(1+m)} E_t \cos \left\{ \left[(\omega_o + \Delta \omega_o) - (\omega_m + \Delta \omega_m) \right] t + \phi_o - \phi_m + \phi_l \right\} \left(1 + \frac{\dot{r}}{c} \right) \quad (5-10)$$

where:

ϕ_u = upper sideband phase shift due to multipath relative to the carrier

ϕ_l = lower sideband phase shift due to multipath relative to the carrier

The received spectrum is first translated down to the first intermediate frequency using a local oscillator frequency which is not generated from the stable ground terminal reference oscillator.



The local oscillator time function is:

$$e_{lo} = E_{lo} \sin (\omega_o - \omega_1 - \Delta\omega_1)t$$

where:

$$\frac{\omega_1}{2\pi} = \text{first intermediate frequency}$$

$$\frac{\Delta\omega_1}{2\pi} = \text{first local oscillator frequency error}$$

$$e_m = e_{mo} - e_{mu} + e_{ml} = \text{first IF time function} \quad (5-11)$$

$$e_{mo} = \sqrt{a_o l_o G_r} \frac{1}{1+m} E_m \sin \left[(\omega_1 + \Delta\omega_1)t + \omega_o t \frac{\dot{r}}{c} + (\Delta\omega_o t + \phi_o) \left(1 + \frac{\dot{r}}{c}\right) \right] \quad (5-12)$$

$$e_{mu} = \sqrt{a\sigma\ell_u G_r} \frac{m}{2(1+m)} E_m \cos \left[(\omega_1 + \Delta\omega_1)t + \omega_o t \frac{\dot{r}}{c} + (\Delta\omega_o t + \omega_m t + \Delta\omega_m t + \phi_o + \phi_m + \phi_v)(1 + \frac{\dot{r}}{c}) \right] \quad (5-13)$$

$$e_{m\ell} = \sqrt{a\sigma\ell_\ell G_r} \frac{m}{2(1+m)} E_m \cos \left[(\omega_1 + \Delta\omega_1)t + \omega_o t \frac{\dot{r}}{c} + (\Delta\omega_o t - \omega_m t - \Delta\omega_m t + \phi_o - \phi_m + \phi_\ell)(1 + \frac{\dot{r}}{c}) \right] \quad (5-14)$$

Using the reference signal,

$$e_{r1} = E_{r1} \sin (\omega_2 + \Delta\omega_2)t \quad (5-15)$$

where:

$$\frac{\omega_2}{2\pi} = \text{second IF frequency}$$

$$\frac{\Delta\omega_2}{2\pi} = \text{frequency uncertainty relative to the final predetection filter.}$$

The energy in the carrier is now phase-locked to a frequency equal to the second intermediate frequency, thus eliminating the following components from the input expressions.

$$\Delta\omega_1 + \omega_o t \frac{\dot{r}}{c} + (\Delta\omega_o t + \phi_o)(1 + \frac{\dot{r}}{c})$$

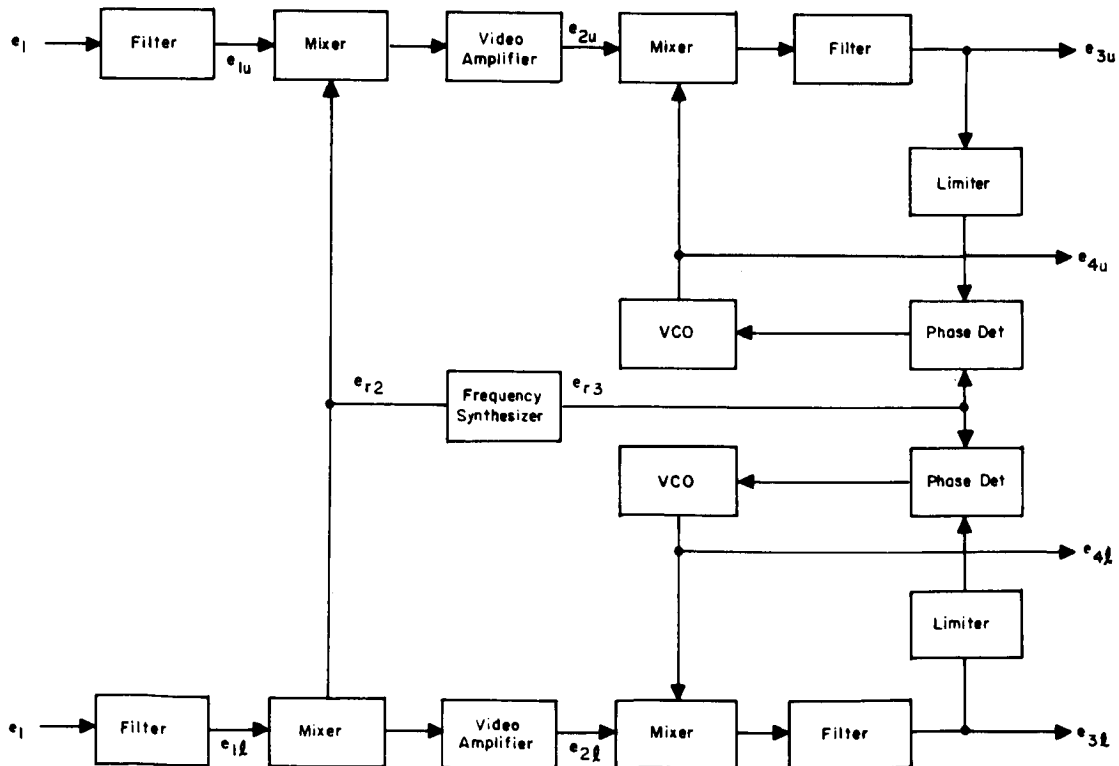
$$e_1 = e_{1o} - e_{1u} + e_{1\ell} = \text{phase-locked receiver output} \quad (5-16)$$

$$e_{1o} = \sqrt{a\sigma\ell_o G_r} \frac{1}{1+m} E_1 \sin (\omega_2 + \Delta\omega_2)t \quad (5-17)$$

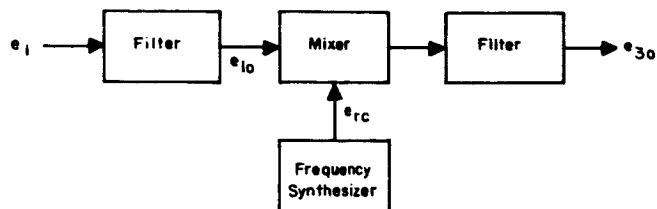
$$e_{1u} = \sqrt{a\sigma\ell_u G_r} \frac{m}{2(1+m)} E_1 \cos \left[(\omega_2 + \Delta\omega_2)t + (\omega_m t + \Delta\omega_m t + \phi_m + \phi_u)(1 + \frac{\dot{r}}{c}) \right] \quad (5-18)$$

$$e_{1l} = \sqrt{a\sigma\ell_l G_r} \frac{m}{2(1+m)} E_1 \cos \left[(\omega_2 + \Delta\omega_2)t - (\omega_m t + \Delta\omega_m t + \phi_m - \phi_l)(1 + \frac{\dot{r}}{c}) \right] \quad (5-19)$$

The carrier and the two sidebands are separated into their respective channels. The energy in both sidebands is simultaneously mixed with a frequency equal to the second intermediate frequency then translated up again to a convenient frequency ω_3 for post detection filtering.



The energy in the carrier is translated directly to ω_3 for post detection filtering.



The frequency synthesizer provides:

$$e_{r2} = E_{r2} \sin (\omega_2 + \Delta \omega_2) t \quad (5-20)$$

$$e_{r3} = E_{r3} \sin (\omega_3 + \Delta \omega_3 + \omega_m) t \quad (5-21)$$

$$e_{rc} = E_{rc} \sin (\omega_2 + \Delta \omega_2 - \omega_3 - \Delta \omega_3) t \quad (5-22)$$

where:

$$\frac{\omega_3}{2\pi} = \text{third IF frequency}$$

$$\frac{\Delta \omega_3}{2\pi} = \text{frequency uncertainty with respect to the final predetection filter.}$$

The video amplifier outputs in the two sideband channels are:

$$e_{2u} = \sqrt{a \sigma l_u G_r} \frac{m}{2(1+m)} E_2 \cos \left[(\omega_m + \Delta \omega_m) t + \phi_m + \phi_u \right] \quad (5-22)$$

$$\left(1 + \frac{\dot{r}}{c} \right)$$

$$e_{2l} = \sqrt{a\sigma l_l G_r} \frac{m}{2(1+m)} E_2 \cos \left[(\omega_m + \Delta\omega_m)t + \phi_m - \phi_l \right] \left(1 + \frac{\dot{r}}{c}\right) \quad (5-24)$$

The energy in the sidebands is now phase-locked to a frequency equal to e_{r3} , thus eliminating the following components from their input expressions so that the predetection filter bandwidth can be minimized:

$$(\Delta\omega_m t + \phi_m + \phi_u \text{ or } -\phi_l) \left(1 + \frac{\dot{r}}{c}\right) + \omega_m \frac{\dot{r}}{mc}$$

The output of the predetection filters which goes to the signal amplitude processors is:

$$e_{3o} = \sqrt{a\sigma l_o G_r} \frac{1}{1+m} E_3 \sin (\omega_3 + \Delta\omega_3)t \quad (5-25)$$

$$e_{3u} = \sqrt{a\sigma l_u G_r} \frac{m}{2(1+m)} E_3 \cos (\omega_3 + \Delta\omega_3)t \quad (5-26)$$

$$e_{3l} = \sqrt{a\sigma l_l G_r} \frac{m}{2(1+m)} E_3 \cos (\omega_3 + \Delta\omega_3)t \quad (5-27)$$

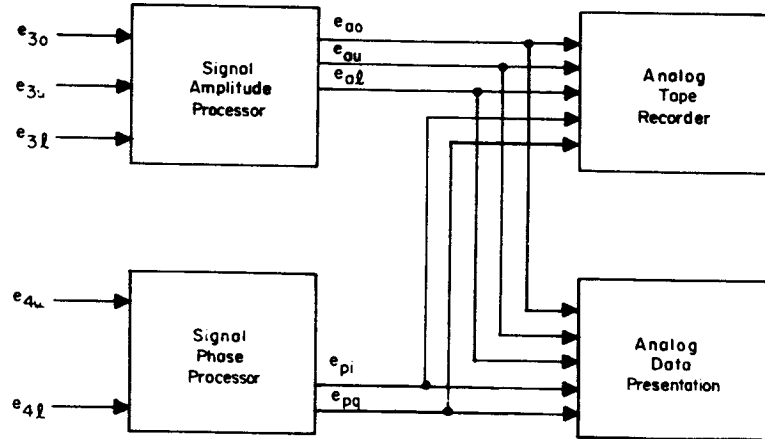
The third IF frequency error, $\Delta\omega_3$, determines the minimum predetection bandwidth. The specific values for minimum bandwidth will be discussed in the following section on signal level analysis.

The output of the voltage controlled oscillators contain the relative phase information of the sidebands which is derived by the signal phase processor. The sinusoidal VCO outputs are:

$$e_{4u} = E_4 \cos \left[(\omega_3 + \Delta\omega_3)t + (\Delta\omega_m t + \phi_m + \phi_u) \left(1 + \frac{\dot{r}}{c}\right) + \omega_m t \frac{\dot{r}}{c} \right] \quad (5-28)$$

$$e_{4l} = E_4 \cos \left[(\omega_3 + \Delta\omega_3)t + (\Delta\omega_m t + \phi_m + \phi_l)(1 + \frac{\dot{r}}{c}) + \omega_m t \frac{\dot{r}}{c} \right]$$

(5-29)



Voltages are recorded which represent the power variations of the carrier and the two sidebands. They are represented by:

$$e_{ao} = \alpha \sigma \ell_o G_r \left[\frac{1}{1+m} E_3 \right]^2 \quad (5-30)$$

$$e_{au} = \alpha \sigma \ell_u G_r \left[\frac{m}{2(1+m)} E_3 \right]^2 \quad (5-31)$$

$$e_{al} = \alpha \sigma \ell_l G_r \left[\frac{m}{2(1+m)} E_3 \right]^2 \quad (5-32)$$

Voltages are recorded which represent the relative in-phase and quadrature components of the two sidebands. They are represented by:

$$e_{pi} = 2\sqrt{e_u e_l \cos(\phi_u + \phi_l)(1 + \frac{\dot{r}}{c})} \quad 1 \gg \frac{\dot{r}}{c} \quad (5-33)$$

$$e_{pg} = 2\sqrt{e_u e_l \sin(\phi_u + \phi_l)(1 + \frac{\dot{r}}{c})} \quad 1 \gg \frac{\dot{r}}{c} \quad (5-34)$$

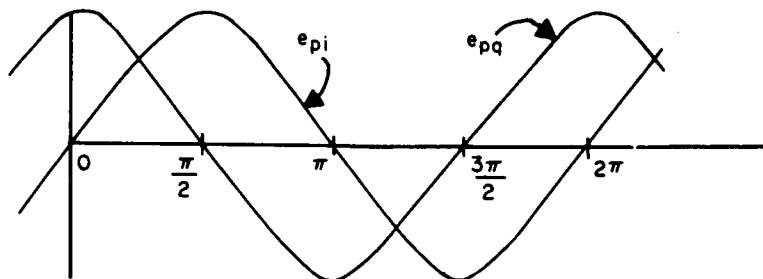
The above expressions can be simplified as follows:

$$e_{pi} \sim \phi_u + \phi_l \quad 0 \geq (\phi_u + \phi_l) \geq \frac{\pi}{4}, \quad \frac{7\pi}{4} \geq (\phi_u + \phi_l) \geq 0 \quad (5-35)$$

$$e_{pi} \sim -\phi_u - \phi_l \quad \frac{3\pi}{4} \geq (\phi_u + \phi_l) \geq \frac{5\pi}{4}$$

$$e_{pg} \sim \phi_u + \phi_l \quad \frac{5\pi}{4} \geq (\phi_u + \phi_l) \geq \frac{7\pi}{4}$$

$$e_{pg} \sim -\phi_u - \phi_l \quad \frac{\pi}{4} \geq (\phi_u + \phi_l) \geq \frac{3\pi}{4}$$



This completes the signal flow analysis for the 16 Gc and 35 Gc down-links from the spacecraft transmitter to the receiver analog tape recorder.

5.2.2 Ground to Satellite

The signal flow for the 94 Gc up-link differs in two key areas:

- 1) The ground transmitter final amplifier gain can be adjusted to compensate for the passive shunt modulator which is across the final amplifier input.
- 2) The satellite signal processor is less sophisticated in that it does not have phase-lock loops which operate on the two AM sidebands to remove delta doppler on the modulating frequency and the modulating frequency error. This simplification in circuitry comes at the expense of wider pre-detection bandwidth.

Instead of transmitting a waveform which is represented by Equation (5-4), the ground transmitter provides the following waveform:

$$e(t) = E_t \left[\frac{1}{\sqrt{1 + m^2/2}} \sin \omega_o t + \frac{m}{2} \frac{1}{\sqrt{1 + m^2/2}} \cos (\omega_o - \omega_m)t - \frac{m}{2} \frac{1}{\sqrt{1 + m^2/2}} \cos (\omega_o + \omega_m)t \right] \quad (5-36)$$

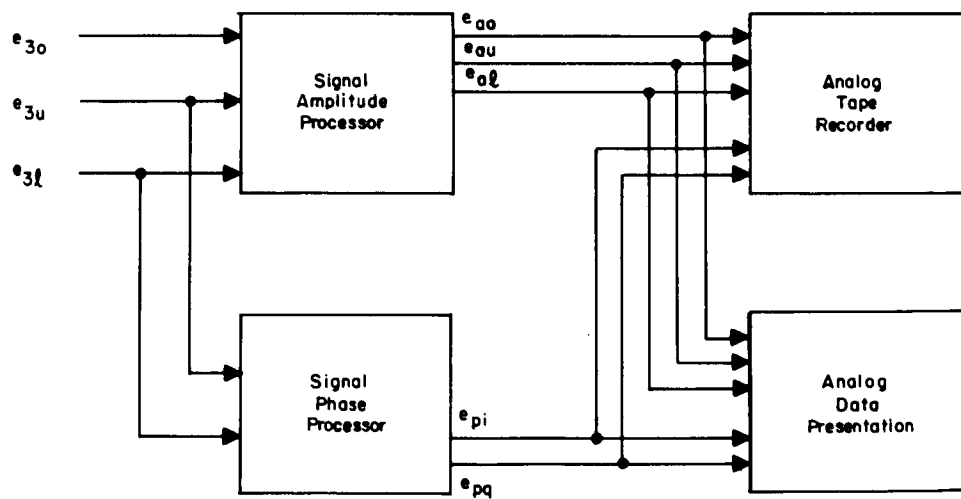
With a modulation index of 1.0 the power in the modulated carrier is 1.8 db below the unmodulated carrier power, and the power in each sideband is 7.8 db below the unmodulated carrier power.

Without the phase-lock loops, each of which consisted of a limiter, a phase detector and a VCO, Equations (5-25), (5-26) and (5-27) containing the signal amplitude information and Equations (5-28) and (5-29) containing the signal phase information no longer apply. The amplitude processor and the phase processor now have common inputs which represent the two sidebands.

$$e_{3o} = \sqrt{a\sigma\ell_o G_r} \frac{1}{\sqrt{1 + m^2/2}} E_3 \sin(\omega_3 + \Delta\omega_3)t \quad (5-37)$$

$$e_{3u} = \sqrt{a\sigma\ell_o G_r} \frac{m}{2\sqrt{1 + m^2/2}} E_3 \cos \left[(\omega_3 + \Delta\omega_3)t + (\Delta\omega_m t + \phi_m + \phi_u) \left(1 + \frac{\dot{r}}{c}\right) + \omega_3 t \frac{\dot{r}}{c} \right] \quad (5-38)$$

$$e_{3l} = \sqrt{a\sigma\ell_o G_r} \frac{m}{2\sqrt{1 + m^2/2}} E_3 \cos \left[(\omega_3 + \Delta\omega_3)t + (\Delta\omega_m t + \phi_m - \phi_l) \left(1 + \frac{\dot{r}}{c}\right) + \omega_m t \frac{\dot{r}}{c} \right] \quad (5-39)$$



The recorded voltages which represent the power variations of the carrier and the two sidebands are:

$$e_{ao} = a\sigma l_o G_r \left[\frac{1}{\sqrt{1+m^2/2}} E_3 \right]^2 \quad (5-40)$$

$$e_{au} = a\sigma l_o G_r \left[\frac{m}{2\sqrt{1+m^2/2}} E_3 \right]^2 \quad (5-41)$$

$$e_{al} = a\sigma l_l G_r \left[\frac{m}{2\sqrt{1+m^2/2}} E_3 \right]^2 \quad (5-42)$$

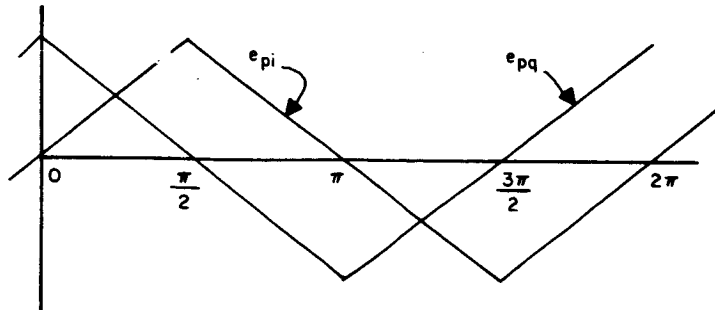
Since the inputs to the signal phase processor are limited, the recorded voltages which represent the relative in-phase and quadrature components of the two sidebands are:

$$e_{pi} \sim \phi_u + \phi_l \quad 0 \geq (\phi_u + \phi_l) \geq \frac{\pi}{2}, \quad \frac{3\pi}{2} \geq (\phi_u + \phi_l) \geq 2\pi \quad (5-43)$$

$$e_{pi} \sim -\phi_u - \phi_l \quad \frac{\pi}{2} \geq (\phi_u + \phi_l) \geq \frac{3\pi}{2}$$

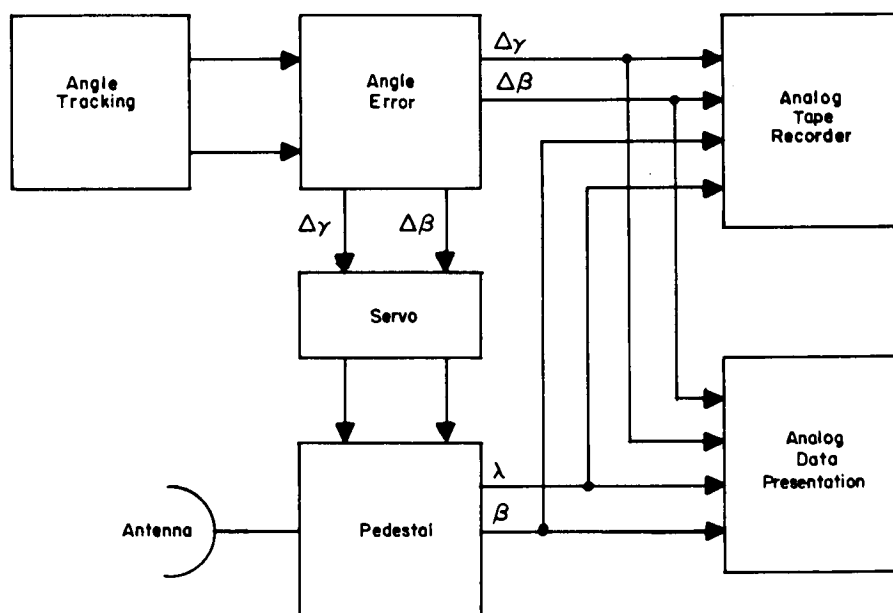
$$e_{pq} \sim \phi_u + \phi_l \quad \pi \geq (\phi_u + \phi_l) \geq 2\pi$$

$$e_{pq} \sim -\phi_u - \phi_l \quad 0 \geq (\phi_u + \phi_l) \geq \pi$$



The following section discusses the signal levels throughout the up-links and down-links just described. The non-real time data processing which is performed on the stored analog data is discussed in Section 6 "Data Processing."

Other items of information are recorded on the same analog type recorder and also presented on a strip line recorder. When using medium altitude satellites, azimuth and elevation data from the angle synchros on the antenna pedestal must be recorded and presented. For those ground stations that have tracking receivers which generate the short term azimuth and elevation angle fluctuations will also be recorded and presented.



γ = elevation angle
 β = azimuth angle
 $\Delta\gamma$ = elevators angle error
 $\Delta\beta$ = azimuth angle error

5.3 Signal Level Analysis

The signal levels and signal to noise ratios at major points in the signal processor are to be specified for each of the three communication channels. These anticipated signal and noise powers are functions of the system parameters and commence with the signal power at the receiver input.

