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FINAL REPORT
VOLUME III
FOR
MILLIMETER COMMUNICATION PROPAGATION PROGRAM
(1 NOV., 1964 – 1 NOV., 1965)

Contract No. NAS 5-9523

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

Raytheon Report No. FR-65-334-3

for

GODDARD SPACE FLIGHT CENTER
SYSTEMS DIVISION
COMMUNICATIONS RESEARCH BRANCH
CODE 733
Greenbelt, Maryland

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SUMMARY

This document is Volume III of the final report for the Millimeter Communication Propagation Program being performed under NASA Contract No. NAS5-9523 by Raytheon's Space and Information Systems Division for Goddard Space Flight Center. This program is a study to design experiments which will determine the effects of the propagating medium on millimeter-wave (10 to 100 gigacycles) space-earth communications. Volume III is a descriptive bibliography of documents which were used during the study.

The documents are broken down into several categories: meteorology, atmospheric propagation, plasma effects, channel characterization, communication system performance, communication system applications, antennas and components, circuits, experimental ground facilities, and other bibliographies. The description of each document includes: the author's title; publication; date; company or agency with which the author was affiliated; author's abstract, summary, preface, or introduction; and other comments which show how the document specifically relates to millimeter-wave propagation, experiment design, and system application.

PRINCIPAL CONTRIBUTORS

The technical officers at Goddard Space Flight Center who were responsible for this study were Mr. Abe Kampinsky and Mr. Walter Elder of the Communications Research Branch in the Systems Division. The key Raytheon participants are given in Table I.

Valuable advice regarding existing theoretical and experimental propagation data and existing experimental ground facilities was received from the following agencies:

Aerospace Corporation, El Segundo, California

Air Force Cambridge Research Laboratories, Bedford, Massachusetts

MIT, Lincoln Laboratory, Lexington, Massachusetts

Electrical Eng. Research Lab., University of Texas, Austin, Texas

KEY RAYTHEON PARTICIPANTS IN MILLIMETER-WAVE COMMUNICATION PROPAGATION STUDY

Name	Raytheon Organization	Technical Area
Mr. Ira Smith	SISD(1), Sudbury, Mass.	Study Director
Dr. Eli Brookner		Atmospheric Propagation Effects, Waveform Analysis, Data Processing
Mr. Joseph Clougherty		Atmospheric Propagation Effects, Plasma Effects
Mr. Edward Gifford		Equipment Design
Mr. Ronald Porter		Correlative Measurements, Meteorology
Mr. Louis Romano		Atmospheric Propagation Effects, Signal Analysis, Equipment Design
Mr. Thomas Servey		Atmospheric Propagation Effects, Meteorology
Mr. Arthur Robichaud	(now with National Radio Astronomical Observatory)	Facilities Survey, Equipment Design
Mr. Robert Savage	SBO(2), SISD, Santa Barbara, California	Equipment Design
Mr. David Barton	SURANO(3), Equipment Division, Wayland, Mass.	Atmospheric Propagation Effects
Dr. Joseph deBettencourt	CADPO(4), Equipment Division, Norwood, Mass.	Atmospheric Propagation Effects
Dr. John Myers	Research Division, Waltham, Mass.	Atmospheric Propagation Effects
Dr. Barret Hazeltine	Consultant, Brown University, Providence, R.I.	Correlative Radiometric & Radar Measurements
Mr. Donald Snyder	Consultant, MIT, Cambridge, Mass.	Data Processing

(1) SISD - Space and Information Systems Division
(2) SBO - Santa Barbara Operation
(3) SURANO - Surface Radar and Navigation Operation
(4) CADPO - Communications and Data Processing Operation

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Section I
INTRODUCTION

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

The scope of work for this study program was defined in Exhibit "A" of Contract NAS5-9523 and supplemented by the Raytheon Proposal, "A Millimeter Communication Propagation Program," BR-3011, 3 June 1964. Another report which supplements Exhibit "A" is, "Program Definition Plan for Millimeter Communication Propagation Program," FR-4-498-B, 29 January 1965. The Program Definition Plan defines the objective 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.

The objective of this experiment design study was to design a series of experiments which show how the objectives of a millimeter propagation program can be met. Wherever design problems could not be solved, courses of action in the form of component tests and breadboard design were recommended. This objective includes development of experiment cost estimates and time schedules, including that for data processing and evaluation. 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 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 propagating medium as they are known today and discussed a one-year space-earth experiment to be performed in 1968 with a 6000 nautical mile medium altitude satellite. The Second Quarterly Report, which was a report of work accomplished during the period 1 February 1965 to 1 May 1965, described a one-year space-earth experiment using a synchronous stationary satellite. The Second Quarterly Report also described in 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 final report consists of three volumes. Volume I is a summary of all the work performed during the program. Volume II is a detailed report of work accomplished during the third quarter, 1 May 1965 to 1 August 1965. The most significant technical areas covered in Volume II are: The usefulness of correlative radiometric and weather radar data; introduction to design of communication and propagation experiments for low altitude and synchronous altitude manned spacecraft; and millimeter-wave propagation data processing and evaluation. Volume III is a descriptive bibliography of reports which were used during the study.

Section II, "Summary of Final Report," which repeats the summary given in Volume I of the Final Report, provides a technical background which shows how the documents described in this bibliography tie in with the experiment design study. Section III, "Contents of Contract Reports," which lists all the subjects covered in the contract reports, was included for the same purpose.

Section IV is the most significant portion of Volume III. It not only describes documents which were referenced in the Quarterly and Final Reports, but also describes other documents which are related to millimeter-wave propagation and communication including system applications of millimeter-waves, lower frequency channel characterization and lower frequency system concepts which can be applied to millimeter-waves, and other useful bibliographies.

As shown in the Table of Contents, the documents described in Section IV were broken down into eleven categories. Many reports could easily fall into more than one category; however, they are only listed under the one in which the document offers the greatest contribution. This bibliography is by no means complete (various important documents are no doubt missing and some are listed without an abstract, summary, or introduction), however, it does give a representative listing of documents in each of the eleven categories, and it serves as a starting point for a more intense literature search on some specific subject.

In the description of each document, the parenthetical item gives the company or government agency with which the author was affiliated at the time the document was written. The portion in quotation marks is the author's abstract, summary, introduction or preface. The portions not in quotation marks are additional comments furnished by the Raytheon study participants to show how the document specifically relates to the experiment design study.

Section V is a cross-reference of contract report reference numbers and the document numbers assigned in Section IV. Section VI is a cross-reference of the Section IV document numbers and an alphabetical listing of authors.

Section 2
SUMMARY

This document is Volume I of the final report for the Millimeter Communication Propagation Program being performed under NASA Contract No. NAS5-9523 by Raytheon's Space and Information Systems Division for Goddard Space Flight Center. This program is a 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 discussed the effects of the propagating medium as they are known today and described a one-year space-earth experiment to be performed in 1968 with a 6000 nautical mile medium altitude satellite. The Second Quarterly Report described a one-year space-earth experiment using a synchronous stationary satellite. It also described in detail the ground and satellite equipment to be used in an experiment, most of which is compatible with either the medium altitude or synchronous altitude Applications Technology Satellites.

This final report consists of three volumes with Volume I being a report on the complete experiment design study. Volume II is actually the third quarterly report which, along with the other quarterly reports, provides detailed backup to Volume I. Volume II describes how the raw data, which is collected during the propagation experiments, should be processed and evaluated and includes an introduction to the design of communication and propagation experiments for low altitude and synchronous altitude manned spacecraft. Volume III contains a descriptive bibliography of related reports and a recommended outline for a propagation data handbook.

This summary of Volume I gives a list of specific recommendations which NASA should consider in order to carry out an effective millimeter-wave propagation program. Problem areas, which require immediate attention, are also identified.

For the most part, this experiment design study was conducted with NASA's Applications Technology Satellites (ATS) in mind. The specific ATS satellites are described as follows:

a.	ATS-A	MAGGE	Medium altitude, gravity gradient stabilized satellite at 28.5° inclination.
b.	ATS-B and C	SASSE	Synchronous altitude, spin stabilized, stationary satellites.
c.	ATS-D and E	SAGGE	Synchronous altitude, gravity gradient, stationary satellites.