5.3.1 Received Power

The power at the input to the receiver

$$P_R = \Phi A \quad (5-44)$$

where:

P_R = power at receiver input

Φ = flux density at receiver antenna

A = effective area of the receiver antenna

This flux density is the power flow through a unit area at the receiver antenna and is expressed as:

$$\Phi = \frac{P_T G_T}{4\pi R^2} \quad (5-45)$$

where:

P_T = input power to transmitter antenna

G_T = gain of transmitter antenna

R = distance between the transmitting and receiving antennas

The effective area of the receiving antenna is defined as:

$$A = \frac{G_R \lambda^2}{4\pi} \quad (5-46)$$

where:

G_R = gain of receiver antenna

λ = wavelength of received energy

Equations (5-45) and (5-46) when substituted into Equation (5-44) result in the following:

$$P_R = \left(\frac{P_T G_T}{4\pi R^2} \right) \left(\frac{G_R \lambda^2}{4\pi} \right) \quad (5-47)$$

Equation (5-47) may now be simplified to read:

$$P_R = P_T G_T G_R \sigma L \quad (5-48)$$

where:

σ = free space attenuation

L = polarization, and atmospheric losses

5.3.2 Free Space Attenuation

Free space attenuation is calculated as

$$\sigma = \left[\frac{\lambda}{4\pi R} \right]^2 \quad (5-49)$$

For a satellite directly over the ground station the free space attenuation is as shown in Table 5-I.

TABLE 5-I
FREE SPACE ATTENUATION FOR A SATELLITE
DIRECTLY OVER THE GROUND STATION

Frequency	16 Gc	35 Gc	94 Gc
Synchronous Satellite -db	207.8	214.6	223.2
6000 nmi Satellite -db	197.6	204.4	213.0

Slant range as a function of elevation angle for synchronous and 6000 nmi satellites is given in Figures 5-5 and 5-6. From these two curves relative free space attenuation versus elevation angle was computed and is shown in Figure 5-7.

5.3.3 Atmospheric Absorption

The atmospheric absorption used in this signal level analysis is based on the weather model established in Section 3 of the First Quarterly Report. The atmospheric absorption at 16 Gc, 35 Gc and 94 Gc which was computed from this weather model is given in Figures 5-8 through 5-10. Propagation fading losses due to multipathing is one of the key parameters which will be measured during the experiment.

5.3.4 Receiver Noise Density

The total noise energy at the receiver input is the sum of the noise generated from within the receiver and the noise energy impinging on the antenna due to the radiation from the earth in the case of the 94 Gc satellite receiver and radiation from the atmosphere in the case of the 16 Gc and 35 Gc ground receivers. The noise power density at the receiver input is expressed as:

$$N_c = K T_o (F L - 1) + K T_A \quad (5-50)$$

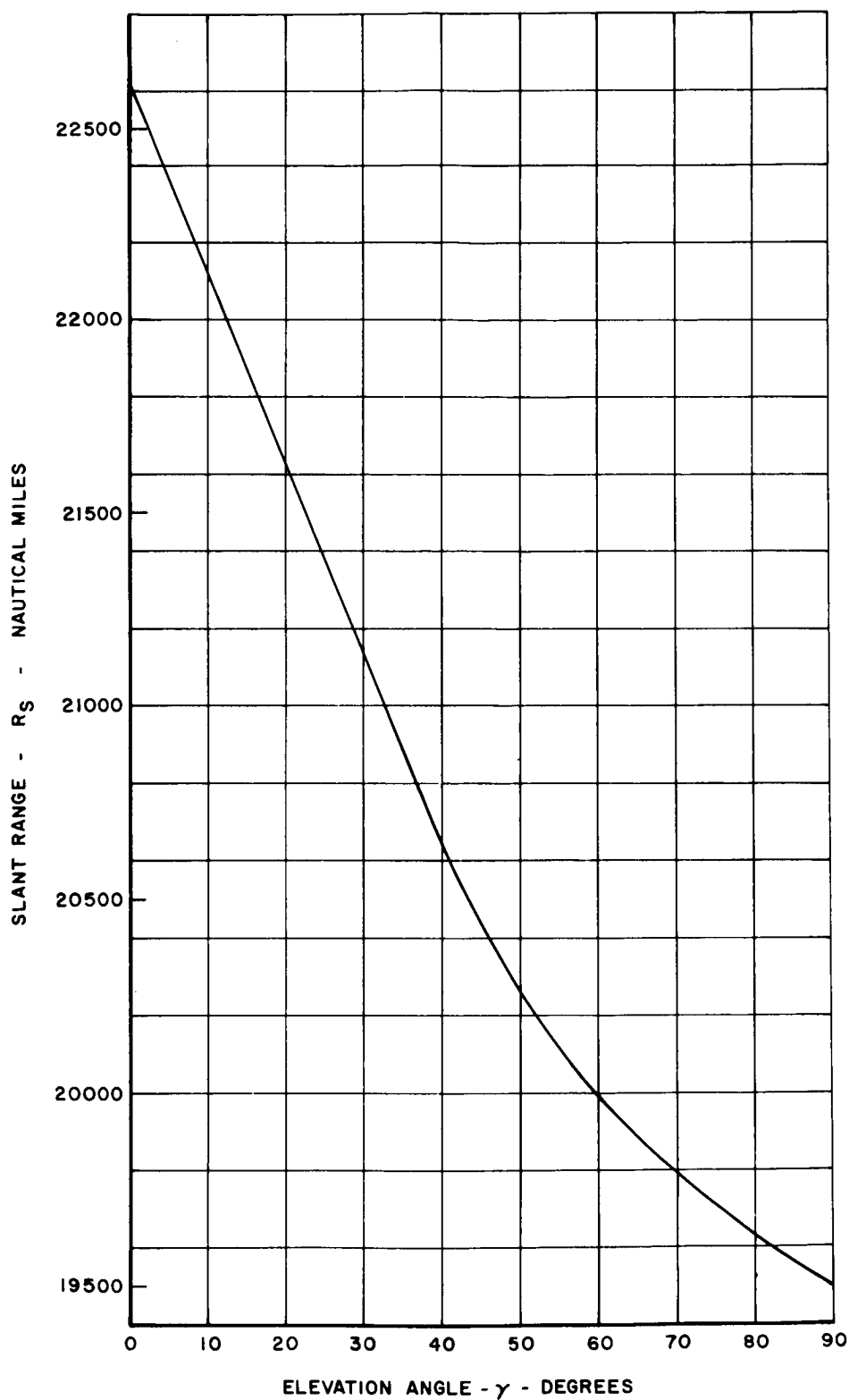


Figure 5-5. Slant Range vs Elevation Angle for a Synchronous Satellite

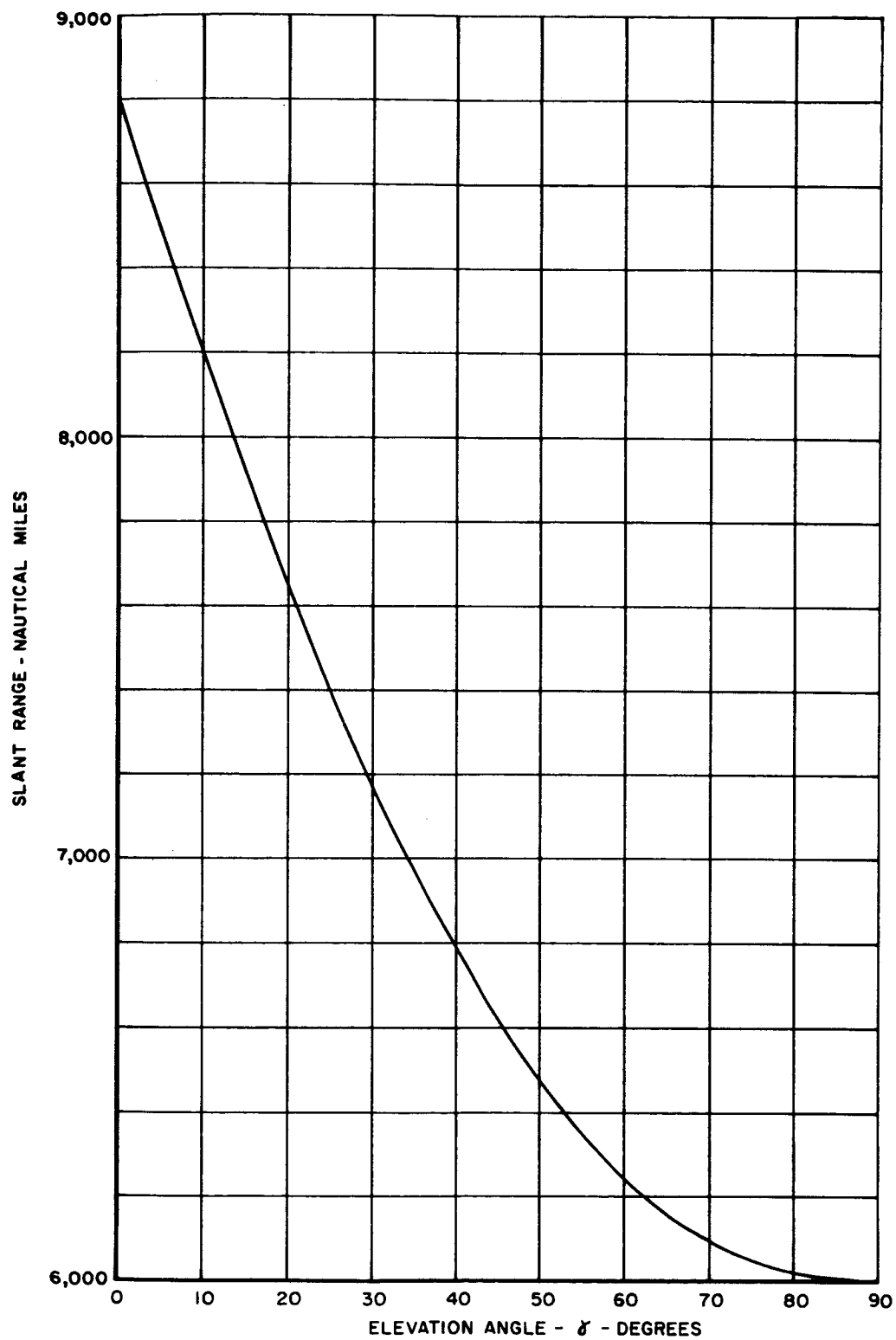


Figure 5-6. Slant Range vs Elevation Angle for a 6000 nmi Satellite

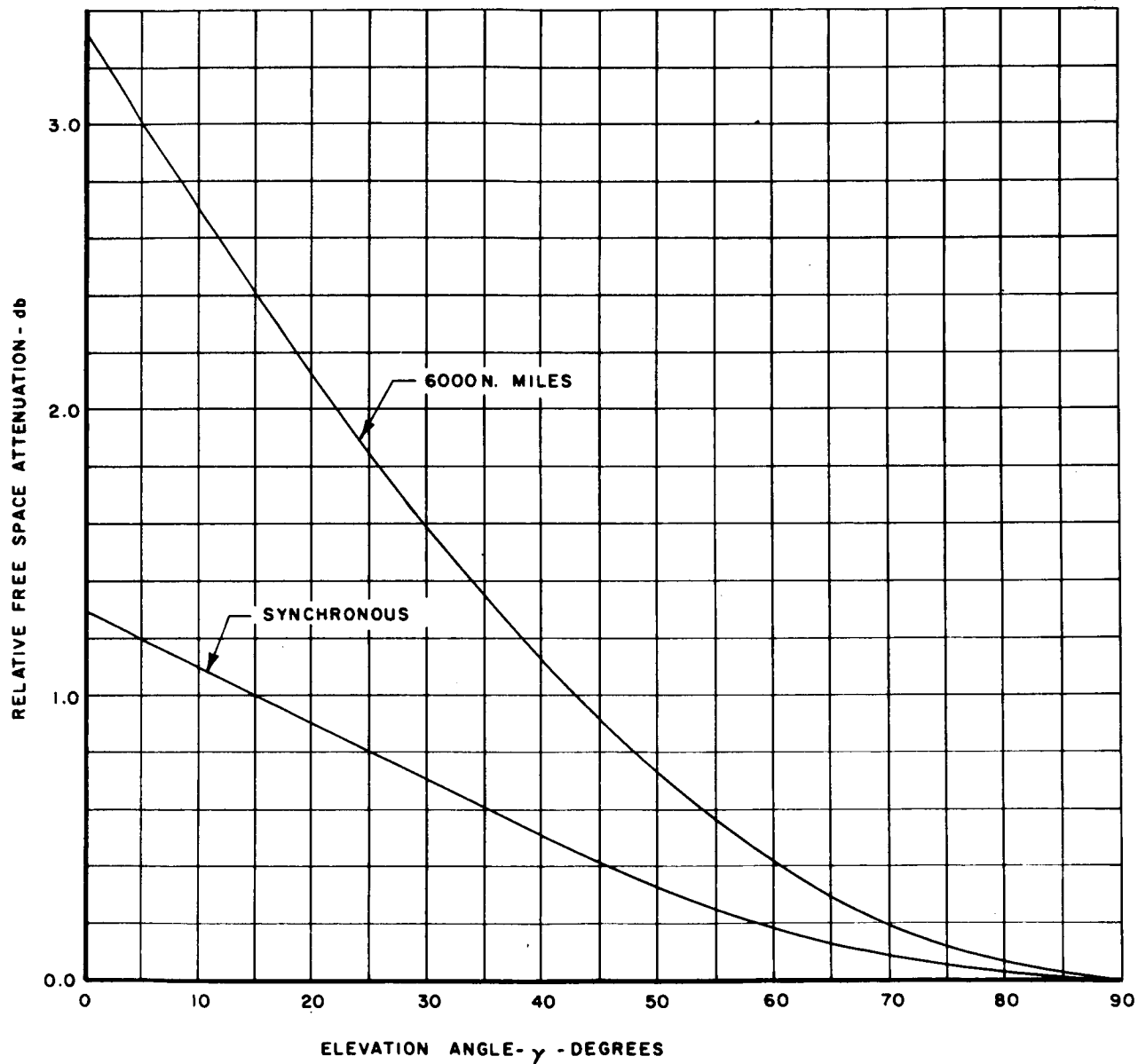


Figure 5-7. Relative Free Space Attenuation for Synchronous and 6000 nmi Satellites

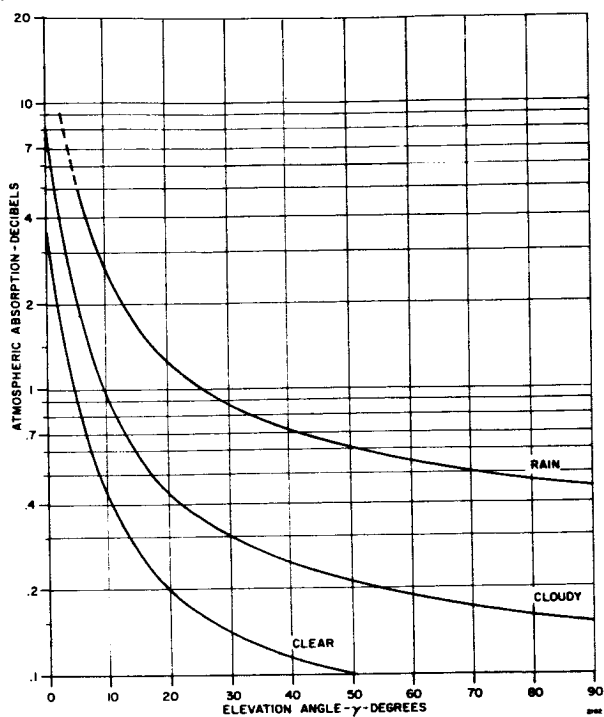


Figure 5-8. Atmospheric Absorption at 16 Gc

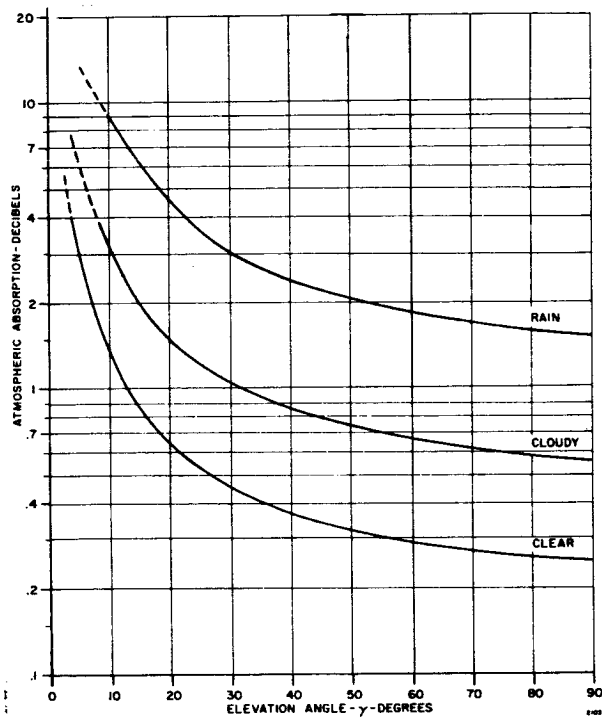


Figure 5-9. Atmospheric Absorption at 35 Gc

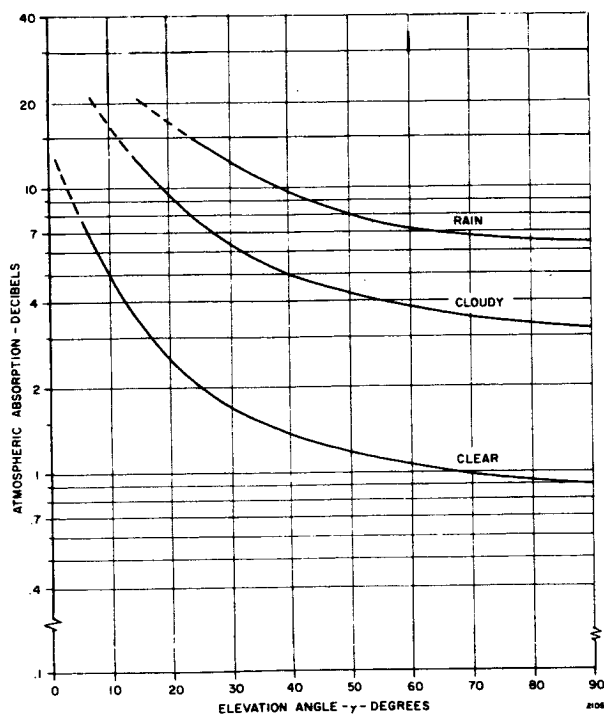


Figure 5-10. Atmospheric Absorption at 94 Gc

where:

- N_c = noise power per cycle bandwidth
- K = Boltzmann's constant = 1.38×10^{-23} watt-seconds/ $^{\circ}$ Kelvin
- T_o = ambient temperature of system
- F = receiver noise figure
- L = receiver signal losses prior to mixer
- T_A = effective antenna temperature

The effective temperature of the satellite antenna is given in Figure 5-11⁽¹⁾. Effective temperature of the ground antennas was derived in Section 3 of the First Quarterly Report and the results are repeated here in Figures 5-12 through 5-14 for 16 Gc, 35 Gc and 94 Gc. The antenna temperature is of interest mainly because it is a useful source of correlative data when making propagation measurements. As for receiver noise density, the receiver noise figures are so high: that is, 25 db for the 94 Gc satellite receiver, 15 db for the 35 Gc ground receiver and 12 db for the 16 Gc ground receiver; that the antenna temperature contribution is of little significance.

5.3.5 Predetection Bandwidth

As the predetection bandwidth is increased beyond that occupied by the signal spectrum, the signal-to-noise ratio naturally decreases. Equations (5-25) through (5-27) in Section 5.2 indicate that minimum predetection bandwidth in the receiver of a satellite-to-ground link is limited by the third IF frequency error $\frac{\Delta\omega_3}{2\pi}$. This error is a result of our inability to adjust the reference oscillator in the frequency synthesizer so that the third IF frequency is perfectly aligned with the specified center frequency of the predetection filters. Equation (5-21) of Section 5.2 represents the reference

(1) Reference 47 in First Quarterly Report.

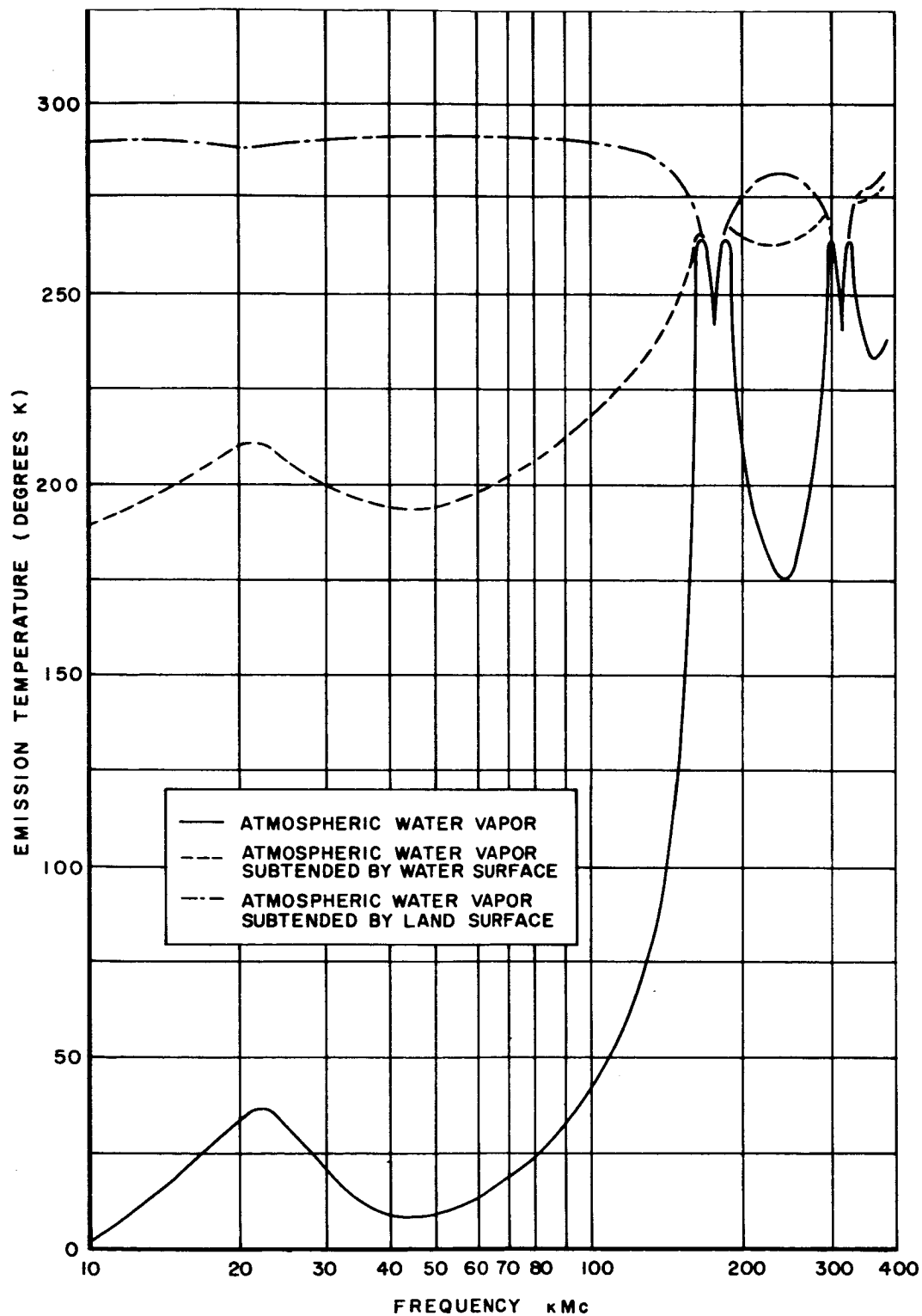


Figure 5-11. Calculated Emission Temperatures into Space from the Earth and its Atmospheric Water Vapor

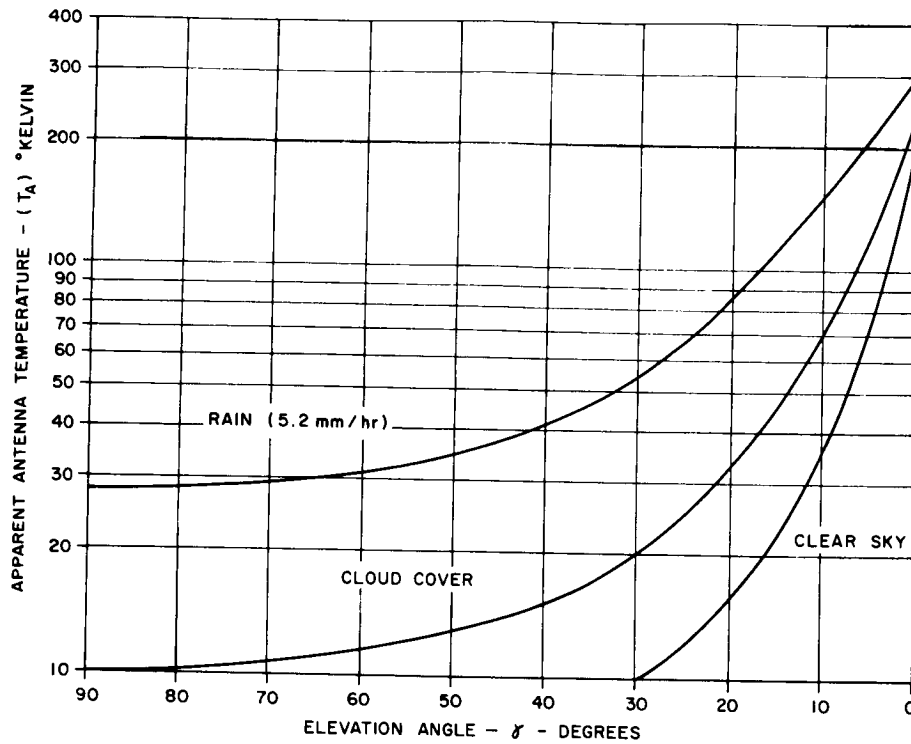


Figure 5-12. Apparent Temperature of the Atmosphere at 16 Gc

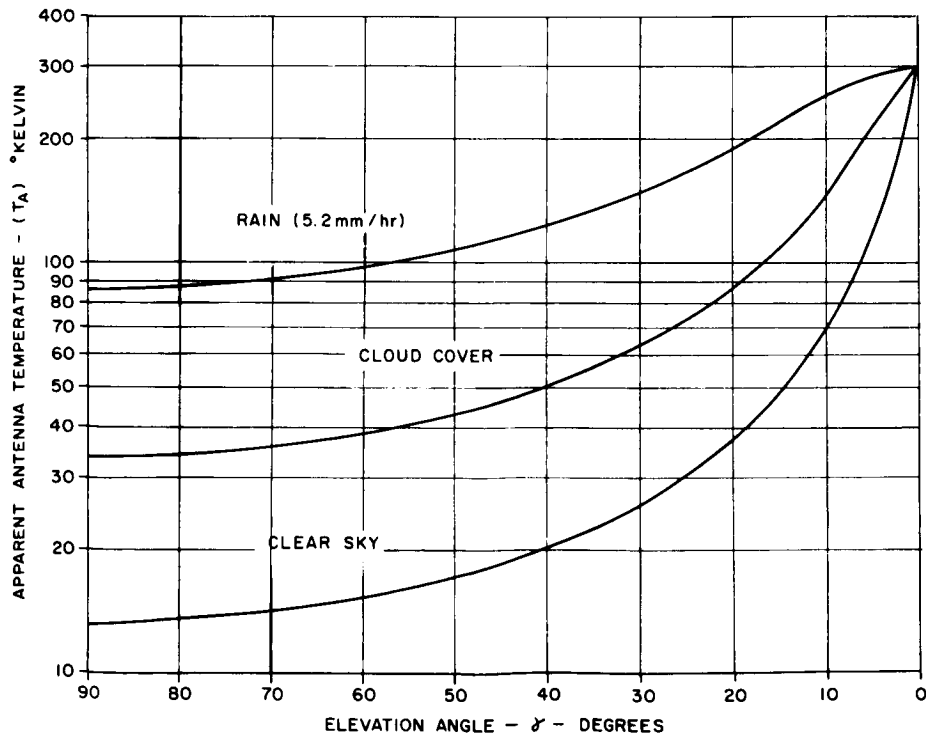


Figure 5-13. Apparent Temperature of the Atmosphere at 35 Gc

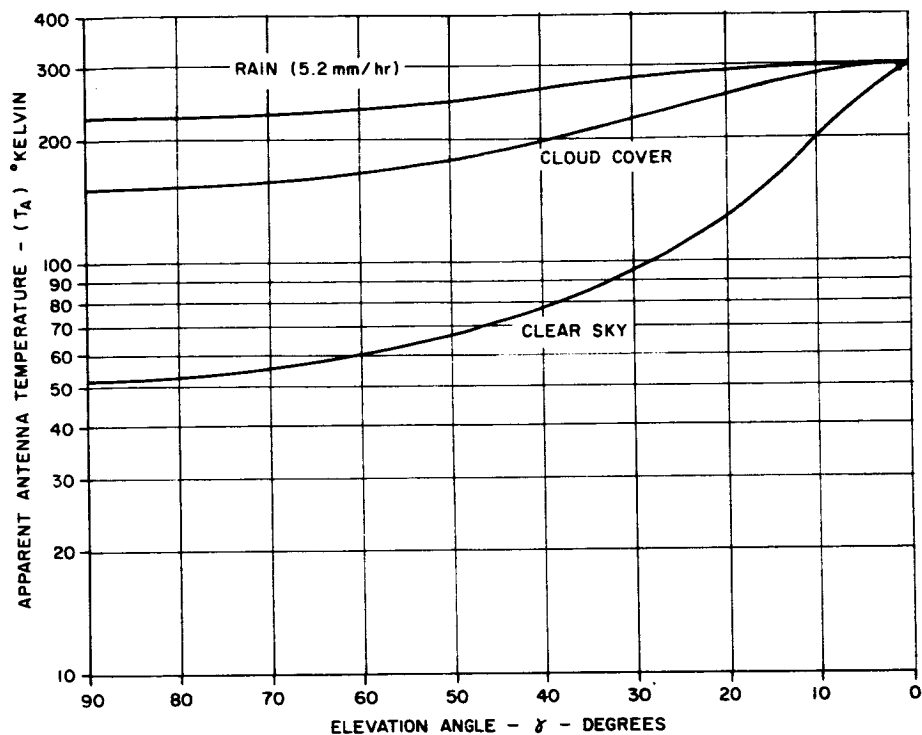


Figure 5-14. Apparent Temperature of the Atmosphere at 94 Gc

signal which is used in the phase-locked loops in the sideband channels. It is assumed that:

$$\frac{\Delta\omega_3}{2\pi} = (k_o + r_1 t) \left[\frac{\omega_3 + (\omega_m)_{\max}}{2\pi} \right] = 83 \text{ cps} \quad (5-51)$$

where k_o = initial adjustment error = 1×10^{-6}

r_1 = oscillator drift rate = $1 \times 10^{-9}/\text{day}$

t = period of drift = 365 days

ω_3 = third IF frequency = 10.7 Mc

$(\frac{\omega_m}{2\pi})_{\max}$ = maximum modulation frequency = 50 Mc

In addition to the above error, a second error $\frac{\Delta\omega_{\text{mfg}}}{2\pi}$ must be included which is a result of the filter manufacturer's inability to provide a center frequency equal to that which is specified. This error could be as much as 100 cycles.

Therefore, for synchronous and medium altitude satellite-to-ground links in which phase-locked loops are used in the sideband channels of the signal processor, the minimum predetection bandwidth is:

$$B_{\min} = 2 \left[\frac{\Delta\omega_3}{2\pi} + \frac{\Delta\omega_{\text{mfg}}}{2\pi} \right] \cong 366 \text{ cps} \quad (5-52)$$

As a margin of safety, these errors are assumed to be of the same polarity and are not root mean squared.

For the ground-to-synchronous satellite links in which there are no phase-locked loops in the sideband channels to cancel transmitter modulation frequency error, $\frac{\Delta\omega_m}{2\pi}$, the minimum predetection bandwidth is increased.

$$\text{maximum } \frac{\Delta\omega_m}{2\pi} = (k_o + r t) \left[\frac{(\omega_m)_{\max}}{2\pi} \right] = 68 \text{ cps} \quad (5-53)$$

In this case the minimum predetection bandwidth is

$$B_{\min} = 2 \left[\frac{\Delta\omega_3}{2\pi} + \frac{\Delta\omega_{\text{mfg}}}{2\pi} + \frac{(\Delta\omega_m)_{\max}}{2\pi} \right] \cong 502 \text{ cps} \quad (5-54)$$

For the ground to medium altitude satellite links the absence of the phase-locked loops permits a delta doppler error. From Figure 3, Appendix VII

in the First Quarterly Report the maximum doppler velocity, $\dot{r}_{\max}$, is 4080 ft/sec. The maximum delta doppler error is:

$$\text{maximum } \frac{\Delta\omega_d}{2\pi} = \frac{(\omega_m)_{\max}}{2\pi} \cdot \frac{\dot{r}_{\max}}{C} = 207 \text{ cps} \quad (5-55)$$

where C = velocity of light = 0.986×10^9 ft/second. The minimum pre-detection bandwidth is:

$$B_{\min} = 2 \left[\frac{\Delta\omega_3}{2\pi} + \frac{\Delta\omega_{\text{mfg}}}{2\pi} + \frac{(\Delta\omega_m)_{\max}}{2\pi} + \frac{(\Delta\omega_d)_{\max}}{2\pi} \right] \cong 916 \text{ cps} \quad (5-56)$$

5.3.6 Signal-To-Noise Density

Signal-to-noise density for an unmodulated carrier from a satellite directly over the ground terminal is used as a reference point from which performance of the 16 Gc, 35 Gc and 94 Gc experiment links are developed. This reference calculation is also based on the complete absence of the atmosphere. For convenience, reference calculations for the 6000 nmi satellite are included in Table 5-II through 5-IV along with those for the synchronous satellite (19,300 nmi altitude).

For the synchronous satellite antenna, a $9^\circ \times 6^\circ$ beam is used which illuminates the Continental United States. A 21 deg beam which illuminates the complete earth would have been preferable, but the additional 9 db gain is required for the propagation measurements. For the medium altitude satellite antenna, a 50 deg beam is used which illuminates the complete earth. Higher gain antennas will be difficult to implement on the medium altitude satellite since the satellite aspect with respect to a given point on earth is continually changing.

Since the synchronous satellite is stationary, the satellite antennas can be linear polarized and the linearly polarized ground antennas can be aligned

to minimize polarization loss. When using a medium altitude satellite, the polarization alignment would be more difficult and therefore 3 db polarization loss is assumed.

Tables 5-II through 5-IV used a 15 ft diameter dish as a reference. Table 5-V gives the variance from this reference for each ground facility being considered so that simple adjustments can be made in the signal-to-noise density values given in Tables 5-II through 5-IV.

TABLE 5-II
SIGNAL ANALYSIS FOR 35 Gc DOWN-LINKS
WITH SYNCHRONOUS AND MEDIUM ALTITUDE SATELLITES

	Synchronous	Medium
Free Space Attenuation ($\lambda = 8.6$ mm) -db	214.6	204.4
Propagation Loss (zero loss as reference) -db	0.0	0.0
Satellite Antenna Gain -db	27.0	10.5
Ground Antenna Gain (15 ft, 55%) -db	61.9	61.9
Noise Density ($T_o = 9200^\circ\text{K}$, $NF = 15$ db, $T_A = 0$) -dbw/cps	-189.0	-189.0
Transmitter Power (200 mw) -dbw	- 7.0	- 7.0
Polarization Loss -db	0.3	3.0
Received Signal Power (unmodulated carrier) -dbw	-132.4	-141.4
Signal-to-Noise Density(unmodulated carrier) -db/cps	56.0	47.0
(modulated carrier) -db/cps	50.0	41.0
(each sideband) -db/cps	44.0	35.0

TABLE 5-III
SIGNAL ANALYSIS FOR 16 Gc DOWN-LINKS WITH
SYNCHRONOUS AND MEDIUM ALTITUDE SATELLITES

	Synchronous	Medium
Free Space Attenuation ($\lambda = 18.7$ mm) -db	207.8	197.6
Propagation Loss (zero loss as reference) -db	0.0	0.0
Satellite Antenna Gain -db	27.0	10.5
Ground Antenna Gain (15 ft, 55%) -db	55.1	55.1
Noise Density ($T_o = 4500^\circ\text{K}$, $NF = 12$ db, $T_A = o$) -dbw/cps	-192.1	-192.1
Transmitter Power (200 mw) -dbw	- 7.0	- 7.0
Polarization Loss -db	0.3	- 3.0
Received Signal Power (unmodulated carrier) -dbw	-133.0	-142.0
Signal-to-Noise Density (unmodulated carrier) -db/cps	59.1	50.1
(modulated carrier) -db/cps	53.1	44.1
(each sideband) -db/cps	47.1	38.1

TABLE 5-IV
SIGNAL ANALYSIS FOR 94 Gc UP-LINKS WITH
SYNCHRONOUS AND MEDIUM ALTITUDE SATELLITES

	Synchronous	Medium
Free Space Attenuation ($\lambda = 3.2$ mm) -db	223.2	213.0
Propagation Loss (zero loss as reference) -db	0.0	0.0
Satellite Antenna Gain -db	27.0	10.5
Ground Antenna Gain (15 ft, 55%) -db	70.5	70.5
Noise Density ($T_o = 95,000^\circ\text{K}$, $NF = 25$ db, $T_A = 290^\circ$) -dbw/cps	-179.0	-179.0
Transmitter Power (10 w) -dbw	10.0	10.0
Polarization Loss -db	0.3	3.0
Received Signal Power (unmodulated carrier) -dbw	-116.0	-125.0
Signal-to-Noise Density (unmodulated carrier) -db/cps	63.0	54.0
(modulated carrier) -db/cps	61.2	52.2
(each sideband) -db/cps	55.2	46.2

TABLE 5-V
REFERENCE CHART FOR VARIATION IN SIGNAL-to-NOISE
DENSITY FOR VARIOUS GROUND ANTENNAS

Ground Facility	35 Gc		16 Gc		94 Gc	
	Antenna Gain	Variance	Antenna Gain	Variance	Antenna Gain	Variance
GSFC	61.9	0.0	55.1	0.0	68.5	-2.0
AEROSPACE	61.9	0.0	55.1	0.0	70.5	0.0
Univ. of TEXAS	62.4	0.5	55.6	0.5	70.5	0.0
AFCRL	66.7	4.8	60.8	5.7	-	-
LINCOLN	67.5	5.6	60.5	5.4	-	-
HAYSTACK	71.0	9.1	69.5	14.4	-	-
Auxiliary	58.4	-3.5	51.6	-3.5	-	-

5.3.7 Carrier Phase-Lock Loop

Phase-lock loops provide an efficient method for tracking narrow band energy spectrums in the presence of narrow band noise. The capability of any phase-lock receiver to stay in lock is a function of the input signal-to-noise density ratio, received signal deviations and loop parameters. This particular receiver employs a frequency-lock loop in addition to the phase-lock loop as seen in Figure 5-15. The addition of the frequency-lock loop has the effect of increasing the frequency pull-in-range of the receiver and decreasing the pre-detection signal-to-noise ratio at phase unlock.

If the received energy is of the exact anticipated frequency, and the post-detection filter is a proportional plus integral network, then the system post-detection noise bandwidths and corresponding predetection signal-to-noise density ratios at which the receiver will unlock in phase may be computed. (1) (2)* A curve of receiver unlock in phase for post detection noise bandwidth vs. predetection signal-to-noise density is plotted as Curve #1 in Figure 5-16. One may conclude from this curve that there is no limit

* Bibliographical listings are presented in Section 9.

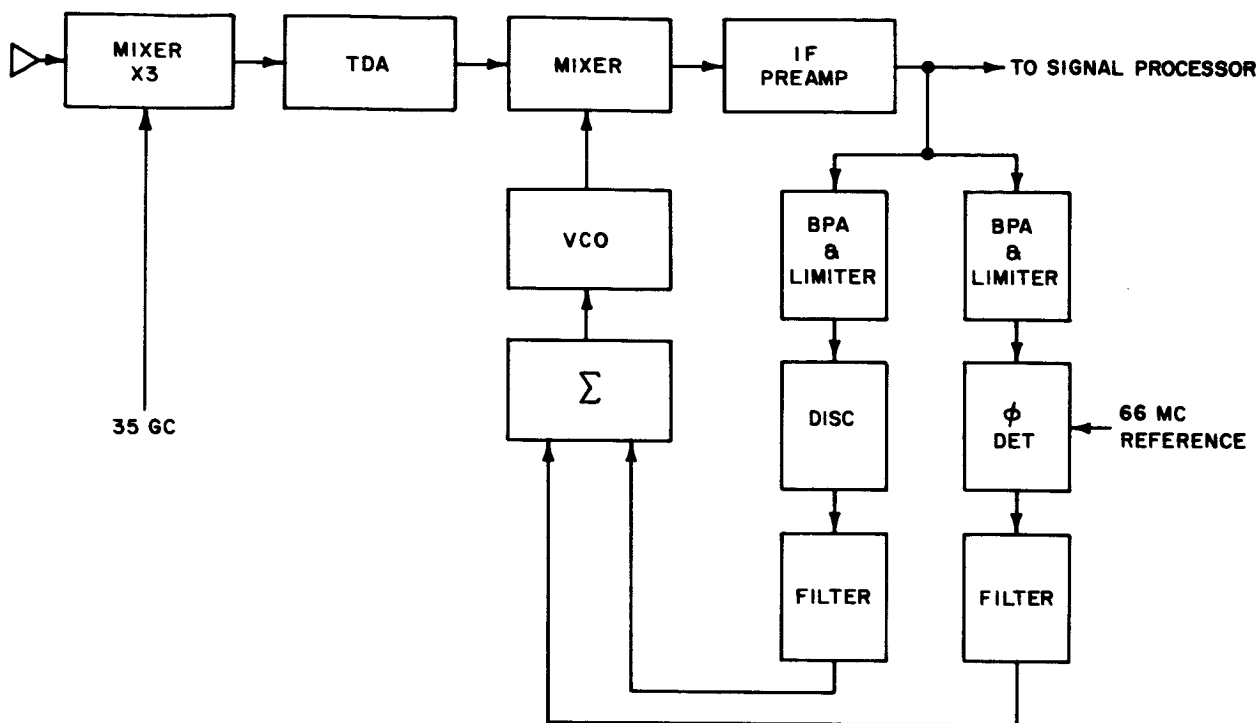


Figure 5-15. Carrier Phase-Lock Loop

to the post detection noise bandwidth; however, this is a fallacy due to the fact that the received signal is unstable; thus it will vary in frequency.

Optimum filters may be designed for specified received frequency stabilities. Curve #2 was generated making the following assumptions:

Loop velocity gain constant	$= 10^7$
System damping factor	$= 0.5$
Received signal stability	$= 1 \text{ part } 10^9 \text{ for } 0.1 \text{ sec}$
Discriminator center frequency offset	$= 100 \text{ Kc}$

This curve defines a filter with a noise bandwidth of 150 cycles as optimum and receivers at signal-to-noise density ratio of 26.5 db for the receiver to unlock. Curves #3 and 4 were for received signal stabilities in 0.1 sec of 1 part in 10^{10} and 1 part in 10^{11} respectively. If the optimum filter is used

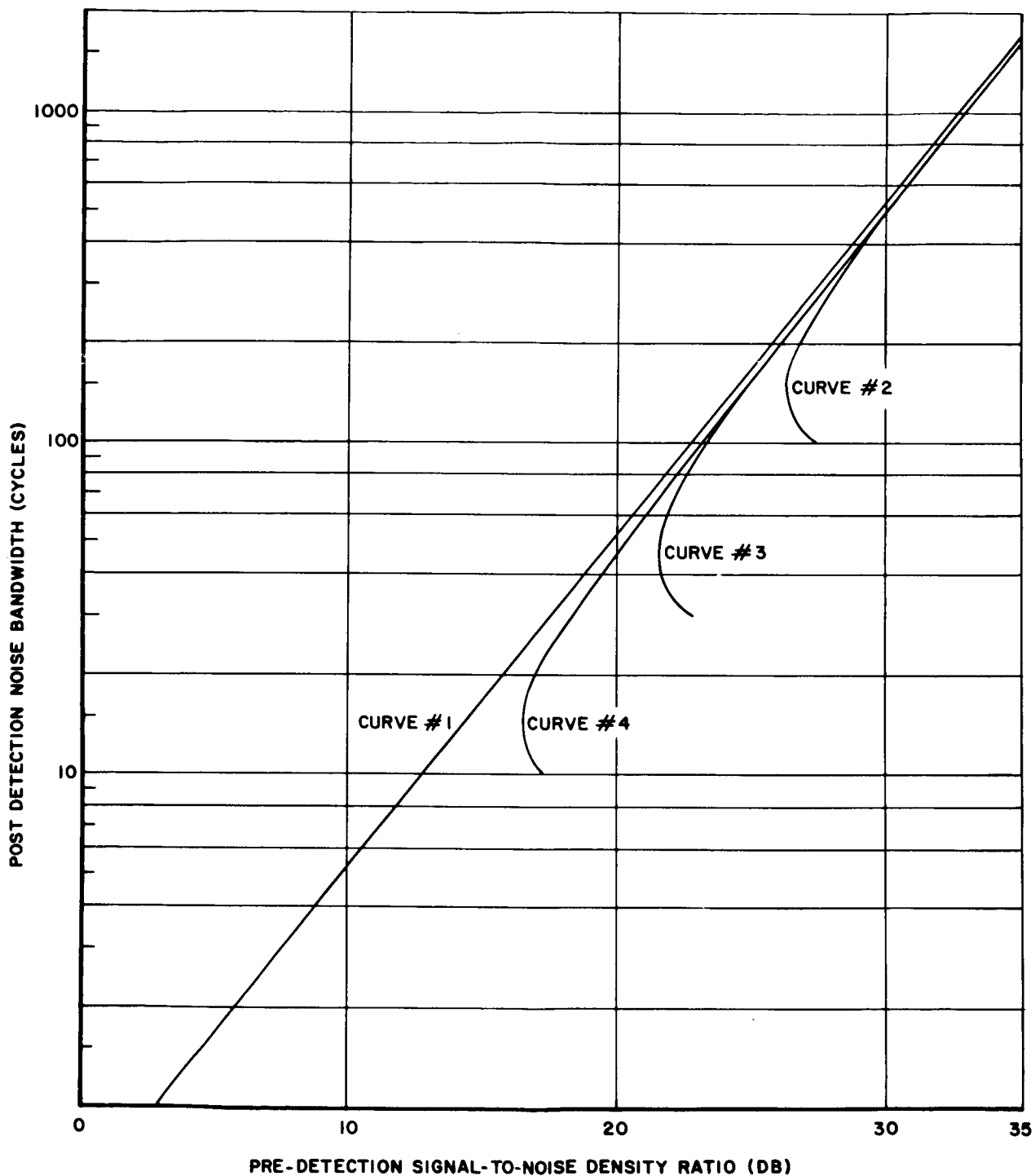


Figure 5-16. Post Detection Noise Bandwidth vs Signal-to-Noise Density when Carrier Phase-Lock Loop Unlocks

for these conditions then the required signal-to-noise density will be 22 db and 17 db respectively.