At present, Flight ATS-E, which is due to be launched late in 1968, is being strongly considered as the space platform for the initial millimeter-wave propagation experiment.

With the establishment of the NASA APOLLO Applications Program (AAP) and the Air Force Manned Orbiting Laboratory (MOL) Program, it was considered appropriate to include, as much as possible, experiment design information involving low altitude and synchronous altitude manned spacecraft.

This final report recommends a specific payload configuration for the initial space-earth experiment which consists of two separate modules: one having a 35 Gc transmitter and 94 Gc receiver/signal processor and the other having a 16 Gc transmitter. However, mainly because of prime power limitations aboard the spacecraft and a deep concern for reliability, a compromise payload, namely, a 16 Gc transmitter and a 35 Gc receiver/signal processor, is being considered for Flight ATS-E. The body of this report does not specifically discuss this compromise because the study was essentially completed before this course of action was taken. However, practically all of the experiment design information is still valid and all recommendations presented in this summary still apply.

Since the design of space-earth communication links represents the ultimate objective of the propagation program, consideration for the water vapor and oxygen absorption regions around 22 Gc and 60 Gc were excluded. The original design of the experiments was therefore centered around the frequencies of 16 Gc, 35 Gc and 94 Gc because they are representative of the 10 Gc to 100 Gc band. From these three frequencies, the primary frequency for the initial experiment 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. Reasons for choosing a down-link instead of an up-link will be discussed in the recommendations.

For the initial experiments a secondary frequency was chosen to be 16 Gc. Although the atmospheric effects are not 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 were recommended for the 16 Gc experiments for the same reasons given for the 35 Gc experiments. However, because of prime power limitations, it was considered not possible for 35 Gc and 16 Gc to be transmitted simultaneously, thus the reason for two separate payload modules.

The third frequency was chosen to be 94 Gc because it represents the next useful atmospheric window above the 60 Gc band. Unfortunately, a down link was not 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.

In an experiment utilizing the compromise configuration, the primary frequency simply becomes 16 Gc because it is transmitted from the spacecraft and the secondary frequency becomes 35 Gc.

The existing ground facilities which were evaluated 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) which is presently being established, would be the chief participant. Since more emphasis is being placed on 16 Gc, additional existing facilities should be considered such as those located at Defense Research Telecommunications Establishment (DRTE), Ottawa, Canada; Ohio State University, Columbus, Ohio; Naval Ordnance Laboratory (NOL), Corona, California; and Applied Physics Laboratory (APL), Howard County, Maryland.

RECOMMENDATIONS

1. General

   NASA should consider the millimeter-wave propagation program as a long-range effort with the initial phase involving simple channel probes (test waveforms) and the payload configurations mentioned above. The program plans should outline subsequent phases which: investigate higher frequencies, investigate frequencies within the water vapor and oxygen absorption bands, demonstrate communications feasibility with actual modulation systems, and utilize manned spacecraft.

2. Channel Characterization

   The basic goal of the millimeter-wave propagation program should be to characterize various channels, which represent the 10 Gc to 100 Gc band in terms of space and frequency and time. This information should be presented in the form which is not only useful in increasing our scientific understanding of the effects of the propagating medium but also provides the communication systems engineer with the necessary data to design space-earth communications links.

2.1 The two-dimensional, frequency-time correlation function is an important portion of this channel characterization which is measured by those experimenters who need fading statistics and which has direct application to the design of communication systems using frequency diversity. Coherence time, coherence bandwidth and fading rates can be determined directly from the two-dimensional correlation function. A two-dimensional Fourier Transform of this correlation function can be taken in order to describe the scattering function and obtain information regarding doppler and multipath spreading by the channel.

2.2 The space-time (lateral coherence) correlation function, for two parallel spatial channels receiving the same signal, is another important characterization of the millimeter channel. From this function the coherence aperture can be determined, which is an important measure of the maximum size antenna to be efficiently employed. In situations where space diversity schemes are being considered, the spatial correlation function specifies the antenna separation required in order to receive uncorrelated signals. A spatial spectral density function can be derived from the two-dimensional Fourier Transform of the spatial correlation function. This function describes the spatial spectrum of the wavefront and the lateral motion of wavefront with respect to the antenna baseline.

2.3 In the initial propagation experiments it <u>is not</u> practical to develop the complete functions just described. Modified two-dimensional correlation functions and their Fourier Transforms should be generated which give reasonable estimates of the boundaries of the space-earth channel in <u>all</u> three dimensions. From this boundary data subsequent experiments can be intelligently designed.

3. Correlative Measurements

Basic correlative measurements are required to classify the weather model existing in each test in order to give statistical merit to the channel characterization functions. Proper emphasis must be placed upon correlative data processing in order to classify the atmospheric conditions existing during each measurement period and determine the probability of each class of conditions during the annual cycle. Good correlative measurements will also help explain why certain things are happening to the test signals which are being propagated through the complex atmosphere.

3.1 In addition to the usual surface meteorological data which must be collected at each ground terminal, radiometric measurements in coincidence with the basic signal measurements are a necessity. The apparent sky temperature, which is the result of these radiometric measurements, directly relates to the total atmospheric attenuation due to the water and oxygen content of the atmosphere. Since the test signals could undergo fading due to multipathing as well as variations in water content within the receiving beam, the radiometric measurements will therefore help distinguish between various mechanisms producing fading. Modified autocorrelations of radiometer signals, cross correlations of radiometer signals with the amplitude envelopes of the test signals and modified two-dimensional space-time correlation functions of radiometer signals should be processed and used in the evaluation of the signal data.

3.2 If a NASA facility is established for the expressed purpose of making propagation measurements throughout a long range program then it is considered worthwhile to employ a 3 Gc weather radar specifically instrumented to record estimates of the rainfall rate along the propagation path. In experiments involving stationary satellites where the propagation path is fixed, surface rate data from rain gauges underneath the path would be a practical supplement to the radar data. Millimeter-wave radar should not be considered for measuring rainfall rate profiles because the radar backscatter is attenuated on its return and knowledge of the water, temperature, and pressure profiles along the propagation path with sufficient accuracy will not be available. A clear definition of the useful four-dimensional, space-time radar resolution cell must be firmly established before a radar is procured.

4. The Measurement Waveform

The basic test waveform to be transmitted in the first experiment should be a carrier and one pair of AM sidebands. A choice between an unmodulated carrier and a modulated carrier must be provided with the modulating frequency being variable in several discrete steps up to at least 50 megacycles. This simple arrangement which uses a passive modulator in the satellite will provide some useful estimates of the space-frequency-time boundaries of 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 this initial experiment.

5. Formulation of Experiments

5.1 Three types of satellites, classified according to orbital altitude, were evaluated in terms of their suitability as space platforms with which to conduct space-earth millimeter-wave propagation experiments. In addition, high altitude aircraft were compared with the satellites because they could play a definite role in the propagation program.

A series of propagation experiments using aircraft would constitute a useful phase in the overall millimeter-wave propagation program. This phase of the program should precede, if possible, the final spacecraft equipment design phase for the initial space-earth experiments. Air-ground experiments, however, should not be considered as a satisfactory substitute for the complete space-earth experiments because of the costs involved in achieving an accurate statistical model. Slow moving aircraft which can fly above most of the sensible atmosphere can provide qualitative data, on the frequency-time characteristics of the channel within a shorter equipment design and fabrication period than that required for spacecraft. This qualitative data would be helpful in designing more intelligent space-earth experiments which are more complete and which yield quantitative results. The aircraft can also be used to evaluate experiment equipment which is to be used aboard a spacecraft.

The synchronous stationary satellite is the best space platform with which to conduct the initial space-earth experiment because considerable operational expense is saved by; not having to generate precise and timely ephemeris data which is required for acquiring and tracking non-synchronous satellites with narrow millimeter-wave beams and; not performing costly modifications for automatic track capability in the existing millimeter-wave facilities. This is the only vehicle, including aircraft, with which accurate spatial characterization can be achieved. The big disadvantage with synchronous spacecraft is that it could be placed beyond line-of-site of many of the important ground facilities including the one planned for GSFC. Early identification of the satellite longitudinal position is required to insure that proper planning can be made regarding useful ground facilities. The optimum position for the propagation experiment would be either 27° W Lg. over the Atlantic or 145° W Lg. over the Pacific.

In the long range program, the medium altitude (6000 n miles) satellite would be a useful space platform with which to conduct propagation experiments. The angular elevation rate of the medium altitude satellite is slow enough to permit ample viewing time per pass with sufficient data samples per degree of elevation and, yet the elevation angular rate is still fast enough to complete a continuous elevation profile before significant weather changes can occur.

The design of experiments using low altitude (100 to 300 n miles) manned spacecraft should be based on the assumption that propagation experiments using aircraft and synchronous altitude satellites have already been performed during preceding phases of the program. Low orbiting spacecraft are not ideal vehicles for basic propagation experiments because they are too close to earth to permit reasonable time for gathering quantitative data by any one aircraft or ground station. Multiple aircraft and ground stations are expensive especially since the spacecraft is traveling at high angular rates relative to the other terminal. Low orbiting spacecraft do, however, offer payload capacities which often surpass that which is available at higher altitudes. Furthermore, the availability of man in a low orbiting spacecraft is of inestimable value in determining the operational potential of millimeter-wave communications, to support future manned spacecraft missions such as the later generations of the AAP and MOL programs.

5.2 For the initial propagation experiments it is recommended that down-links be used instead of up-links whenever possible. The key to a successful experimental program which involves the assistance of several existing ground installations, each controlled by a different agency, depends on the ease with which these facilities can participate.

All of the existing sites which were evaluated are equipped with millimeter-wave receivers which are used in radio astronomy. Since these facilities use interchangeable rf heads to change frequency of operation, it is very reasonable to assume that modifications for receiving test signals from satellites are much easier than those required for transmitting test signals to the satellites.

Another very important reason for wanting to use satellite transmitters is that less coordination is required during the data collection operation and several stations can make measurements simultaneously without interfering with one another. When ground transmitters are used, a closed loop is required to confirm that the transmitted signal is being properly received.

One objection to the down-link has been the high prime power requirements of the space transmitter. However, a satellite receiver would have to be on longer than a space transmitter in order to accommodate each ground station individually.

One of the prime objectives of the propagation experiments is to define the two-dimensional lateral coherence function with at least some points along the spatial axis. These measurements can only be made with a down-link.

When up-links are used, the participating agencies do not have immediate access to the raw data which is being collected. There is a certain delay in obtaining this information which prevents the station operators from evaluating their performance in real time. and taking corrective action. It is certain that in addition to satisfying NASA's requirements, these agencies will want to make specific measurements or data recordings which fulfill special requirements of their own.

An early space-earth experiment has to depend completely on present technology and a satellite receiver is considerably closer to meeting longevity and environmental requirements than a satellite transmitter. For this reason plus the fact that receivers require less power, a 35 Gc up-link for the ATS-E spacecraft is a logical choice.

5.3 A typical work cycle with a stationary satellite which would be satisfactory for the propagation experiments would be to operate during a dozen five day work weeks seasonally spaced throughout the year. A full work week every four or five weeks may be the most attractive arrangement from a manpower scheduling view point and the down time between tests will provide ample opportunity for examining data and making changes in test procedure and ground equipment before the next test.

Each work week should consist of four data collection sessions with a minimum of 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 must include pre-test and post-test data collection check-out and calibration with the spacecraft simulator which is located at a remote boresight facility. Little 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.

The importance of early mission profile planning cannot be over-emphasized because of the competition with other experiments aboard the spacecraft for prime power and telemetry and competition with other experiments being conducted by the participating ground facilities.

6. <u>Ground Facilities</u>

A primary experimental ground facility should be established under the control of NASA which, when supplemented by the facilities of other agencies, can be expanded to meet the needs of the long-range program. Decisions on facility siting and major equipment designs and procurements should be based on a series of flights rather than a single flight, such as the ATS-E.

6.1 The basic element in the primary experimental facility, the antenna pedestal system, must be equipped to automatically track low altitude spacecraft and high altitude aircraft as well as slow moving satellites. The pedestal yoke must be large enough to accommodate a receiver-transmitter compartment which provides easy access to interchangeable r-f packages.

6.2 The equipment layout for the <u>primary</u> facility should include a system of auxiliary antennas and mirrors which can be employed to investigate the two-dimensional lateral coherence function using stationary satellites. This system of reflectors must be designed such that variable baseline configurations are possible. The additional antennas may also be used to solve difficult diplexing problems created by multiple frequency operations.

6.3 The equipment layout for all of the participating facilities should include a well equipped boresite facility which, in addition to the signal sources required for antenna system alignment and receiver calibration, it contains receivers, waveform generators and signal processors which function like those aboard the spacecraft.

6.4 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 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 under some circumstances may not have sufficient antenna gain to investigate the coherence bandwidth of the medium but they could supply important signal fading statistics on a single carrier.

7. Spacecraft Equipment

There are many problems associated with the millimeter-wave 16 Gc transmitter/35 Gc receiver module for the ATS-E spacecraft in the areas of: critical design in the r-f section and; interfaces with supporting sub-systems, other experiment modules and the space-frame.

The small amount of prime power (in the neighborhood of 25 watts) which is available from the electrical power subsystem is the chief cause for concern. Since the efficiencies of transmitters at 16 Gc are poor, the amount of radiated power is limited to approximately 200 milliwatts. This small amount of r-f power in the experimental 16 Gc space-earth down-link demands that careful attention be given to:

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should more than compensate for the propagation losses, high noise figure and receiver sensitivity degradation over the life of the satellite. The main problem with the 35 Gc up-link is the transmission of propagation data back to earth. The PCM telemetry subsystem restricts the sampling rate to three cycles per second (10 cycles per second is desired). Analog data transmission with the 4 Gc/6 Gc communication transmitter may be a better arrangement.

The spacecraft payload for ATS-E poses many questions which require early answers if a useful flight qualified package is to be integrated into the spacecraft in time for a late 1968 launch. The first series of questions to be answered is:

a. What is the longitudinal position of the satellite?
b. What changes in position are anticipated during the first year of operation?
c. What ground facilities can be used?
d. What is the maximum size antenna which can be employed on the spacecraft?

Early laboratory breadboard work must be performed to determine estimates of:

a. Power output level which can be reliably generated at 16 Gc with solid state devices.
b. Efficiency of a solid state 16 Gc transmitter.
c. Values of minimum signal-to-noise density for phase lock receiver acquisition and track using r-f frequency stabilities which are expected to prevail.
d. Noise figure for the 35 Gc receiver.
e. Highest acceptable modulation frequency for the passive AM modulator.

8. Data Processing and Evaluation

The propagation data collected at the various cooperative ground facilities should be processed and evaluated by NASA at a central facility. For the most part, existing computer facilities are equipped to handle the data processing required for the propagation data collection program. Special computer programs can be derived to transform the raw data into estimates of the millimeter-wave channel characteristics. An extensive quantity of data will result from the experimental program, and of course, it is not necessary to statistically process all of the data collected. However, it is necessary to look at the analog presentations for the occurrence of unusual propagation effects to insure that the data which is processed adequately represents the statistical model.

Each ground facility receiver participating in the program should be equipped with identical signal processors and analog magnetic tape recorders to minimize data processing expense. Each ground receiver should share its RF head with a radiometer so that sky temperature measurements can be recorded on the same tape in synchronism with the signal phase and amplitude measurements. When available, short term and long term variations of tracking antenna azimuth and elevation should also be recorded on the same tape. Real-time analog strip line recorder presentations of the same data which was recorded on magnetic tape should be made at each site for calibration check-out and operational monitoring; and to provide the cooperating agencies with immediate access to the raw data. The taped analog data from satellites and ground facilities should be converted to digital form at a central data processing facility.

Once the space-frequency-time characterization of the channel is developed to a reasonable degree, then established computational methods can be used to infer the effects of the atmosphere on conventional modulation systems. Much of this information is already available in existing literature.