5.3.8 Amplitude Detection

The amplitude processor, in part, consists of a square law detection device, the voltage output of which is directly proportional to the power at its input. The output of an ideal square law detector is expressed as:

$$E_{DC} = \rho (P_S + P_N) \quad (5-57)$$

where:

E_{DC} = direct current at detector output

ρ = detector transfer function

P_S = signal power at input to detector

P_N = noise power at input to detector

In addition, there exists amplitude fluctuations in the direct current component at the output of the detector due to the noise power at the detector input. The rms value of these fluctuations is defined as:

$$\sigma_N = \frac{\rho P_N}{\sqrt{B\tau}} = \rho N_c \sqrt{\frac{B}{\tau}} \quad (5-58)$$

where:

B = predetection bandwidth

τ = post-detection integration time

N_c = noise power density

Equation (5-57) defines the output voltage of the square law detector as a function of both signal and noise powers at the detector input. An output voltage that is a function of signal power only, has been generated by subtracting the same gain noise bandwidth product of a spectrum displaced from the desired signal spectrum. A block diagram of this approach was included in Section 5.1. The total noise fluctuation increases by the square root of two at the detector output; however, the output is now directly proportional to the input signal power. The voltage signal-to-noise ratio at this output may now be expressed as:

$$\frac{E_{dc}}{\sqrt{2} \sigma_n} = \frac{P_s}{N_c} \sqrt{\frac{\tau}{2B}} \quad (5-59)$$

The minimum detectable change in amplitude is therefore:

$$\bar{A}_N = \frac{\frac{E_{dc}}{\sqrt{2} \sigma_n} + 1}{\frac{E_{dc}}{\sqrt{2} \sigma_n}} = \frac{\frac{P_s}{N_c} \sqrt{\frac{\tau}{2B}} + 1}{\frac{P_s}{N_c} \sqrt{\frac{\tau}{2B}}} \quad (5-60)$$

and is plotted in Figure 5-17 for $\tau = 0.1$ sec and for $B = 500$ cps. If the carrier phase-lock loop unlocks when the carrier signal-to-noise density becomes 27 db, then $\bar{A}_n \text{ max} = 0.8$ db on the carrier and 2.5 db on each sideband when the modulation index is unity.

5.3.9 Phase Detection

The signal processor in the ground stations utilizes a phase lock-loop in each sideband channel to cancel delta-doppler and modulation frequency error so that the predetection bandwidth can be minimized for better amplitude measurement. Relative phase of the sidebands is measured by comparing, in a phase detector, the outputs of the VCOs which establishes the minimum detectable change in relative phase.

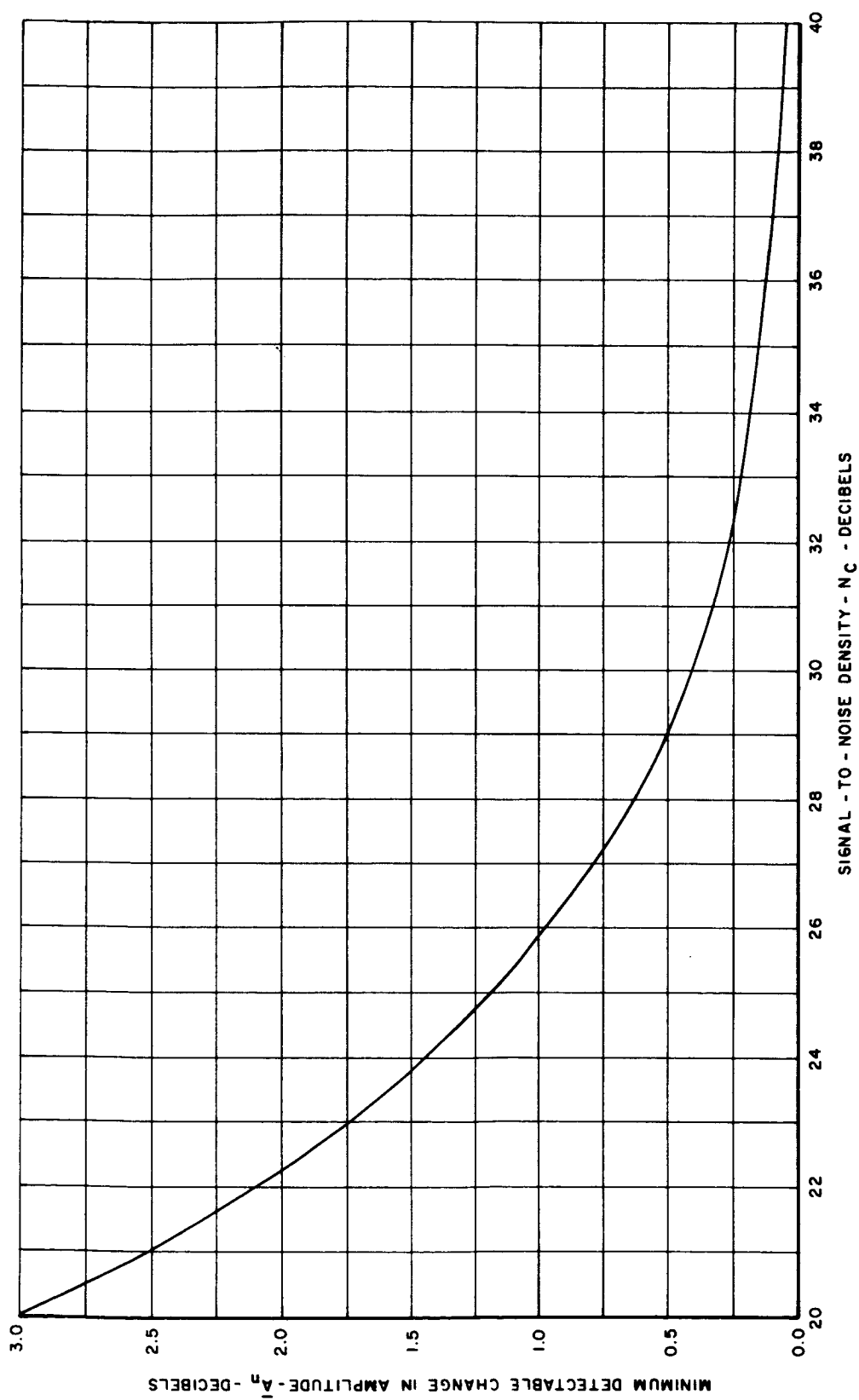


Figure 5-17. Minimum Detectable Change in Signal Amplitude

In the satellite the signal processor does not have phase lock-loops in the sideband channels and therefore the delta doppler and modulation frequency error establishes the predetection bandwidth. Relative phase of the sidebands is measured by comparing, in a phase detector, the actual sidebands themselves.

In either case the rms phase jitter or minimum detectable change in relative phase is expressed as:

$$\overline{\phi}_n = \frac{1}{\frac{P_s}{N_c} \tau} \text{ radians}$$

The rms phase jitter versus signal-to-noise density is plotted in Figure 5-18 for $\tau = 0.1$ sec. If the carrier phase-lock loop unlocks when the carrier signal-to-noise density becomes 27 db then $\overline{\phi}_n \text{ max} = 0.14$ radians when the modulation index is unity.

5.3.10 Gain Requirements

All the outputs of the amplitude processors will have available 5 v across 1000 ohms if the synchronous satellite were directly overhead. Assuming the receivers have 40 db gain, the output level of -16 dbw dictates signal processor gains to be approximately that which is given in Table 5-VI.

TABLE 5-VI
SIGNAL PROCESSOR GAIN REQUIREMENTS

Signal Processor	16 Gc	35 Gc	94 Gc
Carrier Channel - (db)	94	92	75
Sideband Channels - (db)	100	98	81

These large amounts of gain required must be judiciously distributed along the channel in the signal processor, since there exists points in the

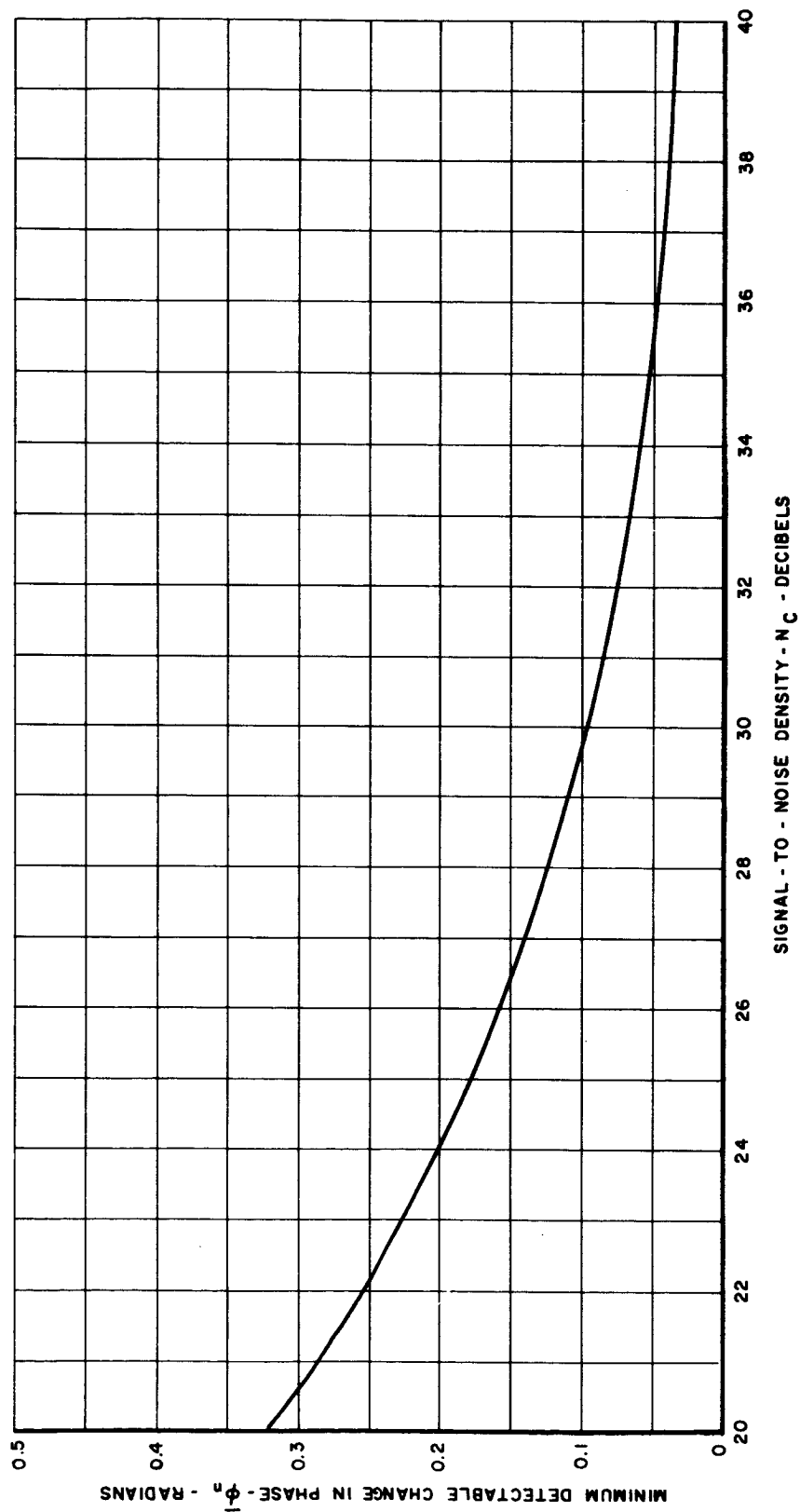


Figure 5-18. Minimum Detectable Change in Relative Phase

channels at which the total noise power greatly exceeds the signal power. For example, in the upper sideband channel at the input to the final mixer, the bandwidth preceding this point is 5 mc and in the 94 Gc processor the total noise power will be 20 db above the signal power.

The signal processor in the satellite will contain a sideband selection and delta doppler correction unit having a gain of twenty decibels, thus limiting the rms value of the noise voltage at the input to the final mixer to 0.08 v, which is well below the limiting level. These same units for the 35 and 16 Gc experiments will have gains of thirty decibels, due to the fact that the noise power density is 10 db lower than the 94 Gc receiver. The remaining required channel gains will be implemented in the signal amplitude and signal phase processors with twenty decibels prior to the crystal filters.

5.4 Experiment Links

5.4.1 Synchronous Satellites

Using the ground facilities discussed in Section 2.1, the assumed synchronous satellite positions identified in Section 2.2 and the signal level analysis in Section 5.3, the various experiment links were evaluated. Table 5-VII eliminates some of these links due to horizon limitations and some of these links because they are simply unnecessary.

For the remaining "yes" links, the signal-to-noise density was determined for the unmodulated carrier and for the modulated carrier. These values for signal-to-noise density, which are based on the cloudy weather model established in Section 3 of the First Quarterly Report, are evaluated against the phase-lock receiver unlock value of 27 db that was established in Section 5.3.7. A sample calculation for determining signal-to-noise density for a specific link is given in Table 5-VIII.

TABLE 5-VII
ELIMINATION OF EXPERIMENT LINKS DUE TO LINE-OF-SITE
LIMITATIONS AND UNNECESSARY LINE-OF-SITE
GROUND STATION ELEVATION ANGLES

Station	Satellite Position ⁽¹⁾			
	PA-45	SA-30	PP-145	SP-165
Aerospace	Yes	NO	Yes	Yes
WSMR	Yes	Marginal	UNNECESSARY	Yes
U. of Texas	Yes	Yes	Yes	Yes
Rosman	UNNECESSARY UNNECESSARY		Yes	NO
GSFC	Yes	Yes	Yes	NO
AFCRL, Lincoln, Haystack	Yes	Yes	Marginal	NO

Criteria:

Yes - Above Horizon

NO - Below Horizon

Marginal - Below 5 degrees elevation

UNNECESSARY - Gap filler receivers at WSMR or Rosman
are not needed for those satellite positions

⁽¹⁾Satellite Positions

PA-45	Primary Atlantic - 0° La, 45° w Lg
SA-30	Secondary Atlantic - 0° La, 30° w Lg
PP-145	Primary Pacific - 0° La, 145° w Lg
SP-165	Secondary Pacific - 0° La, 165° w Lg

TABLE 5-VIII
EVALUATION OF AN EXPERIMENTAL LINK

Ground Station	GSFC
Satellite Position	PA-45 (Table 2-V, Sect. 2.2.1)
Signal-to-Noise Density Reference (Unmodulated Carrier, 90° deviation, no atmosphere)	56.0 (Table 5-II, Sect. 5.3.6)
Relative Free Space Attenuation (90° elevation vs. 33° elevation)	-0.6 db (Figure 5-7, Sect. 5.3.2)
Propagation Loss (cloudy, 33° elevation)	-0.9 db (Figure 5-9, Sect. 5.3.3)
Fading Loss (multipath)	-10.0 db
Antenna Gain Variance (15 foot reference)	0.0 db (Table 5-V, Sect. 5.3.6)
Beam Shape Loss (9° x 6° beam pointed at center of United States)	-2.0 db
Signal-to-Noise Density (unmodulated carrier)	42.5 db
(modulated carrier)	36.5 db
(each sideband)	30.5 db
Minimum Detectable Change in Sideband Amplitude	±0.4 db (Figure 5-17, Sect. 5.3.8)
Minimum Detectable Change in Relative Phase of Sidebands	±8 degrees (Figure 5-18, Sect. 5.3.9)

The signal-to-noise densities for the various links are tabulated in Table 5-IX. The first number is the degrees of elevation of the ground station to satellite line-of-site. The second and third numbers are the signal-to-noise densities for the unmodulated carrier and the modulated carrier respectively. The values for signal-to-noise density indicate that all links except one pass the criteria for acceptability — that is, $S/N_c \geq 27$ db on a cloudy day. The larger the number, the greater the capacity for making observations in bad weather.

By scanning the elevation angles in each vertical row, one satellite position can be evaluated against another in terms of elevation profile. By scanning the horizontal rows, the data gathering potential of each ground site can be evaluated. By omitting any one of the auxiliary receivers, it can be seen that the effect upon the value of the satellite position is significantly altered. If other satellite positions are chosen, the possible links can be quickly evaluated by using Figure 2-9 in Section 2.2.1 to find elevation angles and then following the process shown in Table 5-VIII.

5.4.2 Medium Altitude Satellites

For medium altitude satellites, the elevation profile is complete for each station and auxiliary terminals are not needed as gap fillers. As shown in Tables 5-II through 5-IV, the signal-to-noise densities are 9 db lower because it was felt that a directional $9^\circ \times 6^\circ$ satellite antenna beam could be difficult to implement and control. Because S/N_c is 9 db lower, the medium altitude experiment becomes marginal. For example, on a cloudy day, the GSFC facility would have to wait until the satellite were 30° elevation or higher before it could phase-lock its receiver onto a 16 Gc unmodulated carrier. It would then track the 16 Gc modulated carrier until the satellite receded below 25° elevation and from there to the horizon it could only measure amplitude fading of the unmodulated carrier.

TABLE 5-IX
RECEIVER SIGNAL-TO-NOISE DENSITY IN db FOR
MODULATED AND UNMODULATED CARRIERS IN
SYNCHRONOUS SATELLITE EXPERIMENT LINKS

Frequency (Gc)	Station	Satellite Position			
		PA-45	SA-30	PP-145	SP-165
35	Aerospace(10) ⁽¹⁾	5/33/27		41/39/33	31/38/32
35	WSMR (10) ⁽¹⁾	15/38/32			22/39/33
35	U. of Texas	24/43/37	10/41/35	29/44/38	10/41/35
35	Rosman (10) ⁽¹⁾			15/38/32	
35	GSFC	33/42/36	23/41/35	7/38/32	
35	AFCRL	35/47/41	26/46/40		
35	Lincoln	35/48/42	26/47/41		
35	Haystack	35/51/45	26/50/44		
16	Aerospace (10) ⁽¹⁾	5/39/33		41/43/37	31/42/36
16	WSMR (10) ⁽¹⁾	15/43/37			22/43/37
16	U. of Texas	24/47/41	10/46/40	29/48/42	10/45/39
16	Rosman (10) ⁽¹⁾			15/43/37	
16	GSFC	33/46/40	23/45/39	7/44/38	
16	AFCRL	35/51/45	26/50/44		
16	Lincoln	35/52/46	26/51/45		
16	Haystack	35/55/49	26/54/48		
94	Aerospace	5/21/19		41/42/40	31/40/38
94	GSFC	33/44/42	23/41/39	7/35/33	

Code: Ground Terminal Elevation Angle/Unmodulated Carrier S/N_c (db)/
Modulated Carrier S/N_c (db)

(1) 10 foot diameter antennas.

If more prime power were available in the satellite, a higher output could be designed into the transmitters. If more time is available, a component development program such as that described in Appendix I would be possible or the development of a directional antenna would be possible.

5.5 Signal Processor Design

This section is an expansion of Section 5.1, "Signal Processor Configuration," which gives more detailed information on the design of the satellite and ground signal processors.

5.5.1 Satellite Signal Processor

For this discussion on the satellite signal processor, refer to the block diagram of Figure 5-1 in Section 5.1.

5.5.1.1 Sideband Selector and Delta Doppler Corrector

The upper sideband bandpass filter will pass the frequency band of 76 to 116 mc and will consist of a two section filter and a single stage transistor amplifier. The overall gain will be close to unity due to the broad passband required and the losses encountered in fanning out and matching of the IF signal.

The output of the bandpass filter is fed to a conventional transistor type mixer which is fed with a 66 mc reference. The output at the collector which will be in the band of 10 mc to 50 mc, when the modulating frequency is 10 mc or 50 mc, is then fed to the video amplifier which in reality is a two-channel bandpass amplifier. Since the information signals are at discrete frequencies of approximately 13 mc and 40 mc, there is signal-to-noise improvement to be realized in narrow-banding. One channel centered at 49 mc will consist of a four-pole transitionally coupled stage amplifier with a bandwidth of about 3 mc. The second channel will be centered at 13 mc and will also be a transitionally coupled type of tuned amplifier. The overall gain of these amplifiers will be 26 db.

The output of the video amplifier is then summed with the upper sideband generated by the 5 kc modulation, the derivation of which will be explained later in this discussion. The summation circuit will be made up of resistive networks with filters as required for isolation of the respective sources. Approximately 6 db will be lost in the summation process and the overall gain from the receiver IF output to the summation output will be 20 db.

The summation output is fed to a second mixer whose reference signal is one of three frequencies required to translate the three received signals to a 10.7 mc band. A search lock arrangement is used to decide which frequency is to be fed to this mixer as a reference. This will be explained later. This mixer will be a broadband balanced type which will require no tuning for the three frequencies of interest.

The 10.7 mc signal from the output of the mixer is then amplified in a tuned amplifier with 30 db of gain before it is sent to the amplitude and phase processors. This amplifier is highly temperature compensated and gain stabilized by the utilization of feedback techniques. Approximately 10 db of this gain makes up for the loss in the mixer circuit.

The lower sideband filter will pass the frequency band from 16 mc to 56 mc, and will also consist of a two-section filter and a single stage transistor amplifier. The amplifier will recover the loss, due to power splitting of the IF signal and the insertion loss of the filter. The output is then fed to a transistor mixer which is switched with the 66 mc reference signal. The output of the transistor mixer is then fed to a video amplifier of the type used in the upper sideband channel. The two discrete frequencies which are approximately 49 mc and 13 mc are the same as those in the upper sideband channel.

When the modulation frequency is 5 kc, the 66 mc $\pm$ 5 kc signal at the input to the signal processor is filtered out into secondary upper and lower sideband channels by means of a two or three section L-C tuned circuit. This signal is then mixed with a 60 mc signal from the frequency synthesizer

and the difference signal consisting of the carrier at 6.6 mc plus either the upper or lower sideband is generated at the output of the mixer. The transistor mixer will have a 25 kc bandwidth output circuit at the collector which is tuned to 6.6 mc. Some gain will be realized in this mixer.

The upper and lower sidebands, due to the 5 kc signal are separated by the use of crystal filters. These filters will have a 2 kc bandwidth measured at the 6 db point and will have fast roll-off. The upper and lower sidebands are then separately fed to the second pair of mixers where they are mixed with a 6.6 mc reference signal. These mixers will also be transistor types with the output 5 kc signal available at the collector. A stage of gain consisting of a transistor amplifier will follow the mixer, and the overall gain from the receiver IF output to the 10.7 mc output will be set to have 20 db of stabilized gain.

5.5.1.2 Carrier Selector

The receiver IF output in the 16 mc to 116 mc band is power split and fed to a narrow band transistor amplifier which is centered at 66 mc and will have a bandwidth of 3 mc and a gain of 26 db, in order to realize the required 20 db overall gain between the receiver IF output and the mixer input. Two transistor stages will be used to provide gain stabilization.

This mixer will also be a transistor type with the 10.7 mc output available at the collector and will have some gain. A transistor amplifier will follow the mixer output. This amplifier will have 30 db of overall gain, and a 500 kc bandwidth with gain stabilization incorporated in the design.

5.5.1.3 Signal Amplitude Processor

Each of the three inputs to the signal processor, that is, the carrier and the upper and lower sidebands, is split and fed into two channels. The first stage of each channel is a crystal filter. One crystal filter is tuned to the signal frequency at 10.7 mc and has a 2 kc bandwidth. The second crystal filter is tuned to another 2 kc window in the 500 kc bandpass of the

previous circuit. Crystal filters are used to take advantage of their sharp skirt rejection characteristic and narrow band tuning capability. Although the requirements on these crystal filters are more stringent in terms of accuracy and stability than conventional units, there is a great deal of knowledge and experience available at this particular frequency.