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Second Quarterly (continued)

Second Quarterly (continued)

APPENDIX V
SPACECRAFT MILLIMETER RADIOMETERS FOR VERTICAL SENSING, METEOROLOGY AND GROUND MAPPING

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6.3.4 Air Force Cambridge Research Laboratory (AFCRL) and Lincoln Laboratory

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APPENDIX IX

VIEWING TIME FOR MEDIUM ALTITUDE SATELLITES

APPENDIX X

GAIN AND BEAMWIDTH OF MILLIMETER ANTENNAS

1.3 Bean, B.R., Horn, J.D., Ozanich, A.M., "Climatic Charts and Data of the Radio Refractive Index for the United States and the World," (National Bureau of Standards), NBS Monograph 22, 1960.

This publication is an excellent compilation of geographical, seasonal and diurnal variations in refractive data. This data is useful in estimating the effects of refraction on the propagation of millimeter-waves.

1.4 Kessler, E., III, Atlas, D., "Model Precipitation Distributions," (AFCRL), Aero/Space Engineering, December 1959.

"Theories relating precipitation and clouds to vertical motion in the atmosphere are discussed briefly. Vertical profiles of precipitation rate and precipitation and cloud water contents are presented as models of widespread precipitation. Observed average profiles of radar reflectivity in New England thunderstorms are also presented and related to their water contents. The derived quantities have application to the numerous applied problems in aeronautics and radar detection in which general estimates of the precipitation parameters are required."

This report was used to derive a family of weather model altitude profiles for precipitation, water vapor density, temperature and pressure. Certain combinations of these profiles can be used to represent most any location within the United States. These models can be used in a computer program to derive atmospheric attenuation and sky temperature data as a function of elevation angle.

Section 4
DESCRIPTION OF REFERENCE REPORTS AND OTHER RELATED REPORTS

1.0 Meteorology

1.1 "Local Climatological Data with Comparative Data," Weather Bureau, U.S. Department of Commerce, 1963, 1964.

These publications are provided annually by the Weather Bureau for those cities in the United States which have official Weather Bureau Stations. Each document contains a narrative climatological summary about the city and its surrounding area. Meteorological data for the past year is given in detail along with record summaries of all the years that the particular station has been in existence, which, in many cases, has been 30 to 50 years. These publications are extremely helpful in the process of estimating probabilities of rainfall rate occurence.

1.2 "Rainfall Frequency Atlas of U.S. for Durations from 30 Minutes to 24 Hours and Return Periods from One to 100 Years," Technical Paper 40, Weather Bureau, U.S. Department of Commerce.

This rainfall frequency atlas, which is provided annually, supplements the publications described in Reference 1.1.

to be ingested at various altitudes is required. Other design problems such as aircraft and radome erosion by precipitation elements require a complete knowledge of the variation of the rainfall rate and raindrop size distributions with altitude. Such data must be related to surface rates of rainfall so that the probability of occurrence for specific areas can be determined from available data."

Chapter 6 of this handbook shows how the data from References 1.1 and 1.2 can be used to estimate the percentage time that the rainfall rate will exceed a specific value for a given geographic location.

1.7 Battan, L. J., "Radar Meteorology," (University of Chicago), The University of Chicago Press, Chicago, 1959.

"This book was written for the purpose of briefly describing, in one small volume, the progress made since the birth of radar meteorology. In writing it, I have tried to keep in mind the non-radar meteorologist. Perhaps synoptic meteorologists, knowing a little more about radar meteorology, can make more progress than a radar meteorologist knowing only a little about synoptic meteorology."

Besides being a fairly complete account of the scope of radar meteorology, this book contains an excellent introduction to electromagnetic propagation phenomena, including absorption and scattering. The chapters most pertinent to millimeter communication studies, besides the ones on propagation, describe the use of S band radar as a correlative tool to mea-

1.5 Atlas, D., Kessler, E., III, "A Model Atmosphere for Widespread Precipitation," (AFCRL), Aeronautical Engineering Review, February 1957.

"The vertical variations of precipitation rate, liquid water content, radar reflectivity factor, and particle size distributions are examined in the cases of three models giving widespread precipitation. The derived quantities have application to the numerous applied problems in aeronautics and radar detection in which general estimates of the precipitation parameters are required."

This report was used to derive atmospheric attenuation and sky temperature data in the same manner as Reference 1.4.

1.6 "Handbook of Geophysics for U.S. Air Force Designers," Air Force Cambridge Research Laboratories, Chapter 6 - "Precipitation."

"The frequency of occurrence of given rates or precipitation and the associated vertical distributions of various precipitation parameters must be taken into consideration in the design of many types of equipment and weapons systems.

"In selecting a search radar, for example, designers are concerned with the probability of failure due to attenuation by rainfall. To determine the probability of failure, the frequency of occurrence of the critical rainfall rate must be known over the proposed regions of operation. (Procedures for determining losses due to attenuation and refraction are contained in Chapter 13.) In designing jet engines, the amount of water and ice likely sure rainfall rate profiles to study rainfall, to study clouds, and to study along the space-earth propagation path.

Incidentally, although the book was published in 1959, almost all the material is still of current interest. References 1.8 and 1.17 can serve as excellent supplements to this book.

1.8 Kessler, E., III, "Use of Radar Measurements for the Assessment of Areal Rainfall," (U.S. Weather Bureau), Presentation at the 17th Session of the WMO Executive Committee, Geneva, Switzerland, May 1965.

"The usual variability of rainfall requires that measurements at many places be combined to yield useful estimate of area averages. It is expensive to install and maintain raingages in the desired numbers, and to transmit their data in timely manner to central processing stations. Therefore, there is wide interest in possibilities of using radar to measure rainfall. For example, a distribution of precipitation can be updated several times each minute as the radar receiver detects echoes from precipitation particles as far away as 200 miles.

"It has been known for 15 years that the amount of energy returned to the radar generally increases as the rainfall rate increases. However, operational application of radar data to problems of rainfall measurement has lagged. One reason for this lag is that the correspondence between measured radar signal power and rainfall varies significantly from storm to storm and from season to season. The studies made so far have only partly defined the contributions to the variability. Secondly, techniques for processing and communicating radar data have not yet been adequately tailored to meet all the important human, economic and technological requirements characteristic of weather observing and reporting systems. This paper discusses these and related problems."

The usefulness of this report is similar to that of Reference 1.7.

1.9 Browning, K. A., "Interaction of Two Severe Local Storms," (AFCRL), Proceedings of the 1964 World Conference on Radio Meteorology, Boulder, Colorado.

"On 26 May 1963, near Oklahoma City, two severe local storms displaying hook echoes were traveling side by side, with their hooks separated by only 15 miles. Some of the precipitation falling ahead of one of them was seen by radar to be drawn toward the hook echo of the other. By investigating the detailed three-dimensional structure of the radar echo in the light of nearby wind soundings, it is inferred that an updraft existed at low levels within the "echo-free" indentation ahead of the hook echo as well as within the "echo-free" vault. The analysis illustrates the methodology of using conventional radar to study airflow, and also confirms important features of an airflow model previously proposed by the author."

Two 10 cm radars were used. The chief interest of the author was in obtaining knowledge of the internal structures of the storms.

1.10 Geotis, S.G., "On Sea Breeze Angels," (M.I.T.), Proceedings of the 1964 World Conference on Radio Meteorology, Boulder, Colorado.

"Echoes associated with many sea breeze fronts have been observed with our AN/CPS-9 and SCR-615-B radars operating at wavelengths of 3.2 and 10.7 cm, respectively. These echoes are obvious volume targets, generally a mile or two thick and several miles long, aligned along the sea breeze interface. On the "A" or "R" scope thay are indistinguishable from precipitation echoes as they have similar fluctuation rates. They are identified as "angels" by the lack of the clear inverse λ^4 wavelength dependence found in precipitation echoes. Measurements of the reflectivities at 3.2 and 10.7 cm of six such fronts are included in this study."

1.11 Atlas, D., "Angels in Focus," (AFCRL), Proceedings of the 1964 World Conference on Radio Meteorology, Boulder, Colorado.

"This paper gathers together a number of recent independent observations of "dot" angels from which we can now draw a coherent picture of their physical structure. The present note is an extract of a more comprehensive survey which will appear elsewhere (Atlas, 1964)."

1.12 Ottersen, H., "Occurrence and Characteristics of Radar Angels Observed with a Vertically-Pointing Pulse Radar," (Research Institute of National Defense, Sweden), Proceedings of the 1964 World Conference on Radio Meteorology, Boulder, Colorado.

"During 1963 a study of radar angels has been carried out with a 10 cm vertically-pointing pulse radar at Stockholm, Sweden. Time-height recordings of the angel activity have been performed in the usual photographic manner and the amplitude variations of angel echoes have been studied with a time-gate technique. Data of the radar are, frequency 3000 Mc, transmitted pulse peak power 500 kW, pulse length 0.6 microsec and minimum detectable power 10^{-13} watt. The gain of the 4 m diameter parabola is 40 db. The place is situated on the east coast of Sweden about 3 km from the Baltic. The surrounding terrain is mainly composed of wood. The station is working intermittently and recordings are performed five hours around noon five days a week. Some special studies have been carried out to investigate the 24-hours variation. The purpose of the study is to investigate the characteristics of angels in detail and to study the variation of angel activity in order to correlate the observations to simultaneous meteorological conditions."

1.13 Brown, E.N., Braham, R.R., Jr., "Precipitation Particle Measurements in Cumulus Congestion," (University of Chicago), Journal of Atmospheric Sciences, Volume 20, No. 1, January 1963.

"Precipitation particle measurements from the upper levels of cumulus congestus clouds are analyzed with regard to general cloud characteristics, liquid water content, and precipitation water content as related to the theoretical radar reflectivity. Conclusions are: (1) the majority of the cumulus congestus clouds examined, whose tops exceed

14, 000 ft, contained precipitation particles (250-microns diameter) in the upper levels sometime during their life cycle, (2) particle concentrations in excess of 1000 per m^3 were found in about 20 per cent of the clouds examined, (3) the relationship $Z = 1.6 \times 10^{-2} M^{1.46}$ for radar reflectivity is applicable for cumulus congestus in the early stages of precipitation development."

1.14 Leasure, R.B., Durham, K.S., Tobias, J.J., Dudrow, R.A., "Radar Detection of Angel Activity with Corresponding Refractometer Soundings", (Wright Air Development Center), Proceedings of Sixth Weather Radar Conference, March 1957.

"Some interesting observations of "angel" type activity were made on 2 and 3 May 1955 utilizing an 0.86 cm (35 Gc) vertically pointed radar set. Observations were made by personnel of the Meteorological Radar Section of the Aerial Reconnaissance Laboratory, Wright Air Development Center. At approximately the same time, vertical refractometer soundings were made by the Wave Propagation Section of the same laboratory. Photo recordings of the "angel" activity are shown with corresponding radiosonde and refractometer traces. In addition, several interesting and unusual slides on other "angel" activity are shown. Radiosonde and refractometer data was not included in this paper."

1.15 Braham, R.R., Jr., "Cumulus Cloud Precipitation as Revealed by Radar - Arizona 1955," (University of Chicago), Journal of Meteorology, Volume 15, No. 1, February 1958.

"An AN/TPS-10 radar, located at the Institute of Atmospheric Physics, University of Arizona, has been used to make extensive measurements of radar returns from cumulus clouds in the vicinity of Tucson. Data from ten days in the summer of 1955 have been analyzed with a view toward establishing the level of first formation of precipitation, day-to-day variation, average dimensions of first echo, average duration, and fraction reaching ground. Strong day-to-day variations and mountain effects are revealed. Although echoes form much more frequently over mountains than over nearby valleys, these echoes individually are less likely to produce rain at the ground."

1.16 Plank, V.G., Atlas, D., Paulsen, W.H., "The Nature and Detectability of Clouds and Precipitation as Determined by 1.25 cm Radar," (AFCRL), Journal of Meteorology, Volume 12, No. 4, August 1955.

1.17 Hitschfield, W., Bordan, J., "Errors Inherent in the Radar Measurement of Rainfall at Attenuating Wavelengths," (McGill University), Journal of Meteorology, Volume 11, No. 1, February 1954.

"An equation for the rate of rainfall at a given range from the radar is derived. This is expressed in terms of the power level of the received signal (corrected for attenuation by intervening cloud and atmospheric gases) and takes account of radar attenuation due to intervening rain. The equation includes a constant which measures the performance of the radar and is determined by direct calibration.

"At attenuating wavelengths (at 3 cm; to some extent at 5.6 cm) a small error in the calibration constant causes a large error in the measured rainfall. This error, which varies with range and may thus cause serious distortion, is, in fact, liable to be more serious than that caused if the attenuation were neglected entirely. Correcting for attenuation is therefore not recommended, unless the calibration error may be held within extremely narrow limits.

"Very small calibration errors may be achieved by calibrating the radar by means of a rain gauge located at a point where the attenuation is appreciable. At points of smaller attenuation, a satisfactory degree of accuracy in the calculated rate of rainfall then results.

"At wavelengths such as 10 cm, where the attenuation is negligible, errors in the constant still affect the measured rain, but neither so seriously, nor in a manner involving the range, thus causing no distortion.

"An examination of the relative importance of the attenuation by gases and cloud at three wavelengths similarly emphasizes the difficulties associated with quantitative work at the shorter wavelengths."

This report supplements Reference 1.7.

1.18 Goldwater, F. T., "Low Cost Digital System Records Weather Data," (Hebrew University, Jerusalem), Electronics, January 1964.

"The trend toward bigger machines to do our work sometimes continues because of momentum, despite the fact that the task may call for a relatively simple and inexpensive system. More often than not, by minimizing complexities a better system is evolved. The author has accomplished this with his new meteorological data recording system that features simplicity of operation and low cost. As a result high reliability is ensured."

2.0 Propagation

2.1 Lilley, A. E., Meeks, M. L., "The Microwave Spectrum of Oxygen in the Earth's Atmosphere," (Journal of Geophysical Research, Volume 68, No. 6, March 1963.

"Space probe techniques open the possibility of radio and microwave spectroscopic investigations of planetary atmospheres through the study of resonant transitions in gaseous constituents. Computations were undertaken to determine the opacity and the thermal emission produced by the millimeter-wavelength complex of oxygen lines in the earth's atmosphere. The calculations predict line profiles of individual oxygen transitions in emission or in absorption against the sun. Potential experimental observation heights were assumed; sea level, aircraft heights (5 and 8 Km) a typical high-altitude balloon height (30 Km) and earth-satellite heights. The computed spectrums are based on the Van Vleck-Weisskopf theory of oxygen absorption combined with the ARDC model atmosphere. The transfer equation for the oxygen line complex is complicated by the Zeeman splitting produced by the earth's magnetic field, but this effect is significant only in spectrums predicted for satellite observations and is neglected here. Computed values of the zenith opacity from the earth's surface are in good agreement with measurements that extend down to about 1 Gc. The depths of absorption lines observed against the sun are predicted to be greater by a factor of 20 than the intensity of the same lines in emission.

"Satellite observations of microwave brightness temperature as a function of frequency around 60 Gc/s can yield information about the vertical thermal structure of the atmosphere; this technique, undertaken with a polar satellite, offers the possibility of a global determination of the approximate vertical temperature distribution in the earth's atmosphere. The relationship between the emission spectrum and the temperature as a function of height demonstrates that the emission at a given frequency represents the average temperature in a layer of air roughly 10 Km deep. The mean height of these layers depends on frequency and varies between 0 and 40 Km. It may be possible to increase this height considerably by taking the Zeeman effect into account. Specifications are estimated for the aircraft, balloon, and satellite radiometric systems that would be required to undertake the research program defined in this paper."

2.2 Muchmore, R. B., Wheelon, A. D., "Frequency Correlation of Line-of-Sight Signal Scintillations," (Space Technology Laboratories), IEEE Transactions on Antennas and Propagation, January 1963.