The signal is amplified after passing through the respective bandpass crystal filters. The highly stabilized amplifier filter sections will have about 30 db of gain. Temperature compensation and feedback will be used to maintain the necessary gain stability.

The signal and noise at f_o is square law detected with a positive output, and the noise at $(f_o + \Delta_f)$ is square law detected with a negative output. The square law detectors will be diode type, operating on their square law portion of their characteristic curves. The detected output is then integrated in a simple R-C circuit with a 0.1 second time constant. The two integrated outputs are summed, and the DC offset, due to the noise is reduced. The summing circuit will consist of resistor networks. An emitter follower and stabilized DC amplifier will be used to interface with the telemetry system. The overall gain from the receiver IF output will be 88 db for the sidebands and correspondingly less for the carrier. The integrated outputs of the two sideband $(f_o + \Delta_f)$ processors are differenced to give an indication of differential gain in the two channels to an accuracy of 0.2 db.

5.5.1.4 Signal Phase Processor

The upper and lower sideband signals from the sideband selector are fed to separate limiters. The limiters will consist of two stages of stabilized gain, and will utilize diodes as the limiting elements. The limited lower sideband signal is phase shifted 90 deg in a two-section RC phase shifter. The phase shifted signal is then amplified and used to switch a conventional diode type phase comparator. The other input to this phase comparator is the limited upper sideband. The output is then integrated in a R-C circuit with a 0.1 sec time constant, amplified and interfaced with the

telemetry system. The limited upper sideband is used to reference a second phase comparator. The second input to this phase comparator is the limited lower sideband signal. The output of this diode type phase comparator is then integrated, amplified and interfaced with the telemetry system. By comparing the phase in these quadrature phase detectors, voltages are provided which represent the full range of 0 to 360 deg of phase difference between the two sidebands.

The overall gain requirements between the receiver IF output and the phase processor output are the same as the gain requirements between the receiver IF output and the amplitude processor output.

5.5.1.5 Frequency Synthesizer

The 66 mc from the frequency standard will be divided by digital counters and recombined through harmonic multipliers and mixers to form the specific frequencies required for the signal processor. Buffer amplifiers will be used to provide required drive levels and isolation. Driver amplifiers will be used on all output lines to supply the power output required to drive the mixer circuits in the signal processor.

5.5.1.6 Frequency Selector Circuits

As previously mentioned, a sweep lock arrangement is used to select the correct local oscillator frequency to mix with the incoming sideband modulation signal. A pulse generator running at a 1 cycle rate is fed through a gate to a counter. As the counter changes state, the diode matrix cycles the output between the three frequency gates allowing each of the gates to be open for one second. When the correct frequency is fed to the broadband mixer, an output appears at the summation point, and closes the pulse generator gate which stops the counter with the correct frequency being fed to the broadband mixers. Since the integration time is 0.1 sec, the loop will have sufficient time to detect a signal in the 1.0 sec interval.

The pulse generator will be a free running multivibrator of conventional design with a differentiator circuit at the output to provide the timing pulses for the counter. The gate will be a dual transistor type with the summation output controlling the gate. The counter will consist of three flip-flops fed in a serial manner with the diode matrix sensing the condition of the flip-flops and steering the frequency select gates in a stepped sequence. The frequency select gates will be balanced diode bridge types driven by a transistor. The gates will have 50 ohm input and output impedances.

5.5.2 Ground Signal Processor

The ground signal processor design is based on the block diagram of Figure 5-2 in Section 5.1. Comparison of the two block diagrams associated with the satellite and the ground signal processors show that in most respects the circuitry is essentially the same. Since most of the circuits have been discussed in the previous section, this discussion will refer only to the design differences.

One of the main differences is that the ground signal processor will have to provide greater gain because of the weaker 16 Gc and 35 Gc received signals. The differences in gain were indicated in Table 5-VI in Section 5.3.10.

In the ground signal processor the two sideband channels in the ground signal processor each use a phase-lock loop to correct for delta doppler and modulation frequency error in order to minimize predetection bandwidth to improve amplitude detection. The three reference frequencies for the second mixers in the sideband selector will be derived from VCOs which are part of the phase-lock loops. With a priori information on the frequency of modulation, the correct VCO will be manually selected and set to an accuracy sufficient to cause the loop to lock and track. Transistorized VCOs will be used at each of the required frequencies. A manual selector switch and a vernier control knob will be used to set the loop to operate at the correct frequency. The limited upper and lower sidebands in the 10.7 mc passband

are phase detected against the reference frequency and the phase detector output is used to control the frequency of the VCO. This relieves the frequency stability requirements of the satellite borne modulation sources.

The satellite signal processor will interface with the satellite telemetry system whereas the ground signal processor will interface with the analog data storage and display system. Generally, voltage levels in the order of 0.5 v to 1.0 v are specified in this type of interface, and will be supplied at nominal impedance levels by emitter followers and DC amplifiers.

6. DATA PROCESSING AND EVALUATION

In this report, data processing and evaluation is introduced. During the remainder of the study, this subject will be investigated in considerable more depth.

6.1 General Concept

The taped analog data from the satellite and from all the ground facilities would be converted to digital form and processed at a central data processing facility. The relationship of this facility with the other facilities involved in the propagation data collection program is illustrated in Figure 6-1.

Each ground facility receiver should be equipped with identical signal processors and analog tape recorders to minimize data processing expense. Each ground receiver would share its RF head with a radiometer in order to make sensitive sky temperature measurements using the same antenna beam. Short term and long term variations of antenna azimuth and elevation angle are recorded on tape along with the signal amplitude, relative sideband phase and radiometric temperature. It should also be noted that the bore-sight installation for each of the participating ground facilities should be equipped for calibration and checkout purposes, with a spacecraft simulator which consists of the appropriate transmitters and/or receivers which function like those aboard the satellite.

Real-time analog strip line recoder presentations of the same data which is being recorded on magnetic tape will be made at each site for calibration, checkout and operational monitoring; and to provide the cooperating agencies with immediate access to the raw data. A coarse evaluation is made on the analog presentations for the purposes of planning follow-on experiments

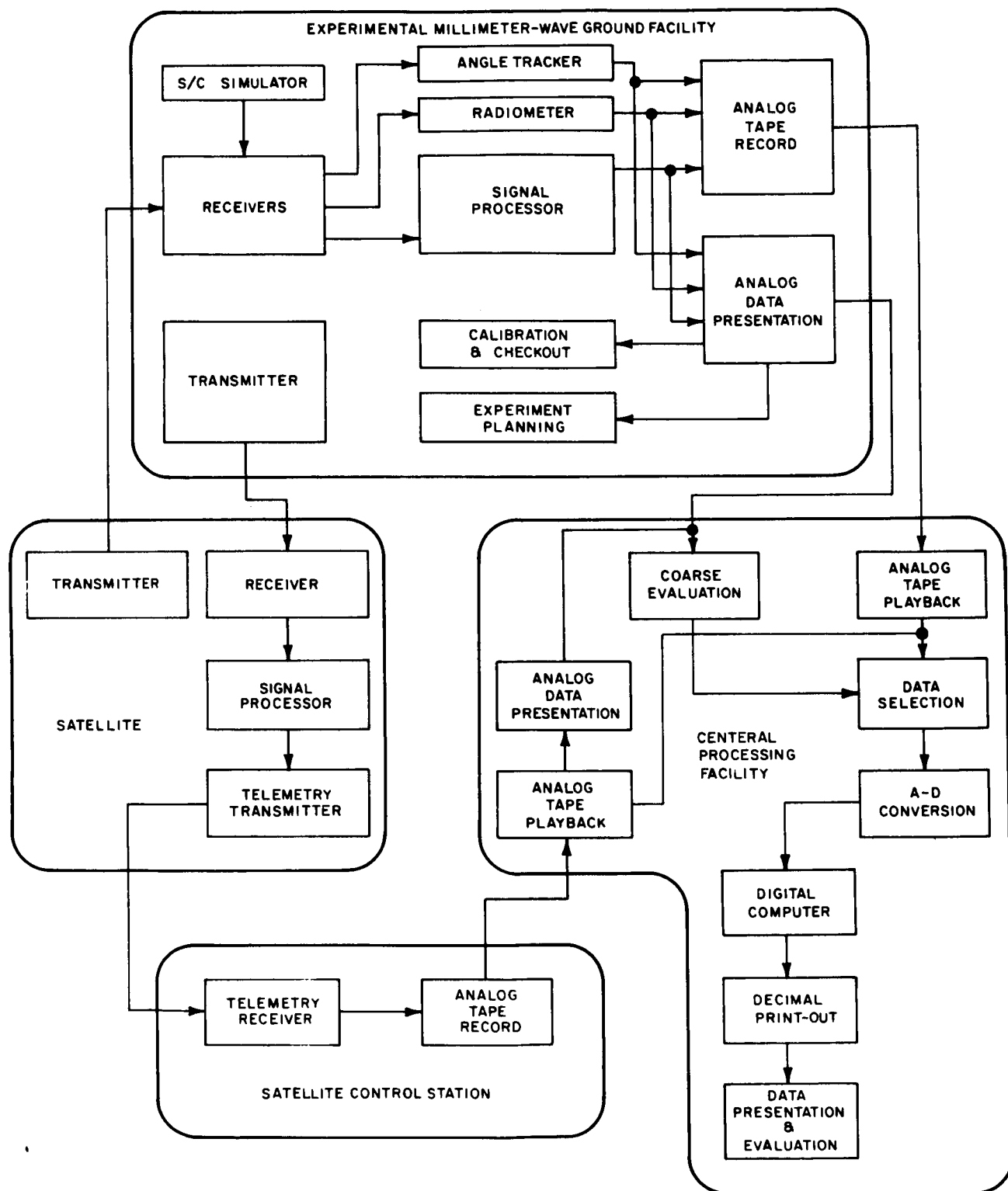


Figure 6-1. General Concept of Data Processing and Evaluation

and selecting those portions of the recorded data which will be subjected to detailed data processing at the central processing facility.

Existing computer facilities are equipped to handle the data processing required for the propagation data collection program. Special-computer programs can be generated, the results of which will provide information on the various channel functions to be described in the following sections. This information will include atmospheric absorption, carrier amplitude distribution and fading spectrum, correlation of sideband amplitude and phase, dependence of fading on receiving antenna beamwidth, spatial decorrelation of carrier amplitude and cumulative probability distributions of signal-to-noise ratio and bit error rates.

6.2 Definition of Channel Parameters

6.2.1 The Two-Dimensional Correlation Function

The Two-Dimensional Correlation Function, $R(\Delta f, \Delta t)$, which was introduced in Section 4.1.1 of the First Quarterly Report of the Millimeter Communication Propagation Program, is an important quantity characterizing the millimeter channel. The importance of $R(\Delta f, \Delta t)$, is discussed by Gallager⁽³⁾, Price and Green⁽⁴⁾, and Green⁽⁵⁾.

The following quantities may be determined directly from $R(\Delta f, \Delta t)$: the coherence time and the coherence bandwidth of the channel; the duration of fades; the Echo-Correlation Function, $R(\Delta t)$; and the Spaced-Frequency Correlation Function, $R(\Delta f)$. Moreover, the Scattering Function, $\sigma(t, f)$, which is the two-dimensional Fourier Transform of $R(\Delta f, \Delta t)$, provides direct information regarding doppler and multipath spreading by the channel.

That $R(\Delta f, \Delta t)$ and $\sigma(t, f)$ are important is demonstrated by the fact that $\sigma(t, f)$ can be used to determine the probability of error in deciding which of m waveforms has been transmitted through the channel^(6, 7, 8). $\sigma(t, f)$ also arises in the consideration of optimum analog communication systems and bounds on their performance⁽⁹⁾.

For the purposes of investigating the physical significance of the various quantities associated with $R(\Delta f, \Delta t)$ and $\sigma(t, f)$, the observations of Gallager⁽³⁾ and Green⁽⁴⁾ are summarized.

The time-frequency-spread channels under consideration have the property that a transmitted sinusoid is received as a narrow-band random process. That is, a transmitted signal of the form:

$$s_t(t) = \text{Re} \{ e^{i2\pi ft} \} \quad (6-1)$$

is received as

$$s_r(t) = \text{Re} \{ \tilde{s}_r(f, t) e^{i2\pi ft} \} , \quad (6-2)$$

where $\tilde{s}_r(f, t)$ is the complex envelope of the received signal; since $s_r(t)$ is narrow-band, the envelope of the received signal is $|\tilde{s}_r(f, t)|$ where $\tilde{s}_r(f, t)$ may be interpreted as a randomly-varying transfer function.

The Two-Dimensional Correlation Function is defined in terms of complex envelopes by:

$$R(\Delta f, \Delta t) = 2E \left\{ \tilde{s}_r^* \left(f - \frac{\Delta f}{2}, t \right) \tilde{s}_r \left(f + \frac{\Delta f}{2}, t + \Delta t \right) \right\} , \quad (6-3)$$

where "E" signifies taking the expected value of the bracketed quantity and "*" indicates complex conjugate.

In order to interpret $R(\Delta f, \Delta t)$, we closely follow Gallager⁽³⁾ and consider $R(0, \Delta t)$ and $R(\Delta f, 0)$ separately.

Referring to Equation (6-3), $R(0, \Delta t)$ is seen to be the autocorrelation function of the complex envelope of the channel response to an input sinusoid of frequency f cps. This autocorrelation function, $R(\Delta t) = R(0, \Delta t)$, is called the "Echo-Correlation Function"; it provides coherence time and fading duration information.

The coherence time of the channel, T_c , is loosely defined as the range in Δt over which $R(\Delta t)$ is non-zero. Very often, T_c is taken to be the solution to:

$$R(T_c) = 1/2 R(0). \quad (6-4)$$

The fact that $R(\Delta t)$ approaches zero largely results from fading in the channel. T_c is related, therefore, to the duration of fades.

Again referring to Equation (6-3), $R(\Delta f, 0)$ is seen to be the cross-correlation function of the complex envelope of the channel response to a sinusoid at $f - \frac{\Delta f}{2}$, cps. with the complex envelope of the response to a sinusoid at $f + \frac{\Delta f}{2}$. The cross correlation function, $R(\Delta f) = R(\Delta f, 0)$, is called the "Spaced-Frequency Correlation Function"; it provides coherence bandwidth information.

The coherence bandwidth, F_c , of the channel is loosely defined to be the range in Δf over which $R(\Delta f)$ is non-zero. If frequency diversity modulation schemes are used to transmit information, the F_c is a measure of how far apart the separate channels must be in order to receive uncorrelated signals on each.

If a signal of bandwidth W , centered around f , is transmitted and W is such that $R(W, 0) \simeq R(0, 0)$, then the received signal will be the same as the transmitted signal except for an overall amplitude and phase that change over a period of time which is on the order of T_c . Conversely, if $R(W, 0) \simeq 0$, the amplitude and phase of different frequency components of the input signal will be changed relative to each other, and the received waveform will no longer bear a simple resemblance to the transmitted waveform.

If $R(\Delta f, \Delta t)$ is unimodal, the T_c is approximately the reciprocal of the doppler spreading and F_c is approximately the reciprocal of the time spreading of the channel.

6.2.2 The Scattering Function

We now wish to examine $\sigma(t, f)$, the two-dimensional Fourier Transform of $R(\Delta f, \Delta t)$. As pointed out in Appendix III of the First Quarterly Progress Report of the Millimeter Communication Propagation Program, $\sigma(t, f)$ has a convenient physical interpretation; it represents the power received from a scintillating scatterer at delay t and doppler shift f .

Consider the two functions, $\sigma(f) = \int \sigma(t, f) dt$ and $\sigma(t) = \int \sigma(t, f) df$, separately. $\sigma(f)$ is called the "Echo Power Spectrum" and $\sigma(t)$ is called the "Power Impulse Response".

$\sigma(f)$ represents the total power received from all scatters producing a doppler shift of f cps. The doppler spread of the channel, B , is loosely defined to be the range in f over which $\sigma(f)$ is non-zero. As previously mentioned, if $\sigma(t, f)$ and $R(\Delta f, \Delta t)$ are well behaved, then $B \simeq 1/T_c$.

$\sigma(t)$ represents the total power received from all scatterers at a delay t . The time spread of the channel, L , is loosely defined to be the range in t over which $\sigma(t)$ is non-zero. If $\sigma(t, f)$ and $R(\Delta f, \Delta t)$ are well behaved, then $L = 1/F_c$.

The Echo-Correlation Function, $R(\Delta t)$, is the Fourier Transform of the Echo Power Spectrum, $\sigma(f)$, and the Spaced-Frequency Correlation Function $R(\Delta f)$, is the Fourier Transform of the Power Impulse Response, $\sigma(t)$.

Figure 6-2 taken from Green⁽⁵⁾ provides a pictorial display of the various quantities which have been defined as well as their interrelationships.

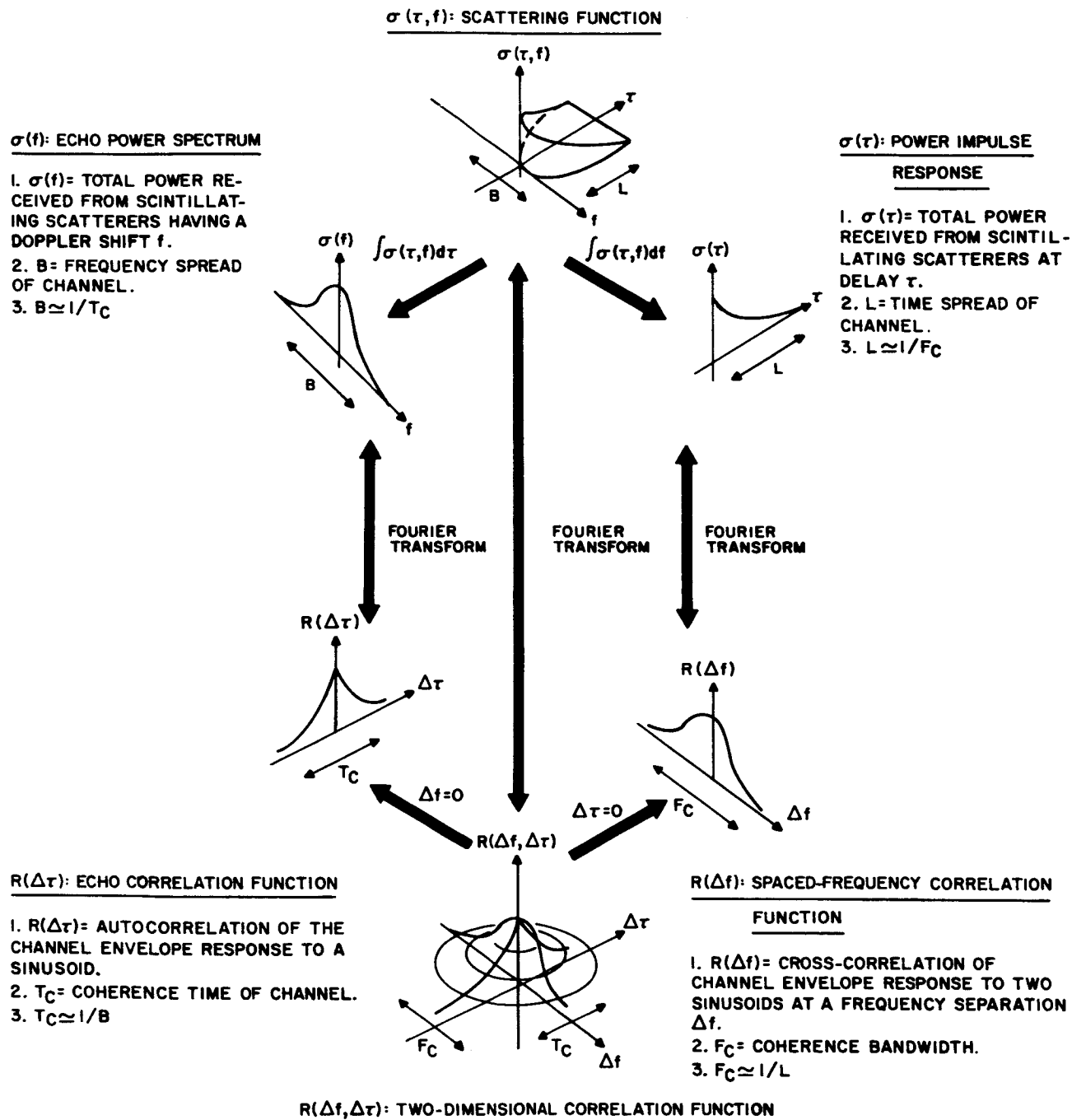


Figure 6-2. Interrelationships of the Channel Functions

6.2.3 The Modified Two-Dimensional Correlation Function

A frequently measured quantity, which has no simple relation to $R(\Delta f, \Delta t)$, is a modified two dimensional correlation function. The modified function, which is denoted by $\hat{R}(\Delta f, \Delta t)$, is defined in terms of the channel envelope response by:

$$\hat{R}(\Delta f, \Delta t) = 2E \left\{ \left| \tilde{s}_r\left(f - \frac{\Delta f}{2}, t\right) \right| \left| \tilde{s}_r\left(f + \frac{\Delta f}{2}, t + \Delta t\right) \right| \right\}. \quad (6-5)$$

Since $\hat{R}(\Delta f, \Delta t)$ depends on the envelope of the channel response, rather than the complex envelope, it is insensitive to phase fluctuations, and therefore provides less information than $R(\Delta f, \Delta t)$. $\hat{R}(\Delta f, \Delta t)$ is used in practice because of the relative ease in measuring it compared to measuring $R(\Delta f, \Delta t)$, (5, 10). Associated with $\hat{R}(\Delta f, \Delta t)$ is a complete set of quantities; $\hat{R}(\Delta f)$, $\hat{R}(\Delta t)$, $\hat{T}_c$, $\hat{F}_c$, $\hat{\sigma}(t, f)$, etc., each of which is defined in a parallel fashion to its counterpart associated with $R(\Delta f, \Delta t)$.

6.2.4 The Spatial Correlation Function

Transmitted plane-waves will become distorted in passing through a scatter channel so that irregularities exist in the received waves. One effect of such irregularities is to cause a decorrelation in the signals received at separated locations.

We consider the simultaneous reception of a transmitted sinusoid at two receivers separated by a distance, d . Let $\tilde{s}(f, t; -\frac{d}{2})$ and $\tilde{s}(f, t; +\frac{d}{2})$ be the complex envelopes of the two received signals.

The Spatial Correlation Function, $R(d)$, is defined by:

$$R(d) = 2E \left\{ \tilde{s}\left(f, t; -\frac{d}{2}\right) \tilde{s}^*\left(f, t; +\frac{d}{2}\right) \right\}.$$

We loosely define D as the range of values of d such that $R(d)$ is non-zero. D provides information about the distances over which a signal can be received coherently.

For simplicity, a modified Spatial Correlation Function, $\hat{R}(d)$, is usually measured. It is defined in terms of the envelopes of the received signals by:

$$\hat{R}(d) = 2 E \left\{ \left| \tilde{s}(f, t: -\frac{d}{2}) \right| \left| \tilde{s}^*(f, t: +\frac{d}{2}) \right| \right\} .$$

$\hat{R}(d)$ provides no information about decorrelation effects due to phase fluctuations because of the use of envelopes rather than complex envelopes.

6.3 Measurement of Channel Parameters

This section discusses the measurement of the various quantities that were defined in Section 6.2 and are Tabulated in Table 6-I. The discussion will concern the general problem of the measurement of correlation functions and power density spectra. The results obtained will apply to any one of the quantities of interest.

The functions of interest are of two types, correlation functions and spectral densities. These functions are defined by ensemble averages, or equivalently, assuming ergodicity, infinite time averages. In practice, of course, such averages cannot be performed so that instead of obtaining the actual functions, we obtain estimates of the functions. These estimates are subject to statistical variations and it is to these variations that we address our attention.

The problem of the estimation of correlation functions and spectral densities is discussed in the classic work of Blackman and Tukey⁽¹¹⁾ and more recently by Hannan⁽¹²⁾, Watts⁽¹³⁾ and Bendat⁽¹⁴⁾. We shall present a brief review of these studies in the discussion which follows.

We consider a random process having an unknown correlation function $R(t)$ and an unknown spectral density $S(f)$. Let $x(t)$ be a sample function

TABLE 6-I
Channel Parameters to be Measured

Correlation Functions	
$R(\Delta f, \Delta t)$	Two-Dimensional Correlation Function
$\hat{R}(\Delta f, \Delta t)$	Modified Two-Dimensional Correlation Function
$R(\Delta f)$	Spaced-Frequency Correlation Function
$\hat{R}(\Delta f)$	Modified Space-Frequency Correlation Function
$R(\Delta t)$	Echo-Correlation Function
$\hat{R}(\Delta t)$	Modified Echo-Correlation Function
$R(d)$	Spatial Correlation Function
$\hat{R}(d)$	Modified Spatial Correlation Function
Spectral Densities	
$\sigma(t, f)$	Scattering Function
$\hat{\sigma}(t, f)$	Modified Scattering
$\sigma(t)$	Power Impulse Response
$\hat{\sigma}(t)$	Modified Power Impulse Response
$\sigma(f)$	Echo Power Spectrum
$\hat{\sigma}(f)$	Modified Echo Power Spectrum

from the process and assume $x(t)$ is available over an interval of length T seconds. Let $\text{est } R(t)$ and $\text{est } S(f)$ be the estimates of $R(t)$ and $S(f)$ based on the finite sample, $x(t)$.

Because of the fact that T is finite, $\text{est } R(t)$ and $\text{est } S(f)$ will not equal $R(t)$ and $S(f)$, respectively. Provided $\text{est } R(t)$ and $\text{est } S(f)$ are properly defined - the definitions will be given later - the errors; $[R(t) - \text{est } R(t)]$ and $[S(f) - \text{est } S(f)]$, will satisfy:

$$E \{R(t) - \text{est } R(t)\} = 0$$

and

$$E \{S(f) - \text{est } S(f)\} = 0,$$

where "E" stands for "Expected value". Estimates satisfying these relations are called unbiased.

A measure of the spread of the error is provide by the quantities:

$$\text{Var} [\text{est } R(t)] = E \{R(t) - \text{est } R(t)\}^2$$

and

$$\text{Var} [\text{est } S(f)] = E \{S(f) - \text{est } S(f)\}^2,$$

where "Var" stands for "Variance". It can be shown that $\text{Var} [\text{est } R(t)]$ is approximately inversely proportional to T so that as the duration of the sample increase, the estimate of $R(t)$ becomes increasingly better. On the other hand, it can be shown that $\text{Var} [\text{est } S(f)]$ does not decrease as T increases, but remains essentially constant; the variance is, in fact, relatively large since it is approximately equal to the square of the true spectral height at the point of estimation. The situation with regard to the estimation of the spectral density can be proved by special techniques at the sacrifice of resolution.

In future reports, the measurement errors will be described more precisely. A set of curves will be developed which will indicate the various trade-offs between error-variance, resolution, and sample length.

7. PROGRAM SCHEDULES AND COST ESTIMATES

Before discussing schedules and cost estimates, the problem areas in hardware design are identified. To solve these problems, breadboarding of critical items is required to determine their performance.

7.1 Breadboarding of Key Items

The following two sub-sections give a listing of priority items which should be implemented in such a way that these design developments are available to the millimeter experiment designer prior to final commitment of final package design. These design development areas will require a time period of six months to one year to perform adequate evaluation of the proposed design approaches.

The best possible means of properly evaluating these key items is by constructing breadboard models and/or purchase of certain items whose performance specifications may be in doubt or improved upon by a better understanding of their performance.

7.1.1 Transmitter Breadboarding

Insofar as the 35 Gc and 16 Gc transmitters are concerned, three items fall under this category. First and foremost, the Pound discriminator should be built and thoroughly evaluated. This item is of the greatest importance for the following reasons:

1. The ultimate sensitivity is achieved when the receiver bandwidth is narrowed to 1 cps. Anything approaching this can only be obtained if the transmitter is stable to within this bandwidth. It is, therefore, well worthwhile to experimentally determine the best achievable stability without a major development program.

2. This form of microwave discriminator, although tried and true, has not been materially improved since its early use. With the advent of improved semiconductor diodes, klystrons and low-noise dc amplifiers, it should be possible by means of good design techniques, to improve the overall capability of the Pound discriminator.

The second key item in the transmitter is the shunt modulator. For this particular application, a modulation depth of 20 db or better is desirable. This feature by itself is not very difficult to achieve. The important point is that this modulation range must occur simultaneously with a very low insertion loss. The presently allocated insertion loss is 1.5 db for the modulator. Certainly this must not be exceeded, and, if possible, lowered to less than 1 db.

Two types of shunt modulators will be evaluated - the reflective type and the absorption type. The implementation of the reflective type is closest to present-day capabilities, but would require the introduction of low-loss millimeter wave isolation to prevent the reflected energy from reaching the stabilized transmitter source and any frequency converters supplied by this source.

The shunt modulator, therefore, should ideally be an absorption type of modulator. The desirability of this feature is the fact that when the modulator is in the non-transit bias position, all the non-transmitted energy will be absorbed. The only presently available true absorbing semiconductor modulator is the PIN diode. Therefore, the operation of a PIN diode modulator at 35 and 16 Gc must be thoroughly investigated and documented. The main evaluation of this device would be to determine the actual change in match due to a change in the percent modulation. This, then, would be compared with a reflective model coupled to an isolator.

To this end, two, or possibly three, suitable modulators would be purchased and tested. On the basis of these results, a decision will be made as to the most suitable unit. As part of this work, any required modifications will be made.

The following are some typical manufacturers of diode modulators including some of the performance specifications.

Manufacturer	Insertion Loss (db)	Modulation Range (db)	Max. Required Power
Philco	1.5	20	50-60 mw
Somerset Radiation	4	60	1 w
Microwave Associates	3	30	100 mw
Hewlett Packard	Not high enough in frequency	--	--
Microwave Technology Inc	Less than 1.0	20	100 mw

The third critical item is the choice of the power supply. This unit must be capable of withstanding high g forces during launch and remain highly stable with a minimal change in the output levels. Power supplies of the SCR type are generally in use in space applications, but are usually tailor-made for any specific experiment. A thorough search of manufacturers literature will be made, circuit diagrams will be examined, and specifications will be scrutinized in order to arrive at the best choice.

7.1.2 Receiver Breadboarding

Three items in the receiver require early and special attention. The establishment of a firm foundation of knowledge and skill in these areas is somewhat lacking, as a general rule, and the best solution to problems of this nature is the construction of, and experimentation with, actual hardware.

The first of these key items is the harmonic mixer which receives signals at 94 Gc and uses the 35 Gc transmitter power for the local oscillator drive, thus delivering an IF signal at X-band. The loss and noise figure of this mixer has, of course, a direct relation to the sensitivity of the receiver and methods should be determined to optimize this sensitivity. For instance, it may be possible to obtain an improved performance by means of a small, external diode bias. This bias would certainly improve the IF impedance with respect to that of the tunnel diode IF amplifier input, another crucial item.

The next key item is the IF amplifier itself. The stability, impedance match and lowest available noise figure must be firmly established. A shortcoming of the tunnel diode amplifier, namely its limited dynamic range, will be carefully studied and suitable technology applied to overcome this shortcoming. Low-pass filtering techniques will be employed to avoid diode burnout due to dc transients.

Thirdly, the carrier phase-lock loop must be scrutinized in minute detail. The S/N ratio values required for lock and unlock are still theoretical postulates. Thus, it is essential that a loop be constructed and various levels of signals plus noise be injected into the loop in order to gain a firm feel for the possible improvements in this unit.

In order to retrieve the upper and lower sidebands of the 94 Gc signal, it is of course necessary to maintain a stability in the satellite, comparable to that of the ground terminal transmitter. Considering that hardly any restrictions are imposed on the size, weight and volume of the ground equipment, it is expected that the transmitted signal will be stable indeed. Thus, an extremely tight loop is required and should be given early attention.

7.2 Schedules and Budgetary Estimates for Flight Hardware

The schedules for design, fabrication and test of flight qualified hardware is given in Figure 7-1. Eighteen months are required to produce three

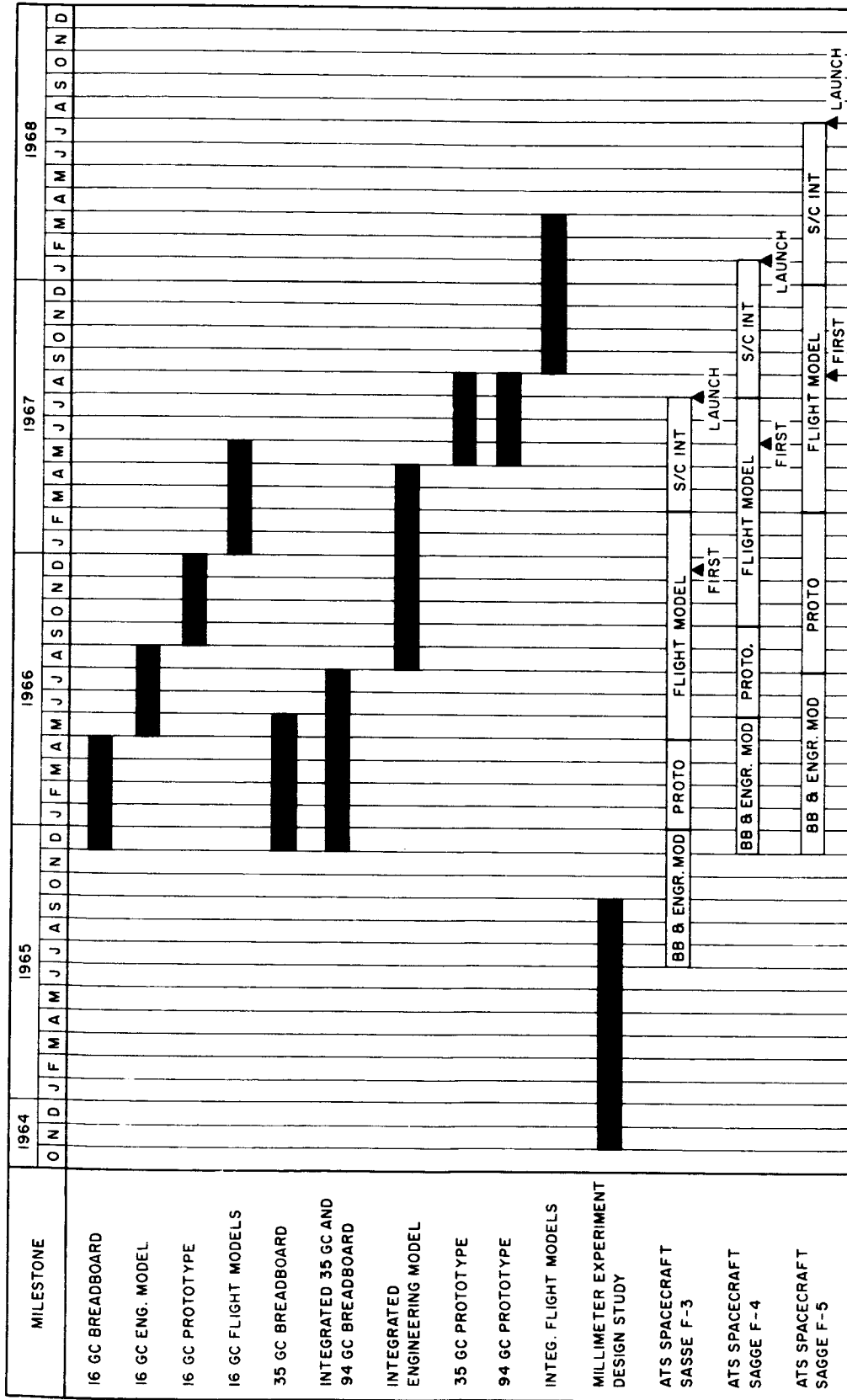


Figure 7-1. Time Schedule for Flight Hardware

flight models of the 16 Gc transmitter module and twenty-eight months are required to produce three flight models of the 35 Gc transmitter/94 Gc receiver module. Schedules for the ATS spacecraft, which were deduced from Reference 15, are also shown. To an acceptable degree, the time schedule for the 16 Gc payload appears to match flight F-4 and the time schedule for the 35 Gc/94 Gc payload appears to match flight F-5.

The various millimeter experiment models which are indicated on the schedule are defined as follows:

Breadboard Model

The breadboard model will consist of subsystems that are designed, built and tested to ascertain the approach required to implement system philosophy and will be used to establish the system and subsystem electrical parameters.

Engineering Model

The engineering model will consist of subsystems that are mechanically packaged and electrically tested to determine the physical size, weight and electrical performance characteristics of the proposed flight hardware. This model will function in a temperature cycled environment; but will not be capable of operation in the other physical environmental specifications required of flight models.

Flight Model Prototype

This model will consist of subsystems assembled and tested under the complete expected electrical and mechanical environmental specifications of the flight program and will determine the final system operational capabilities. This model will be a flight qualified system and will be subjected to the required flight qualifying testing.

Flight Models

These models will be assembled and tested to deliver the desired operational functions as part of a flight program. These units will be subjected to flight assurance testing.

A rough estimate of costs to produce this flight hardware is given in Table 7-I so that budgetary requests can be initiated.

TABLE 7-I
BUDGETARY COSTS FOR FLIGHT HARDWARE
(Thousands of Dollars)

<u>Unit</u>	<u>Cost (\$ Thousands)</u>
16 Gc Transmitter	225 - 275
35 Gc Transmitter and 94 Gc Receiver	450 - 525
Total	675 - 800

7.3 Budgetary Estimates for Ground Equipment

In order that GSFC can initiate budgetary requests for funds required for this program, results of a preliminary cost analysis for the ground equipment is presented. More detailed analysis would be necessary before cost data can be developed which is comparable to a formal cost quotation in a contractual commitment. This cost data is presented in shopping list form such that a choice can be made, depending upon available development time, budget limitations, urgency for the scientific information and payload allocations aboard the satellites. Costs for equipment operation, maintenance and data processing are not included in this analysis.

7.3.1 Signal Sources

Cost estimates for the signal sources are based on the block diagram of Figure 4-1 and the performance specifications given in Section 4.5.1. The following configurations are given:

Configuration A - The basic system consists of the frequency sources, the frequency measurement equipment, the AM modulators and their common modulation generator and driver.

Configuration B - This consists of the basic system plus the FM modulation capability which requires FM converters and a common FM signal generator.

Configuration C - This configuration consists of 8 Gc, 16 Gc and 94 Gc power amplifiers added to the system in Configuration B.

Configuration D - This configuration consists of Configuration C plus an automatic level control on the power amplifiers, RF switching for the FM modulators, and variable attenuators on the power amplifier outputs.

Configuration E - This configuration consists of Configuration D plus a tube development for a 35 Gc power amplifier.

The cost estimates for the five signal source configurations including system integration are as follows:

<u>Configuration</u>	<u>Cost (\$ Thousands)</u>
A	125
B	150
C	200
D	225
E	300

7.3.2 Main Receivers

Cost estimates for the main receiver system are based on the block diagrams of Figure 4-2 and Figure 5-2 and the performance specifications given in Section 4.5.2. The following receiver configurations are given:

Configuration A - This is the basic single channel system which includes either two interchangeable RF heads (16 Gc and 35 Gc) or four interchangeable RF heads (8 Gc, 16 Gc, 35 Gc, 94 Gc), a communication IF receiver, a radiometric IF receiver, a signal processor and an analog recording system.

Configuration B - This is a dual channel system which includes two or four dual channel interchangeable RF heads, two communication IF receivers, a radiometric receiver, a signal processor and an analog recording system. This system is capable of supplying angle error signals, in either the elevation plane or the azimuth plane, which give an indication of wavefront tilt. This system is also capable of being modified to perform automatic angle tracking in both planes.

Configuration C - This is Configuration B modified with mechanical RF switching and receiver angle error detectors to provide an automatic angle tracking capability.

The cost estimates* for the three main receiver configurations including system integration are as follows:

Configuration	Cost (\$Thousands)	
	Four RF Heads	Two RF Heads
A	200	150
B	225	200
C**	300	225

* Since the mechanical characteristics of the antenna-pedestal assembly have not been clearly defined, the cost of the cable interconnections between the IF preamplifier in the receiver compartment aboard the assembly and the IF receivers inside the building have not been included.

** These figures do not include the cost of the servo system.

7.3.3 Spacecraft Simulator

Cost estimates for the spacecraft simulator are based on the block diagrams for the satellite equipment given in Section 3-1 and the performance specifications given in Section 4.5.3. Two configurations are given:

Configuration A - This configuration consists of the 16 Gc and 35 Gc transmitters.

Configuration B - This configuration consists of the 16 Gc and 35 Gc transmitters plus a 94 Gc receiver.

<u>Configuration</u>	<u>Cost (\$Thousands)</u>
A	75
B	100

These figures are based on the costs to produce units whose design is based upon the developed engineering model of the flight hardware.

7.3.4 Auxiliary Receiver

Cost estimates for the auxiliary receiver which are based on the performance specifications given in Section 4.5.4 are \$75,000.

7.3.5 Ground Equipment Configurations

Several ground equipment configurations are possible in the costing analysis. Table 7-II suggests four interesting configurations the cost estimates of which give a fair idea of the total program cost for the ground equipment and the relative costs of the different items. The cost estimates are as follows:

<u>Configuration 1</u>		
<u>Quantity</u>	<u>Item</u>	<u>Costs (\$Thousands)</u>
1	Signal Sources "E"	300
1	Main Receivers "C" (four heads)	300
1	Spacecraft Simulator (engineering model of Flight Hardware Program)	0
2	Auxiliary Receivers	<u>150</u>
Total:		750

Configuration 2

<u>Quantity</u>	<u>Item</u>	<u>Costs (\$Thousands)</u>
1	Main Receivers "C" (two heads)	225
1	Spacecraft Simulator (engineering model)	0
2	Auxiliary Receivers	<u>150</u>
Total:		375

Configuration 3

1	Main Receivers "C" (two heads)	225
3	Main Receivers "A" (two heads)*	375
1	Spacecraft Simulator (engineering model)	0
1	Spacecraft Simulator "B"	100
3	Spacecraft Simulator "A"	225
3	Auxiliary Receivers	<u>225</u>
Total:		1150

Configuration 4

1	Signal Sources "E"	300
1	Main Receivers "C" (four heads)	300
3	Main Receivers "A" (two heads)	375
1	Spacecraft Simulator (engineering model)	0
1	Spacecraft Simulator "B"	100
3	Spacecraft Simulator "A"	225
3	Auxiliary Receivers	<u>225</u>
Total:		1525

* Unit costs are reduced because development was absorbed in cost of Main Receivers "C."

TABLE 7-II
GROUND EQUIPMENT CONFIGURATIONS
for
PRELIMINARY COSTING ANALYSIS⁽¹⁾

Config- uration	Item	GSFC	Aero- space	Univ. of Texas	AFCRL	Lincoln	Hay- stack
1	Signal Sources	1					
	Main Receivers	1					
	Spacecraft Simulator ⁽²⁾	1					
	Auxiliary Receiver	2					
2	Main Receivers ⁽³⁾	1					
	Spacecraft Simula- tor ⁽²⁾	1					
	Auxiliary Receivers	2					
3	Main Receivers ⁽³⁾	1		1	1		1
	Spacecraft Simula- tor ⁽²⁾	1	1	1	1		1
	Auxiliary Receivers	2	1				
4	Signal Sources	1					
	Main Receivers	1		1	1		1
	Spacecraft Simulator	1	1	1	1		1
	Auxiliary Receivers	2	1				

(1) Unless otherwise noted, items included in costing analysis are those marked by asterisk in Table 2-IV.

(2) GSFC simulator is Engineering Model of Flight Hardware.

(3) Main facility includes all asterisked items except the 8 and 94 Gc RF receivers and the demodulators.

8. PROGRAM FOR NEXT PERIOD

The program for the remainder of this study shall include the following major items.

8.1 Millimeter-wave Propagation Data Handbook

Make an outline of the propagation data handbook which should be the major result of the millimeter communication propagation experiments. The handbook should contain a theoretical section on propagation of millimeter waves, a presentation of basic data collected during the propagation program, and a performance evaluation of certain key modulations inferred from this basic data.

8.2 Descriptive Bibliography

Write a descriptive bibliography of reports related to this experiment design study. It should include such technical areas as theory of millimeter wave propagation, millimeter wave communication system technology, millimeter wave components, and existing experimental millimeter wave ground facilities.

8.3 Correlative Measurements

Investigate further the usefulness of weather radar as a correlative tool to be used in conjunction with other meteorological and radiometric devices.

8.4 Equipment Design

Devote further study to the critical design problems discussed in Section 7.1.

8.5 Data Processing and Evaluation

Describe the data processing requirements as specified in the Program Definition Document using Section 6 as an introduction.

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APPENDIX I

COMPONENT DEVELOPMENT FOR ADVANCED MILLIMETER COMMUNICATION / PROPAGATION EXPERIMENTS

This appendix to the report deals with a proposed development program designed to bridge the gap between the present state-of-the art millimeter equipment and that equipment required for future satellite communication systems. These proposed systems are considered to be a logical extension of the previously described spacecraft experiments, and are designed to make maximum use of the presently available millimeter technology and the lower frequency microwave developments. In particular, this section of the report presents three proposed packages which could be utilized in a spacecraft vehicle and operate in a mode similar to those previously discussed in Section 3. These proposed packages would utilize development to optimize the systems' RF bandwidth capabilities and would introduce communications technology via the implementation of FM communication link techniques.

These proposed systems would make use of two basic techniques used in present communication systems philosophy and extend these techniques into the millimeter area: first, the proposed development programs would make use of the currently utilized RF source and amplifier technology and would then apply through this development program the techniques for improving the sources' total overall efficiencies; and second, improve the overall receiver's efficiency via improved receiver noise figure techniques and the receiver's critical interface with stable low level local oscillator sources which supply the first converter signal. In considering the first development program, namely that of efficient RF sources, it is proposed that low level sources followed by amplifiers be considered. Basing this development on previously demonstrated system efficiencies, which have been utilized in communication satellites it is felt that the TWT and/or the distributed type of amplifying system would yield the best results in a development program of this nature. These devices have been employed primarily in

satellite communication systems utilizing FM modulation techniques for information channel characterization. This allows the systems designer to obtain maximum efficiency out of this final driver amplifier system by utilizing saturated power outputs.

The success which has been prominent in the area of efficient tube developments for devices of this nature prompts this study to recommend a development devices in the millimeter area similar to those previously developed in the centimeter regions. There does presently exist a number of companies which do possess the basic device technology and have proven their ability to generate an efficient RF amplifier package capable of space-craft environment while exhibiting extreme reliability, which is of prime consideration in a satellite communications system. It is further recommended that the development of efficient 10 w millimeter sources begin at 16 Gc and 35 Gc. The results of the development would present the system designer with a useful tool in considering the extension of communications up into the millimeter region.