"The frequency autocorrelation of amplitude and phase scintillations of radio signals propagated over turbulent line-of-sight paths is calculated theoretically. The single scattering (Born) approximation to the electromagnetic response of the turbulent irregularities is used, limiting the results to small amplitude and phase variations. However, the results are valid for both Fresnel (near zone) and Fraunhofer (far zone) scattering. The calculations are made for an arbitrary model of the turbulent irregularities by using the spectrum method, which postpones the specialization of the analysis to a particular turbulence model until the wave-propagation aspects of the problem are completed. It is shown that the signal variations on adjacent carrier frequencies have high correlation for frequency separations comparable to the carrier frequency for all propagation conditions, indicating that the "medium bandwidth" for line-of-sight paths is very large. This also means that there should be negligible pulse distortion for high-speed data links or high resolution radars operating on line-of-sight paths. These predictions are compared with the few available experimental results."

2.3 Muchmore, R. B., Wheelon, A. D., "Line-of-Sight Propagation Phenomena," (Space Technology Laboratories), Proceedings of the IRE, Volume 43, No. 10, October 1955.

"The effect of variations in index of refraction on line-of-sight propagation of electromagnetic waves in the troposphere is investigated using, in this paper, a ray theory approach. Mean-square variations in phase delay and phase correlation between two paths are calculated. It is shown that these quantities are relatively insensitive to the form of space correlation functions assumed for the index of refraction. The mean square phase is proportional to $\overline{\Delta N^2} L_0$ where L_0 is scale length and $\overline{\Delta N^2}$ is the mean-square variation in index of refraction, whereas in beyond line-of-sight propagation, the received power is proportional to $\overline{\Delta N^2}/L_0$.

"Variations in angle of arrival are also calculated and it is shown that here the assumed space correlation of index of refraction is critical in determining the angle of arrival characteristics. It is shown, however, that a certain portion of the angle-of-arrival spectrum is insensitive to the choice."

2.4 Barrett, A. H., Chung, V. K., "Method for the Determination of High Altitude Water-Vapor Abundance from Ground-Based Microwave Observations," (M.I.T.), Journal of Geophysical Research, Volume 67, No. 11, October 1962.

"The microwave resonance line at 22,235 Mc/s ($\lambda = 1.35$ cm) arising from uncondensed H_2O in the terrestrial atmosphere is examined in detail as a means of providing easily obtained data on the physical structure of the atmosphere. It is shown that the line profile is drastically influenced by the vertical distribution of H_2O and that the anomalous abundance of uncondensed H_2O above 15 to 20 Km should be detected easily and monitored by ground-based passive microwave observations. The method, capable of 24 hours per day operation, can be used to determine abundance changes on a time scale as short as several seconds, if necessary, and to reveal horizontal fine structure with a resolution of 150 meters at an altitude of 30 Km with a 10-foot parabolic receiving antenna. Other atmosphere constituents that have microwave resonance spectrums, for example O_3, are amenable to study by this procedure."

The calculations used in this millimeter-wave experiment design study to determine the theoretical values of apparent sky temperature are based on the method presented in this paper.

2.5 Hathaway, S. D., Evans, H. W., "Radio Attenuation at 11 Kmc and Some Implications Affecting Relay System Engineering," (Bell Telephone Laboratories), Bell System Technical Journal, Volume 38, January 1959.

"Radio waves at 11 Kmc are attenuated by rain. In order to derive rules for engineering radio relay systems at 11 Kmc, a one-year experiment was conducted in a region of frequent heavy rainfall. The attenuation of paths 27 and 12 miles long was measured, together with rainfall at two-mile intervals along the paths. The instrumentation and the test results are described, and some implications related to systems engineering are pointed out."

As the authors point out, there is some evidence that the signal attenuation observed in this study was produced by ducting and by multipath. One reason the paper is useful is that both the experimental technique and the results are presented in detail.

2.6 Millman, G. H., "Atmospheric Effects on VHF and UHF Propagations," (General Electric), Proceedings of the IRE, August 1958.

"This paper is mainly concerned with the effects of the troposphere and ionosphere on the propagation of VHF and UHF radio waves.

"Tropospheric refractive index profiles and ionospheric electron density models representative of average atmospheric conditions are presented.

"Mathematical relationships are derived for calculating refraction effects, time delays, Doppler errors, polarization changes, and attenuation experienced by radio waves traversing the entire atmosphere."

Extrapolations of VHF and UHF data presented in Millman's paper shows that the ionosphere has negligible effect upon the propagation of millimeter waves.

2.7 Gunn, K. L. S., East, T. W. R., "The Microwave Properties of Precipitation Particles," (Quarterly of the Journal of the Royal Meteorological Society, No. 80, October 1954.

2.8 Van Vleck, J. H., "The Absorption of Microwaves by Oxygen," and "The Absorption of Microwaves by Uncondensed Water Vapor," (Physical Review), Volume 71, No. 7, April 1947.

"Even though electrically non-polar, oxygen gas absorbs microwaves because the magnetic moment of the O_2 molecule interacts with electromagnetic fields. The resulting absorption is most pronounced, exceeding 10 db/Km for wavelengths in the vicinity of 1/2 cm, for then there is resonance to the spacings in the "rho-type-triplet" or spin fine-structure in the $^3\Sigma$ ground state of O_2. There is also a subsidiary resonance near 1/4 cm, and a non-resonant absorption at long wavelengths due to diagonal matrix elements. The calculated values of the absorption are given in Table II and depend on the choice of the line-breadth constant $\Delta\nu$ which represents the effect of broadening by collision. Comparison is made of these theoretical results with the absorption in the 1/2 cm region, observed by various experimentalists with different methods. It is concluded that 0.02 cm^{-1} is probably the best choice for $\Delta\nu/c$. The theoretical dependence of the absorption on pressure is discussed, and is particularly interesting because of the relation to the mechanism of collision-broadening and because the resonances to individual rotational lines are resolved at low pressures."

2.9 Van Vleck, J. H., Wiesskopf, V. F., "On the Shape of Collision Broadening Lines," Review of Modern Physics, Volume 17, April - July 1945.

2.10 Dicke, R. H., et al, "Absorption of Microwave Radiation and Radiometry," Physical Review, Volume 70, September 1946.

The absorption of microwave radiation in travers ng the earth's atmosphere has been measured at three wavelengths (1.00 cm, 1.25 cm and 1.50 cm) in the region of a water-vapor absorption line. The measurement employs a sensitive radiometer to detect thermal radiation from the absorbing atmosphere. The theory of such measurements and the connection between absorption and thermal radiation are presented. The measured absorption together with water-vapor soundings of the atmosphere permits the calculation of the absorption coefficients at standard conditions (293°K, 1015 millibar). These are 0.011, 0.026 and 0.014 db/Km/g H_2O/ -- for the wavelengths 1.00 cm, 1.25 cm and 1.50 cm, respectively. These values are (50 per cent) greater than those given by the theory of Van Vleck. The collision width of the line and its location are in better agreement with the theory and infra-red absorption measurement. It is also found that there is very little ($< 20°K$) radiation from cosmic matter at the radiometer wave lengths."

This paper presents a good discussion of radiometry techniques, both experimental and analytical, as well as including valuable data. It is highly recommended as an introduction to radiometry.

2.11 Holzer, Walter, "Atmospheric Attenuation in Satellite Communications," (ITT Intelcom), Microwave Journal, March 1965.

"Atmospheric attenuation is far more important in satellite communications than it is in terrestrial communications. The reasons for this become apparent when one considers a typical satellite system. The Syncom III satellite feeds a maximum of 2 watts of radio frequency power to an antenna that provides only 6 db of gain, yet it relays multichannel voice and data communications, requiring radio frequency bandwidths of 10 mc over paths more than 20,000 miles long.

"These facts, combined with the high cost of producing satellites and installing them in suitable orbits --not to mention the costs of the earth terminals -- point up the need for precise engineering calculations of the effects of atmospheric attenuation. The so-called fading allowances normally included in the design of terrestrial radio links to offset uncertainities in the prediction of path attenuation are too wasteful for satellite link power budgets.

"Fortunately the combination of high path elevation angles and microwave frequencies most appropriate for satellite systems reduces the uncertainties by virtually eliminating the effects of the most unpredictable element, atmospheric refraction. It does not, however, eliminate the attenuation introduced by certain constituents of the atmosphere which absorb and scatter microwave energy. This atmospheric attenuation is quite pronounced in tropical regions during seasons of heavy rainfall and in temperate regions during thunderstorm activity. Its effect on communications and the necessity for providing ample design margins as compensation have been demonstrated on the presently operational satellite links.

"This article presents a method for computing conservation margins to compensate for atmospheric attenuation. These margins are based on the climatology of the areas in which the earth terminals are located. Actually, they depend on the weather, but that independent variable defies prediction; hence, the resort to climatology, which is, after all, the history of weather."

2.12 Mondloch, A., "Observations of Short-Term Fading at Millimeter Wave-Length," (Sylvania Electronic Systems), Presentation to Boulder Millimeter Wave and Far Infra-Red Conference, Estes Park, Colorado, August 1965.

"The observations of short-term fading at millimeter wavelengths discussed in this paper are the result of a study of fluctuations in received signal level recorded during a millimeter propagation test. The short-term fading envelope distribution, the fade rate and the maximum fade depth observed during the experiment are of interest to designers of millimeter systems and equipment, especially in areas such as fade margin, AGC response, signal reliability, diversity improvement and choice of polarization.

"Short-term fades are caused by interference between two or more received signals or by refractive changes in the atmosphere. Interference between two signals can occur at the receiver because of different paths in the atmosphere, or because of reflections from the surface. Refractive changes result in bending of the transmitted wave. All of these conditions can occur at the same time so that their effects are almost inseparable.

"The experimental configuration, the format of the raw data, and the method of data analysis and reduction are described, and the results and conclusions presented. Conclusions concerning short-term fading are restricted by such factors as the limited number of samples taken and the limited duration of the test program. The results should therefore be interpreted more as an indication of trends rather than as a statistical basis for predicting system performance."

2.13 Herbstreit, J. W., Thompson, M. C., "Measurements of the Phase of Radio Waves Received over Transmission Paths with Electrical Lengths Varying as a Result of Atmospheric Turbulence," (National Bureau of Standards/AFCRL), Proceedings of the IRE, October 1955.

2.14 Westwater, E. R., "Ground-Based Passive Probing Using the Microwave Spectrum of Oxygen," (National Bureau of Standards), Radio Science Journal of Research, NBS/USNC-URSI, September 1965.

"The determination of the kinetic temperature structure of the troposphere from ground-based measurements of oxygen emission spectra in the microwave region is discussed. Molecular absorption properties of oxygen and water vapor are reviewed. A new "inversion" technique is described. This technique uses a least squares-iteration solution which is applicable to Fredholm integral equations of the first kind. The inversion technique is used to reconstruct two types of tropospheric temperature profiles. The effects of certain types of errors in the brightness temperature on the derived temperature distribution are computed."

2.15 Janes, H. B., Kirkpatrick, A. W,, Waters, D. M., Smith, D., "Phase and Amplitude Diversity in Over Water Transmissions at Two Microwave Frequencies," (National Bureau of Standards), NBS Technical Note No. 307, April 1965.

"Radio scientists of the NBS Central Radio Propagation Laboratory have measured certain characteristics of microwave radio signals transmitted over water at the Eleuthera Island portion of the Atlantic Missile Range Mistram tracking system. The Air Force had asked CRPL to obtain information on relative variations in phase and amplitude at two microwave frequencies. The findings will aid in appraising the stability of over-water microwave links.

"The microwave system studied at Eleuthera Island, in the Bahamas, is an essential part of the Mistram precision missile trajectory measurement system, since it transmits phase information to a central station for conversion to target position and velocity information. The accuracy of the tracking system depends in part on the phase and amplitude stability of these transmissions. Changes in phase and amplitude occur when a signal encounters spatial and temporal variations in the three-dimensional structure of the atmospheric refractive index along its path.

"The Bureau made propagation measurements at two stations, one at each end of a 47 Km (29 1/2 miles) over-water microwave linkon Eleuthera Island. One of the terminals is a central station using a 3-m parabolic reflector mounted 32 m above sea level to communicate at 9.2 and 9.4 GHz. The other station is the Powell Point terminal; it has a 2.4-m dish located 71 m above sea level."

This paper is representative of the type of information which should be obtained at millimeter-wave frequencies propagated over space-earth links.

2.16 Janes, H. B., Thompson, M. C., Jr., "Errors Induced by the Atmosphere in Microwave Range Experiments," (National Bureau of Standards), Radio Science Journal of Research NBS/USNC-URSI, Volume 68D, No. 11, November 1964.

"This paper describes experimental measurements designed to study atmosphere-induced errors in microwave baseline tracking systems. The ground-to-air configuration was simulated by 300 to 400 m baselines on level ground east of Boulder, Colorado, and a fixed target antenna on a mountain top at a range of about 15 Km and a path elevation angle of 44 milli-radians. A radio frequency of 9.4 Gc/s was used. Continuous recordings were made of variations in apparent range, range difference and refractive index. The data are analyzed in terms of power spectra. The correlation between range and surface refractivity variations and the correlation of range variations on adjacent paths are discussed."

This paper reports results in one of a long series of experiments. The results are quite useful although no information is given about amplitude changes due to atmospheric effects (only phase changes).

2.17 Westwater, E. R., "A Method for Determination of the Tropospheric Temperature Structure from Ground-Based Measurement of Oxygen Emission," (National Bureau of Standards), Proceedings of Third Symposium on Remote Sensing of the Environment, University of Michigan, 1964.

"A method of determining termperature structure of the lower 5 Km of the atmosphere using brightness temperature, T_b, measurements from a vertically oriented antenna in the frequency region 50-55 Gc/s is described. The thermal emissions in this region are due principally to a series of oxygen absorption lines centered near 60 Gc/s. The temperature is represented by a polynomial expansion whose coefficients are initially determined with use of a standard absorption model. Subsequent iterations are made until a self-consistent set of absorption coefficients (as determined from the Van Vleck formula) and temperature expansion coefficients is obtained. Power series and Chebyshev polynomial temperature determinations are compared. The effect of experimental errors on the solutions is discussed."

2.18 Abbott, R. L., "Width of Microwave Lines of Oxygen and Their Relationship to the Thermal Noise Emission Spectrum of the Atmosphere," (National Bureau of Standards), Proceedings of Third Symposium on Remote Sensing of the Environment, University of Michigan, 1964.

"Calculations of the thermal noise emitted by the atmosphere using values of the line widths of O_2 from measurements of the line widths at very low and at atmospheric pressure, are presented. The approximate calculation of line widths of previous investigations are described briefly. Some modifications necessary to calculate the anomalous behavior of the line widths of O_2 at atmospheric and lower pressures are given. These modifications enable many calculations to be made which were previously not feasible, and the results are much more precise than previous calculations. An example of such a calculation is presented. A brief view of the kinds of atmospheric probing information which are expected to result from the investigation is given. A brief comment will be given on how atmospheric probing can help in improving our understanding of molecular collision processes."

2.19 Norton, K. A., "Effects of Tropospheric Refraction in Earth-Space Links," (National Bureau of Standards), XIVth General Assembly of URSI, Japan, September 1963.

"This paper is a survey of the current state of knowledge of tropospheric refraction phenomena. Of necessity, some selection of topics has been made since it would be impracticable to describe in detail all aspects of this problem. Emphasis will be given to the basic scientific aspects of tropospheric refraction and only passing mention made of the applications. Methods of measuring and methods of predicting tropospheric refraction variables will be discussed, and it will be shown that excellent progress has been made in recent years in the accurate prediction both of the magnitudes of the variables involved and their variances. It is convenient to consider separately the bending of the radio waves in the vertical and horizontal directions."

2.20 Barsis, A. P., Barghausen, A. F., Kirby, R. S., "Studies of Within-the-Horizon Propagation at 9,300 Mc," (National Bureau of Standards), IEEE Transactions on Antennas and Propagation, Volume AP-11, No.1, January 1963.

"Propagation characteristics of radio signals in the 9300 Mc frequency range were investigated over a 113 Km tropospheric within-the-horizon path in Eastern Colorado. Special attention was given to the short-term fading characteristics of the received carrier envelopes and to the bandwidth capability of the medium in this frequency range, which was studied by the comparison of amplitude variations of two CW carriers separated by 100 Mc in frequency. For this purpose, correlation coefficients between carrier envelopes as well as the distributions of carrier amplitude ratios were analyzed. Although these parameters are related, the amplitude ratio has some advantages as an indicator of selective fading phenomena for within-the-horizon paths.