The second area of development as seen by this report is that of improving the receiver's sensitivity via the introduction of improved first converter receiver noise figures and in parallel with this development there would be an extension of the present technology in the area of generating low level RF signals via solid state techniques for utilization as first converter signal bias. This two-fold development area, it is felt, can best be implemented via the utilization of sensitive high conversion efficiency Sharpless type of diode configurations which have demonstrated their ability to perform on very low level local oscillator signals. As is currently known, available millimeter mixers presently utilize conventional diode techniques which require approximately one milliwatt per crystal of local oscillator bias. In the consideration of utilizing the Sharpless type of mixer, converter local oscillator biases in the order of 200 to 500 mw of signal is considered to be adequate for the generation of optimum receiver noise figure.

This local oscillator bias signal is augmented via the introduction of a dc biasing network which establishes the normal operating point on the diode converters. This technique has been explored by several laboratories and has allowed the utilization of harmonic mixers and converters to be implemented into the sub-millimeter region. Hence the development program which is proposed would utilize this technology as presently known as a logical extension into the assembly of a receiver system capable of surviving a satellite environment with optimum reliability.

The block diagrams in Figures I-1 through I-3 indicate the proposed configurations of the two transmitter packages and the one receiver package just described. As noted in the transmitter block diagrams an FM modulator driving solid state VCO systems would be utilized as the driving signal to the final power amplifier output tube. These transmitter systems, as outlined, it is felt would require a minimum of development in the areas of the low level solid state devices required for their operation.

There presently does exist capabilities up through 16 Gc, as off-the-shelf items from several manufacturers. The device at 35 Gc, namely that of the solid state VCO would require some development in the area of the final multiplier stage. This, it is felt, can be accomplished through present state-of-the-art technology as demonstrated by several of the manufacturers' ability to generate 35 Gc signal levels in the order of 10 milliwatts which would be required to drive the final driver amplifier.

Tables I-I through I-III, weight, volume and power budgets, were developed to estimate the physical characteristics of the transmitters and the receiver. Table I-IV has been introduced to graphically show the goals of this proposed development by comparing the characteristics of the equipment suggested for the initial experiments with the equipment which should result from this development.

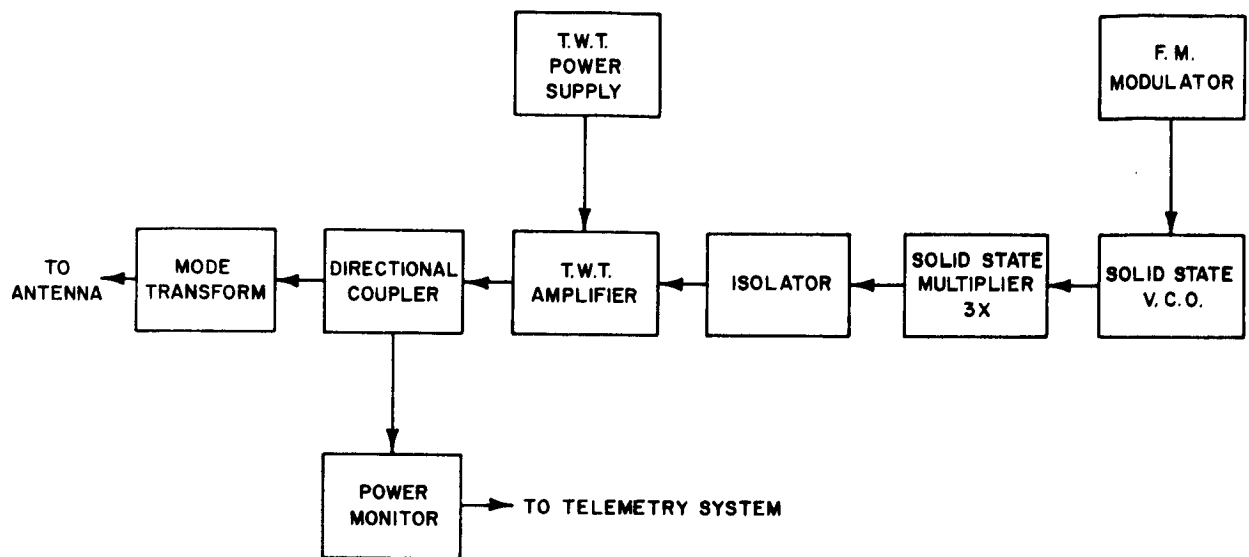


Figure I-1. 35 Gc Developmental Transmitter

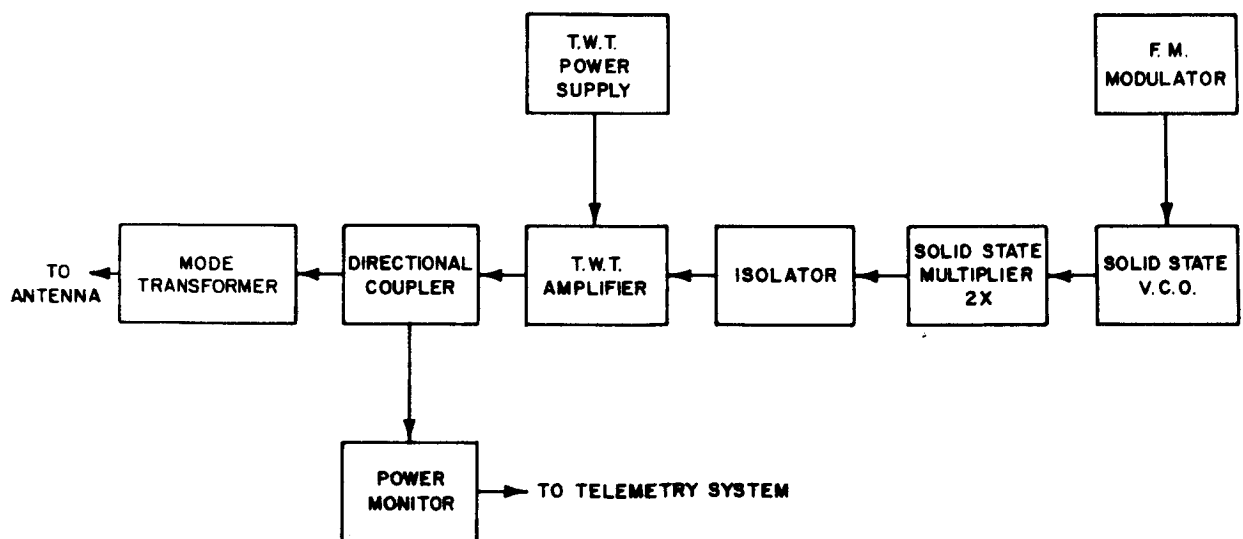


Figure I-2. 16 Gc Developmental Transmitter

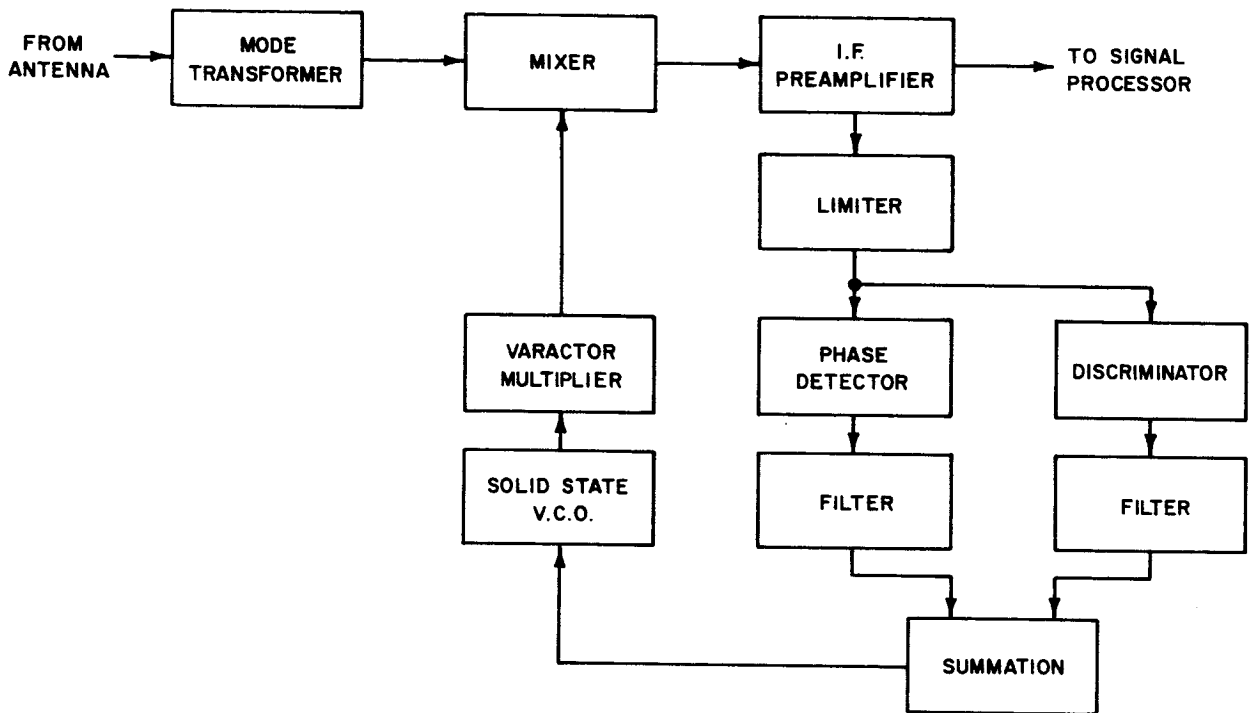


Figure I-3. 94 Gc Developmental Receiver

Finally, Figure I-4 gives a simple development program schedule and a rough estimate of the costs involved is given in Table I-V so that budgetary planning could be initiated.

TABLE I-I

POWER, WEIGHT AND VOLUME FOR 35 GC, 10 WATT
DEVELOPMENTAL SATELLITE TRANSMITTER

<u>Item</u>	<u>Weight (ounces)</u>	<u>Size (inches)</u>	<u>Prime Power Required (watts)</u>	<u>Remarks</u>
Direct. Coupler	5	2x1x1	54.0	For 1 year devel- opment for Bread- board + Eng Model
Crystal Det.	2	1x1x3		
TWT 10-watt Power	160	10x12x3-1/2		
Ampl. & Power Supply				
Isolator	3	2x1x1	15.0	
Solid State 3X Mult	5	2x2x2		
Solid State VCO	12	2x8x2		
F. M. Mod	6	2x1x3		
Connectors	16	1x1x8	1.0	
Miscellaneous	16	3x6x6	0.2	
Waveguide	8	2x2x12		
Power Monitor	3	1x1x2		
TOTALS:	19 lbs 12 oz	639 cu in.	69.2 watts	

TABLE I-II

POWER, WEIGHT AND VOLUME FOR 16 GC, 10 WATT
DEVELOPMENTAL SATELLITE TRANSMITTER

<u>Item</u>	<u>Weight (ounces)</u>	<u>Size (inches)</u>	<u>Prime Power Required (watts)</u>	<u>Remarks</u>
Direct. Coupler	6	2x1x1	0.2 50.0	1 year development for B. B. + Eng Model
Crystal Det.	2	1x1x3		
Power Monitor	3	1x1x2		
TWT 10 watts Ampl and Power Supply	160	10x12x3-1/2		
Isolator	3	2x1x1	9.0 0.8	
Solid State 2X Mult.	5	2x2x2		
Solid State VCO	12	2x8x2		
F. M. Mod	6	2x1x3		
Waveguide	16	2x2x12		
Connectors	16	1x1x8		
Miscellaneous	16	3x6x6		
TOTALS:	15 lbs 5 oz	639 cu in.	60.0 watts	

TABLE I-III

POWER, WEIGHT AND VOLUME FOR 94 GC
DEVELOPMENTAL SATELLITE RECEIVER

	<u>Weight (ounces)</u>	<u>Size (inches)</u>	<u>Prime Power Required (watts)</u>	<u>Remarks</u>
Mixer	10	3x2 -1/2x2 -1/2		Will obtain one Breadboard + one Eng. Model
Varactor Mult Chain	24	2x2x6	15.0	
I. F. Preamp	4	3x2x1	0.5	Development Required Will Build Will Build
Limiter	4	2x2x1	0.5	
Det. Disc Filters and	5	3x2x1	0.5	
Waveguide	16	1x2x12		
Connectors	8	1x1x8		
Miscellaneous	16	3x3x2		
TOTALS:	5 lbs 7 oz	109 cu in.	16.5 watts	

TABLE I-IV

IMPROVEMENTS IN MILLIMETER-WAVE SATELLITE
EQUIPMENT RESULTING FROM DEVELOPMENT PROGRAM

	<u>Present Capability</u>	<u>Development Results</u>
35 Gc Transmitter		
Output Power	.2 watt	10 watts
Prime Power	80 watts	70 watts
Weight	10 lbs	15 lbs
Parts Volume	370 cu in.	640 cu in.
16 Gc Transmitter		
Output Power	.2 watt	10 watts
Prime Power	55 watts	60 watts
Weight	10 lbs	15 lbs
Parts Volume	350 cu in.	640 cu in.
94 Gc Receiver		
Noise Figure	20 db	15 db
Prime Power	60 watts	17 watts
Weight	10 lbs	6 lbs
Parts Volume	350 cu in.	110 cu in.

TABLE I-V

BUDGETARY COSTS FOR DEVELOPMENT PROGRAM
(Thousands of Dollars)

<u>Unit</u>	<u>Cost</u>
35 Gc Transmitter	250-300
16 Gc Transmitter	225-275
94 Gc Receiver	<u>225-275</u>
Total:	700-850

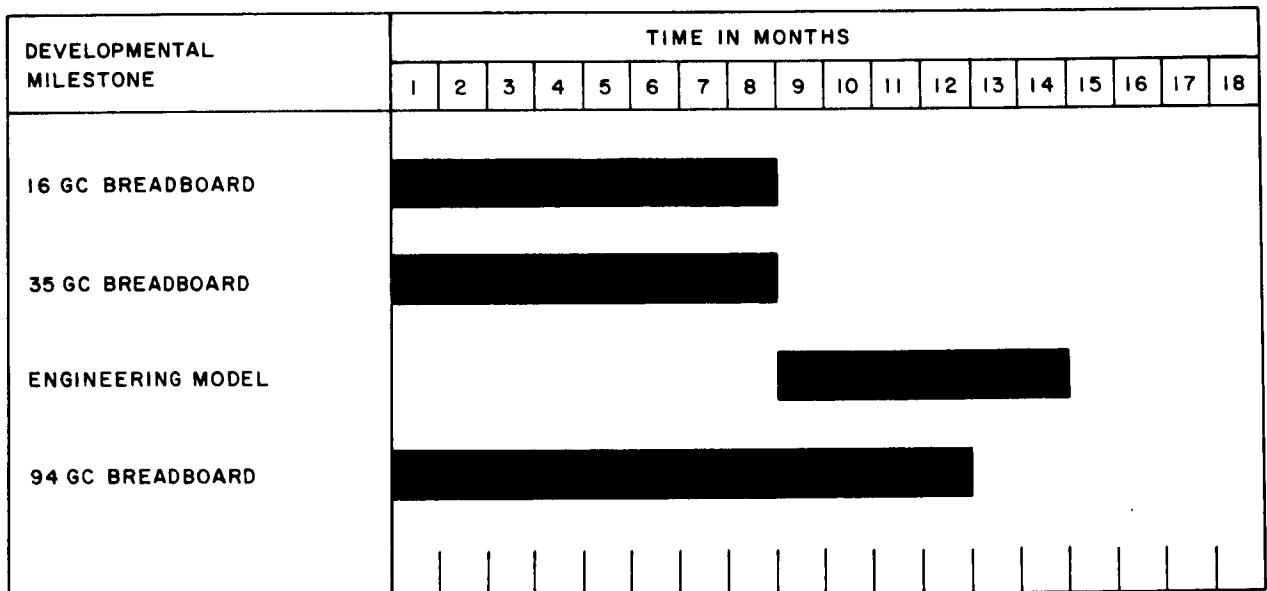


Figure I-4. Developmental Time Schedule

APPENDIX II

MILLIMETER-WAVE SATELLITE COMMUNICATION SYSTEMS

System configurations should be developed for millimeter-wave satellite communication systems which indicate specifically where millimeter-wave (10 Gc to 40 Gc) equipment could be applied to fulfill future communication requirements. Areas of subsystem and component development indicated by these system configurations should provide a time scale which shows when these millimeter-wave systems become technically and economically competitive with the lower frequency systems. Manned space stations should be included in the development of useful system configurations.

The system configurations would consist of ground terminal and satellite transponder block diagrams accompanied by the appropriate systems analysis which describes the signal levels throughout the system. The system configurations chosen should be based on system trade-off studies which establish optimum design parameters such as ground and satellite transmitter outputs, ground and satellite antenna sizes, receiver sensitivities and methods of modulation. The problems associated with directional high gain satellite antennas and the frequency instabilities associated with millimeter wave RF sources should be defined and possible methods for solution provided. The system configurations should include geometric dimensions; that is, geographic location of ground terminals and satellite orbital parameters. The effects of the propagation medium must be considered in terms of margins against signal fading and atmospheric absorption which are based on weather statistics and ground terminal operational elevation angles.

Results of the study should indicate clearly the subsystem capabilities of the satellite and ground equipment which must be achieved before useful system applications are possible. A subsystem and component development program should be recommended which is based on the present state-of-the-art and which is projected into the 1968-1975 time period.

To illustrate the feasibility of future millimeter communication systems and to indicate those areas where subsystem and component development is most necessary, United States-Europe FM television links via a synchronous stationary satellite at 4 Gc/6 Gc, 15 Gc/16 Gc, 33 Gc/35 Gc are compared.

Washington was chosen as the ground terminal because orbital data and meteorological statistics for that area are readily available from the propagation experiment design study. The satellite is positioned at 30° west longitude near the position of the present Early Bird satellite. Figure 2-10 in Section 2 of this report shows that 30° west longitude is suitable for European cities such as London and Berlin. Figure 2-11, also in Section 2, shows that the ground terminal line-of-sight to the satellite from Washington (GSFC) has an elevation angle of 23 degrees. From Figures 5-8 and 5-9, the atmospheric attenuation during heavy rainfall is 1.2 db for 16 Gc and 4.0 db for 35 Gc for 23 degrees elevation. Figures 5-12 and 5-13 give apparent antenna temperatures of 80° K for 16 Gc and 200° K for 35 Gc. These numbers are based on a 0.2 inch per hour rainfall rate which, for the Washington area, occurs 0.5 per cent of the time (see Figure 3-10 in the First Quarterly). It is expected that similar heavy rainfall statistics prevail for most United States and European cities.

Table II-I gives the characteristics of the ground terminal and the satellite transponder. The 4 Gc/6 Gc system characteristics are similar to those being considered for systems presently under development. The apparent antenna temperatures have little effect on the ground and satellite receiver 16 Gc and 35 Gc noise densities because of the high receiver noise figures and receiver losses which are assumed. The receiver noise density at the receiver input in watts per cps is computed as:

$$N_d = KT_o(FL-1) + KT_A$$

where

K = Boltzman's constant - 1.38×10^{-23} watts-sec/°K

T_o = Receiver noise temperature - °K

F = Receiver noise figure

L = Receiver signal losses prior to mixer

T_A = Apparent antenna temperature - °K

Table II-II is a system performance chart for a single channel television link which shows the signal levels throughout the Washington to Europe link. Fading losses due to multipathing were assumed to be insignificant because of the 23 degree elevation angle. However, actual propagation tests must be made in order to validate this assumption.

Table II-III is an extension of Table II-II by showing how multiple TV channels can be accommodated by increasing satellite antenna size. This exercise points out the following important conclusions:

- 1) Development of high capacity (multiple channel television, voice and teletype) millimeter satellite communication systems are feasible within the next few years.
- 2) Effects of propagation do not appear to be serious over most of the range of useful elevation angles and ground terminal locations. However, statistical propagation data for each ground-space link should be obtained before any large system development commitments are made.
- 3) The key to high capacity millimeter links is development of high gain satellite antennas. The size of the antennas are not prohibitive but the antenna pointing problem and the multiple access problem must be overcome.
- 4) Other areas of development required are in the areas of transponder efficiency and reliability, receiver sensitivity, high power ground transmitters and larger all weather millimeter-wave ground antennas.

TABLE II-I

SYNCHRONOUS SATELLITE COMMUNICATION SYSTEM CHARACTERISTICS FOR WASHINGTON-EUROPE FM TELEVISION

(Single Channel)

GROUND TERMINAL			
	<u>Transmitter</u>		
Frequency (Gc)	6	16	35
Power (w)	2000	500	500
Losses (db)	1.0	1.0	1.0
Video Bandwidth (Mc)	4	4	4
RF Bandwidth (Mc)	25	25	25
Modulation Index -m	2.5	2.5	2.5
	<u>Receiver</u>		
Frequency (Gc)	4	15	33
Noise Figure (db)	1.0	4.0	7.0
Losses (db)	1.0	1.0	1.0
Antenna Temperature ($^{\circ}$ K)	20	80	200
Noise Density (db/cps)	-205.9	-200.1	-196.2
FM Processing Gain (db)	18.2	18.2	18.2
	<u>Antenna</u>		
Frequency (Gc)	4-6	15-16	33-35
Diameter (ft)	85	85	60
Beamwidth (deg)	0.14 to 0.21	0.054	0.035
SATELLITE TRANSPONDER			
	<u>Transmitter</u>		
Frequency (Gc)	4	15	33
RF Power (w)	10.0	10.0	10.0
Prime Power	35.0	60.0	70.0
Losses (db)	3.0	3.0	3.0
Bandwidth (Mc)	25	25	25
	<u>Receiver</u>		
Frequency (Gc)	6	16	35
Noise Figure (db)	7.0	11.0	14.0
Losses (db)	3.0	3.0	3.0
Antenna Temperature ($^{\circ}$ K)	290	290	290
Noise Density (db/cps)	-194.1	-189.9	-187.1
	<u>Antenna</u>		
Frequency (Gc)	4.6	15-16	33-35
Diameter (in)	10.1	5.7	8.2
Beamwidth (deg)	21.0	9.4	3.0

TABLE II-II

SYNCHRONOUS SATELLITE COMMUNICATION SYSTEM PERFORMANCE
CHART FOR WASHINGTON-EUROPE FM TELEVISION

Single Channel

UP-LINK			
Frequency (Gc)	6	16	35
Transmitter Power (dbw)	33.0	27.0	27.0
Transmitter Losses (db)	-1.0	-1.0	-1.0
Ground Antenna Gain (db)	62.1	70.6	74.4
Space Attenuation (db) (1)	-200.2	-208.7	-215.5
Propagation Losses (db) (2)	-0.2	-1.2	-4.0
Spacecraft Antenna Gain (db)	18.0	25.0	35.0
Antenna Beam Shape Loss (db)	-2.3	-0.5	-0.5
Receiver Losses (db)	-3.0	-3.0	-3.0
Received Carrier Power (dbw)	-93.6	-89.8	-87.6
Receiver Noise Density (dbw/cps)	-194.1	-189.1	-187.1
Receiver Noise Bandwidth (db/cps)	74.0	74.0	74.0
Receiver Noise Power (dbw)	-120.1	-115.9	-113.1
Carrier-to-Noise Ratio (db)	26.5	27.1	25.5
DOWN-LINK			
Frequency (Gc)	4	15	33
Transmitter Power (dbw)	10.0	10.0	10.0
Transmitter Losses (db)	-3.0	-3.0	-3.0
Spacecraft Antenna Gain (db)	18.0	25.0	35.0
Antenna Beam Shape Loss (db)	-2.3	-0.5	-0.5
Space Attenuation (db) (1)	-196.7	-208.2	-215.0
Propagation Losses (db) (2)	-0.2	-1.2	-4.0
Ground Antenna Gain (db)	58.4	70.1	73.9
Receiver Losses (db)	-1.0	-1.0	-1.0
Received Carrier Power (dbw)	-116.8	-108.8	-104.6
Receiver Noise Density (dbw/cps)	-205.9	-200.1	-196.2

Table II-II (Continued)

Receiver Noise Bandwidth (db/cps)	74.0	74.0	74.0
Receiver Noise Power (dbw)	-131.9	-126.1	-122.2
Carrier-to-Noise ratio -down (db)	15.1	17.3	17.6
Carrier-to-noise ratio. -up (db)	26.5	27.1	25.5
Carrier-to-noise ratio -total (db)	14.8	16.9	16.9
FM Processing Gain	18.2	18.2	18.2
Video S/N Ratio	33.0	35.1	35.1

(1) Slant range = 21,470 n. miles

(2) Atmospheric absorption only

TABLE II-III
SATELLITE TRANSPONDER CHARACTERISTICS
for
MULTIPLE CHANNEL TELEVISION

Number of One-Way Channels	Power (w)		Antenna Gain (db)		Antenna Diameter (in)		Beamwidth (deg)	
	16 Gc	35 Gc	16 Gc	35 Gc	16 Gc	35 Gc	16 Gc	35 Gc
1	10.0	10.0	25	35	5.7	8.2	9.4	3.0
4	10.0	10.0	31	41	11.4	16.4	4.7	1.5
10	10.0	10.0	35	45	18.1	26.0	2.9	.9

APPENDIX III

MILLIMETER-WAVE SPACE COMMUNICATION SYSTEMS*

Little effort has been performed to show specific applications of millimeter-wave systems in space communications. Full system trade-off comparisons between the 1 Gc to 10 Gc band and the 10 Gc to 300 Gc band are needed for future earth-orbiting, lunar and planetary missions in order to orient our millimeter-wave component and system technology research and development efforts.

System analysis and feasibility studies should be aimed to establish overall systems design criteria and utilization of the millimeter-wave technology for future space communication. What kind of millimeter-wave sources should be used for support of future space missions? What should their particular characteristics be in order to be most useful? Can a millimeter-wave system be advantageously integrated into the presently available worldwide communications networks?

Particular attention should be focused on comparison of optimum designed systems operating at important discrete points within the 1 Gc to 300 Gc band. To accomplish this, specific space missions, which are representative of the 1968 to 1975 era, should be chosen and, through a series of equipment trade-offs, the optimum system be designed at each frequency for each mission. This parametric comparison should also include advances in state-of-the-art throughout the 1968 to 1975 period in such technical areas as antennas, receiver sensitivity, transmitter output levels and efficiency and performance vs. weight and volume.

* This work statement is patterned after GSFC RFP No. 513-18731/235, April 16, 1965, which discusses a study to be performed on laser space communication and tracking systems.

As a result of these studies, it is expected that such questions as the following be answered:

1. Do millimeter space communication systems have any application in interplanetary missions? If so, does the spacecraft communicate directly to the earth through the atmosphere or indirectly through an earth satellite or a lunar base?
2. Do millimeter space communication systems have any application in lunar missions whether it be moon-earth, moon-spacecraft or line-of-site on the lunar surface?
3. Do millimeter space communication systems have any application in spacecraft-to-earth and spacecraft-to-spacecraft communications near the earth? If so, what are the limitations on distance between terminals?
4. What methods should be employed to overcome acquisition and tracking problems associated with pointing the narrow millimeter-wave beams?
5. How can the acquisition and tracking problems associated with large doppler effects and millimeter source instabilities be handled?

In addition to answering the above questions, the results of the study should include all parametric data and block diagrams of the equipment used in designing the optimum system. This parametric data includes such factors as specific weight of energy sources, spacecraft transmitter watts per pound, spacecraft antenna gain per pound, mission time, duty cycle and data rate. Because of the large number of variables involved, recommendations should be made regarding the development of computer programs which would be valuable in solving future space communication problems.

APPENDIX IV

DESIGN OF MILLIMETER-WAVE COMMUNICATION / PROPAGATION EXPERIMENTS FOR MANNED EARTH- ORBITING MISSIONS *

A study should be performed to investigate the importance of conducting millimeter-wave communication/propagation experiments aboard manned earth-orbiting spacecraft by describing and assessing the direct benefits to be achieved by conduction of the experiments. The study should also determine what benefits could be derived from future operational space systems and programs to which the experimentation under consideration would contribute. The study must determine the degree to which the successful conduct of each experiment requires a manned orbital vehicle. Experiments or portions of particular experiments that could be conducted or verified aboard balloons, high altitude aircraft and/or unmanned spacecraft prior to, or in lieu of, flight on manned earth-orbiting vehicles, should be clearly and specifically identified.

The study includes an investigation of the feasibility and utility of conducting meteorological experiments aboard manned earth-orbiting spacecraft, and define in depth a series of such experiments which would give due consideration to exploiting the advantageous capabilities peculiar to manned spacecraft for:

1. The conduct of research necessary for the better understanding of the earth's atmospheric structure and behavior needed to promote the development of future millimeter wave communication systems;
2. The development of equipment and techniques applicable to future unmanned communication satellites; and

* This work statement is patterned after NASA Hq. RFP No. 10-5805 "Meteorological Experiments for Manned Earth-Orbiting Missions," March 22, 1965.

3. The test and assessment of the applicability of these equipments and techniques to operational needs.

To complete the study, the following items associated with the conduct of millimeter experiments on manned earth-orbiting spacecraft should be defined and analyzed:

1. The specifics of each millimeter experiment, the data to be obtained, the anticipated results, the application of the data, and the manner in which each experiment relates to other experiments and to the capabilities of unmanned satellites.
2. The desirable operating regimes (altitude, orbit inclination, etc.), receiver sensitivity, transmitter power, signal levels, antenna gain and spacecraft stabilization required by each experiment. As set forth above, experiments or portions of experiments which could be conducted or verified aboard balloons, high-altitude aircraft and/or unmanned spacecraft prior to flight on manned earth-orbital vehicles should be specifically identified.
3. The specific types of equipment required, their design, configuration, mode of operation, and availability. If necessary equipments are not available, estimates of development costs and time should be included.
4. The requirements imposed by each experiment in terms of equipment, weight, volume, power, environment, number and skills or functions of the astronauts and the ground crew, operator time, transmission and recovery of data, etc.
5. Spacecraft integration and operational problems including those associated with the conduct of multiple experiments with the same equipment, concurrent experiments which compete for operator attention, and experiments by a non-specialist member of the crew.

APPENDIX V

SPACECRAFT MILLIMETER RADIOMETER FOR VERTICAL SENSING METEOROLOGY AND GROUND MAPPING

1. INTRODUCTION

This appendix deals with a brief introduction to the possible uses of radiometric receivers in earth orbiting satellites. The discussion considers three types of systems and three types of satellite platforms. One type is the vertical sensor which uses millimeter radiometry. This system is implemented with best achievable accuracy when working on a stable oxygen absorption line frequency near 60 Gc.

Two other types of systems, the meteorological and ground mapping systems, are discussed in the general term of resolution cells. It should be pointed out that this section of the report is not considered a design study, but is only intended to present the overall potential capabilities of these approaches.

The summary and conclusion drawn are considered to be gross indications of the feasibility of such an implementation when considering present vehicle performance and environment specifications. The vehicles considered are: (1) the low altitude 300 - 500 n mi. satellite; (2) the medium altitude 5000 - 7000 n mi. satellite; and (3) the synchronous altitude satellite. These are further elaborated in that two stabilization systems are considered - (1) the spun stabilized vehicle, and (2) the stabilized vehicles such as gravity gradient or gas jet system.

2. Vertical Sensing Utilizing Radiometric Techniques

The local vertical of an earth orbiting vehicle may be established through temperature sensing and comparison of the earth's rim. Many schemes have been discussed, however at this time, only one is to be considered.

The block diagram of a typical radiometer system capable of producing and output directly proportional to the difference in temperature as seen between two antennas included as Figure V-1. This radiometer also generates noise fluctuations at its output, which are expressed as:

$$\Delta T(\text{RMS}) = \frac{\sqrt{\pi} |F_s - 1| T_o}{\sqrt{B \tau}} \quad (\text{V-1})$$

where

$\Delta T(\text{RMS})$ = RMS fluctuations at radiometer output

F_s = system noise figure

T_o = ambient temperature in degrees kelvin

B = predetection bandwidth in cycles

τ = post-detection integration time in seconds

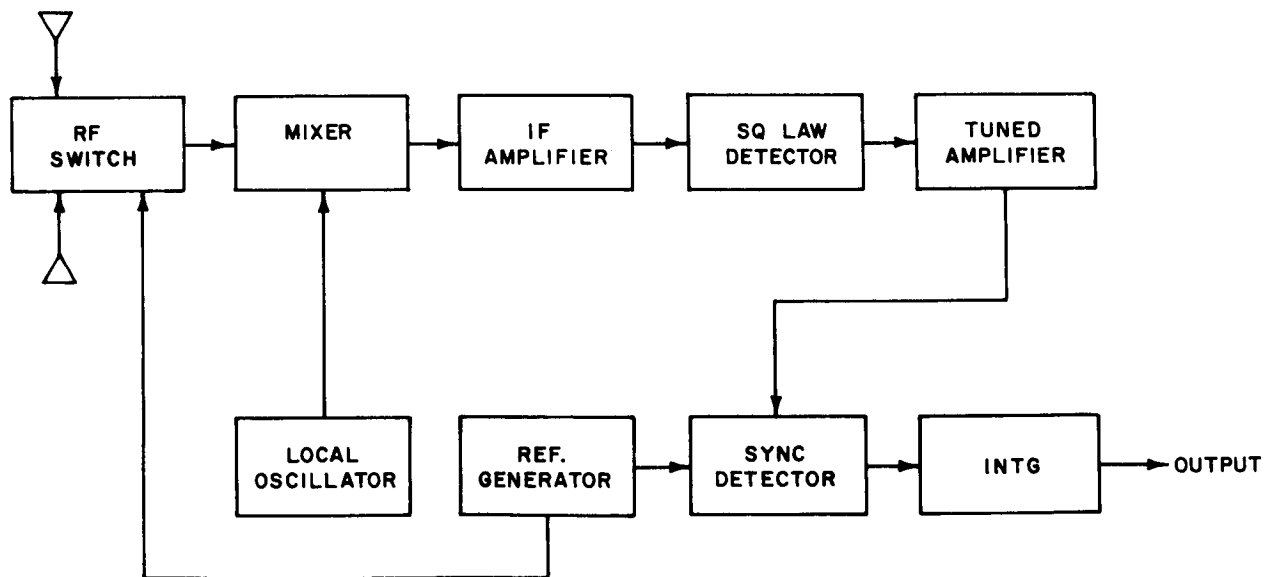


Figure V-1. Vertical Sensor Radiometer

These two antennas, in the case of a stationary vehicle, could be spaced so that their beam axes are displaced by the angle subtended by the earth or in the case of a spinning vehicle, could be spaced 180° apart.

If one were to assume square antenna beam patterns, and the angle between two antenna beam axes is equal to the angle subtended by the earth; the anticipated radiometer output vs rotation of the vehicle about its longitudinal axis is shown as Figure V-2. The accuracy to which it may be determined when the local vertical is exactly one half the angular spacing of the two antennas, is a function of the noise fluctuations at the radiometer output. This angular accuracy may be defined as the inverse slope of the 's' curve in Figure V-2 times the noise fluctuations.

$$\delta \theta = \left(\frac{\theta_A}{2T_A} \right) \Delta T (\text{RMS}) \quad (\text{V-2})$$

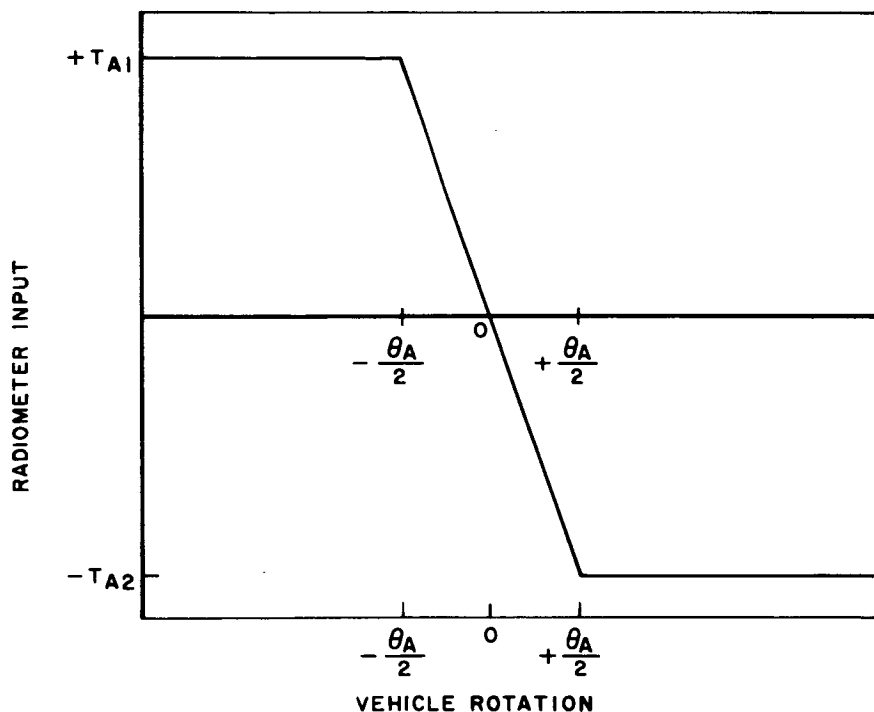


Figure V-2. Radiometer Input vs Vehicle Rotation

where:

$\delta\theta$ = angular error (rms)

θ_A = antenna beamwidth

T_A = antenna temperature when pointing at earth

Substituting Equation (V-1) into Equation (V-2) results in:

$$\delta\theta = \frac{\theta_A \sqrt{\pi} |F_s - 1| T_o}{2 T_A \sqrt{B} \tau} \quad (V-3)$$

Equation (V-3) specifies the angular error in defining the local vertical as a function of system parameters. However, this equation is valid in the system open loop configuration, only if the system parameters are the exact reproduction of the differential antenna temperature as a function of antenna position. The ability of the radiometer to reproduce the antenna input function is a function of the beamwidth scan time to system integration ratio. Where beamwidth scan time is the time it takes the antenna to scan one antenna beamwidth. The radiometer output time function for various ratios of antenna beamwidth scan time to system integration time is in Figure V-3. From this figure, one readily sees that large antenna beamwidth to system integration time ratios are mandatory to adequately reproduce the antenna time function.

The vehicles destined for the communication experiment includes a vehicle spinning about its longitudinal axis at a rate of 100 revolutions per minute. Angular local vertical position sensing capabilities of a system, utilizing the 94 Gc communication receiver in the satellite were calculated with Equation 3 assuming $\sigma = 2.5$, and the results are tabulated in Table V-1. These values of $\delta\theta$ were calculated assuming a constant vehicle spin rate, however, in reality this spin rate may vary anywhere from 50 to

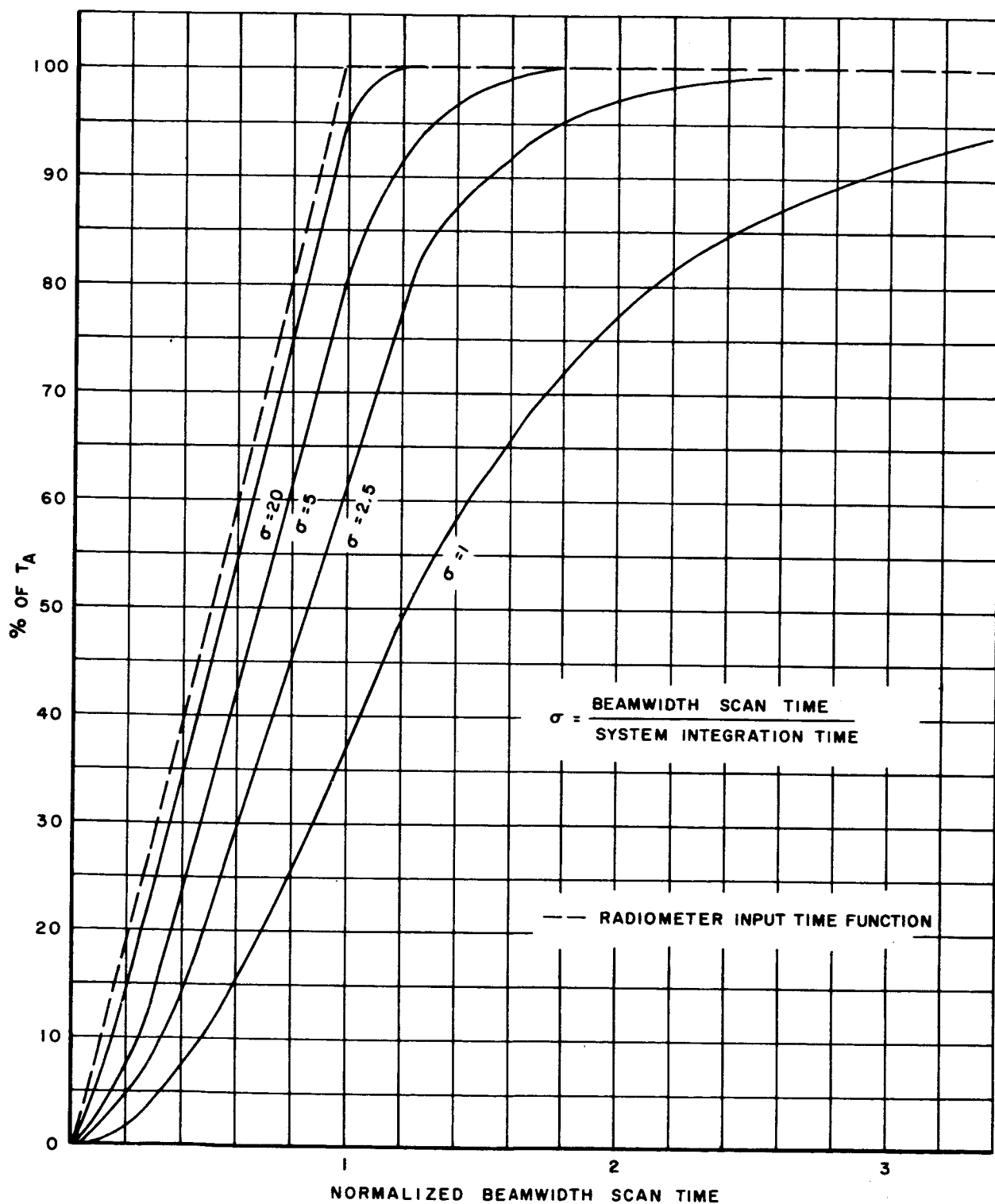


Figure V-3. Radiometer Output Time Function

150 revolutions per minute. In the case where the vehicle spin rate decreases to 50 revolutions per minute, σ increases to 5, thus increasing the error by 0.25 times the antenna beam width.

TABLE V-1 94 Gc RECEIVER LOCAL VERTICAL SENSING

Antenna Beamwidth (degrees)	Angular Error (degrees)	Integration Time (seconds)
10	6.7	.007
20	9.5	.014
30	11.7	.020

The nonspinning vehicle, utilizing a radiometric vertical sensing system with both antenna axes tangent to the earth's surface, attains positioning capabilities an order of magnitude better than the sensor in the spinning mode. However, due to the fact that the antenna temperature of the atmosphere subtended by the earth differs by 25% from the antenna temperature due to the atmosphere subtended by an ocean, the error could be approximately .12 times the antenna beamwidth.

Vertical sensing systems, utilizing radiometric techniques and operating in the atmospheric oxygen radiation spectrum (60 Gc), have capabilities of resolving the local vertical to within ± 3 minutes of arc. One great advantage of this system is the antenna temperature consists of radiation originating from the oxygen in the upper layers of the atmosphere only, thus no system errors can result from inhomogeneities in the lower atmosphere and differential temperature of the earth, since this energy is attenuated greatly by the atmospheric oxygen.

As examples of potential errors in the infrared system due to the atmosphere's mantel, the subtended angle due to this mantel for the two altitudes of interest are listed below.

Satellite Altitude (n miles)	Subtended Angle (minutes)
300	47
500	34
6000	8

The above table defines the error due to the mantle of the infra-red system as an inverse function of the vehicles orbiting altitude.

Vertical sensing is presently implemented with infrared systems which are adequate for present requirements of vehicles orbiting at altitudes greater than 300 nautical miles. The infrared system accuracy degrades below 300 nautical miles, due to the fact that the atmosphere; in which most of the system inaccuracy is generated, subtends an angle of approximately one degree.

Vertical sensing with radiometric techniques is feasible, however the infrared system is presently adequate in vehicles orbiting at altitudes in excess of 300 nautical miles, and radiometric system at 94 Gc would be degraded in accuracy by orders of magnitude.

A radiometer operating as a vertical sensor in a non spinning vehicle, at any altitude, will demonstrate accuracies similar to the infrared systems. Vehicles at lower orbiting altitudes say from 6000 nautical miles, the 60 Gc radiometric sensor will excell, however the radiometer system occupies about four times the volume on an infrared system.

3. Meteorological and/or Ground Mapping

In introducing this area, let us first examine the physics of the earth and atmosphere in the millimeter region. In Figure 5-11 is the temperature profile as viewed from an earth satellite vehicle. This figure shows the effect that water vapor has on the expected antenna temperature and also

shows the effect of land and sea masses on this emission temperature. Note that this curve does not include the effect of oxygen line absorption which will introduce approximately 290°K in the 60 Gc region.

Hence, with this information, it would then be necessary to instrument an antenna system which would have resolution cells of 50 to 500 n.m., such that beam position on the earth may be readily correlated to local weather condition and on sea state in order that true qualitative measurements of the actual effects of these variables may be obtained.

For purpose of indicating the instrumentation problems, the following table shows for three frequencies, namely 10, 30 and 100 Gc, the size of the receiving aperture for ground resolution cells of 50 and 500 n.m. when viewed at 500, 5000, and 19,500 n.m. The calculations were based on a flat earth.

	SATELLITE ALTITUDE IN NAUTICAL MILES		
	500	5000	19,500
Beamwidth for 50 n.m. resolution(degrees)	5.7	.57	.14
Receiver Ant. size at 10 Gc (ft)	1.2 ft.	12.0	47.8
Receiver Ant. size at 30 Gc (ft)	.4 ft.	4.0	15.5
Receiver Ant. size at 100 Gc (ft)	.12 ft.	1.2	4.7
Beamwidth for 500 n.m. resolution(degrees)	53.1	5.7	1.4
Receiver Ant. size at 10 Gc (ft)	less than .5 ft.	1.2 ft	4.7
Receiver Ant. size at 30 Gc (ft)	less than .5 ft	less than .5 ft	1.6
Receiver Ant. size at 100 Gc (ft)	less than .5 ft.	less than .5 ft.	less than .5 ft.

Calculations based on the following condition:

- 1) Considering flat plane and ignoring curvature of the earth.