"By sampling the 9250 and 9350 Mc instantaneous carrier amplitudes at the rate of one per second, an over-all value of 0.91 was obtained for their cross-correlation coefficient. The standard deviation of the amplitude ratios expressed in db at 9250 and 9350 Mc averaged 0.76 db, with a maximum hourly value of 1.81 db. These results include the effect of space diversity, as separate antennas were used for transmission and reception of the two carriers, but they support the feasibility of wide-band modulation techniques for within-the-horizon paths if judged by the statistics of amplitude variations at discrete frequencies at the limits of the band considered.

"Short-term and long-term fading characteristics at 9300 Mc are similar to the ones previously observed on lower frequencies over this path. An analysis of prolonged space-wave fadeouts in this frequency range resulted in fadeout depths up to 25 db below weekly transmission loss medians, approximately log-normal distributions of fadeout durations, and the expected diurnal variations of fadeout occurrence typical of a continental climate."

There is some question about the mechanism producing the facing observed in this study because it appears that ground reflection occurred.

2.21 McGavin, "A Survey of the Techniques for Measuring the Radio Refractive Index," (National Bureau of Standards), NBS Technical Note 99, May 1962.

2.22 Norton, K. A., Herbstreit, J. W., Janes, H. B., Hornberg, K. O., Peterson, C. F., Barghausen, A. F., Johnson, W. E., Wells, P. I., Thompson, M. C., Jr., Vetter, M. G., Kirkpatrick, A. W., "An Experimental Study of Phase Variations in Line-of-Sight Microwave Transmission," (National Bureau of Standards), NBS Monograph 33, November 1961.

"During 1956 an experiment was conducted at Maui, Hawaii, to study the time variations in the phase of arrival of microwave signals propagated over a 15-mile line-of-sight path and the time variations in the phase difference of signals originating at a common antenna and received at two points on a horizontal baseline normal to the propagation path. These time variations are analyzed in terms of their serial correlation functions and power density spectra for different times of day, and for several baseline lengths ranging from 2.2 to 4,800 feet. The slope of the power spectra and the total variance of phase difference variations are shown to be dependent upon baseline length. In some instances there was evidence of a diurnal cycle in total variance of both phase and refractive index, with larger variances during the day time, but in other instances this diurnal effect was not detectable. The slope of the phase spectra appeared to be independent of time of day or meteorological conditions. The long-term variations in single-path phase were well correlated with variations in the mean value of refractive index measured at 5 points along the path."

2.23 Thompson, M. C., Janes, H. B., Kirkpatrick, R. W., "An Analysis of Time Variations in Tropospheric Refractive Index and Apparent Radio Path Length," (National Bureau of Standards), Journal of Geophysical Research, Volume 65, January 1960.

2.24 Smith, E. K., Weintraub, S., "The Constants in the Equation for Atmospheric Refractive Index at Radio Frequencies," Proceedings of the IRE, August 1953.

"Recent improvements in microwave techniques have results in precise measurements which indicate that the conventional constants, K_1 = 79°K/mb and K_2' = 4,800°K in the expression for the refractivity of air, $N = (n-1)10^6 = [K_1/T]\ (p + K_2'\ e/T)$ should be revised. Various laboratories appear to have arrived at this conclusion independently. In much of radio propagation work the absolute value of the refractive index of the atmosphere is of small moment. However, in some work, it is important and it seems highly desirable to decide upon a particular set of constants."

2.25 Deam, A. P., Fannin, B. M., "Phase-Difference Variations in 9,350 Mc Radio Signals Arriving at Space Antennas," (University of Texas), Proceedings of the IRE, October 1955.

2.26 Crain, C. M., Straiton, A. W., Von Rosenberg, L. E., "Statistical Survey of Atmospheric Index of Refraction Variation," (University of Texas), IRE Transactions on Antennas and Propagation, October 1953.

2.27 Straiton, A. W., Tolbert, C. W., "Factors Affecting Earth-Satellite Millimeter Wavelength Communications," (University of Texas), IEEE Transactions on Microwave Theory and Techniques, September 1963.

"The use of millimeter wavelengths for earth-satellite transmissions is suggested by the large bandwidths and high gain with small antennas possible at these wavelengths. The factors discussed are (1) propagation path loss, (2) refraction and (3) antenna temperature.

"The attenuation through the entire atmosphere over the millimeter spectrum is given as a function of elevation angle of the antenna beam. The attenuation and scattering loss due to water and ice particles varies over a wide range of values depending on the number of particles and their sizes.

"Refraction by the atmosphere is less than one milliradian for elevation angles for which the absorption is low enough to make the transmission practical. Fluctuations due to refraction may, however, be quite severe.

"Contribution to antenna temperatures from the atmosphere, the earth, the sun and moon are given for earth-based antennas and antennas in space."

2. 28 "Final Report on Research Activities in Millimeter Radiowaves and Geomagnetics," (University of Texas), Contract No. 375(01)NR-371-032, June - April 1951.

"This report describes work done at wavelengths between 8. 6 mm and 2. 15 mm. The emphasis was on the study of water vapor and oxygen absorption spectra. Experimental measurements and theoretical analyses were performed. Measurements were made on line-of-sight propagation paths of various lengths near sea level over land and water, on similar paths at 4 Km elevation between mountain peaks, and in controlled environments in a 250 foot microwave radiometer. Other investigations were concerned with absorption due to rain, surface reflection characteristics, antenna patterns, signal amplitude and phase fluctuations arising from a turbulent atmosphere, height gain variations, and measurement of millimeter wavelength dielectric constants. Using solar radiation, measurements were obtained of the total water content of the atmosphere and the total attenuation for paths through the entire atmosphere. Actually, this report merely summarizes work presented in other reports from the same group. It is a good introduction and index to these other reports."

2. 29 Tolbert, C. W., Brunstein, S. A., Britt, C. O., "Field Strength Fluctuations of 4. 3 Millimeter Radio Waves and Their Effects on Antenna Patterns," (University of Texas), Report No. 5-33, October 1958.

"By use of an array of receivers spaced horizontally at five points over a fifty foot interval, the differences in the field strength of

4.3 millimeter radio waves were measured. The propagation path was 40,000 feet in length and relatively free of sources of reflected signals. The measured field strength differences are used to evaluate the probable distortion of antenna patterns."

2.30 Tolbert, C. W., Straiton, A. W., Douglas, J. H., "Studies of 2.15 mm Propagation at an Elevation of 4 Kms and the Millimeter Absorption Spectrum," (University of Texas), Report No. 104, November 1958.

"The water vapor losses at a wavelength of 2.15 millimeters were found to be 0.12 db/Km/gram/m^3 at an elevation of 4 kilometers. Oxygen losses at the 4 Km elevation were unmeasurably small and the scintillation of the signal over a 1.73 Km path was less than 0.2 decibel.

"A calculated water vapor and oxygen absorption spectrum of the millimeter wavelengths, using the Van Vleck-Weisskopf equation and line breadth constants of 0.27 cm^{-1} and 0.02 cm^{-1}, respectively, was found to fit the measured values of absorption at wavelengths of 8.6, 4.3, 3.35 and 2.15 mm much better than do the normally accepted line breadths of 0.1 cm^{-1} for water vapor and 0.02 cm^{-1} for oxygen."

2.31 Tolbert, C. W., Britt, C. O., Straiton, A. W., "Atmospheric Attenuation of 3.35 Millimeter Radio Waves on a 7.5 Mile Path," (University of Texas), Report No. 90, March 1957.

"Radio propagation measurements at a wavelength of 3.35 millimeters over a 7.5 mile path are reported. From a plot of attenuation as a function of water vapor content of the atmosphere, an attenuation of 0.07 db per kilometer is found for oxygen and an attenuation of 0.033 db per kilometer per gram for cubic meter is found for water vapor. By use of these and other data taken by this laboratory, it is possible to sketch the water vapor loss curves in the millimeter region and to compare the oxygen loss with the calculated value. Severe scintillations of the millimeter signal were noted at and shortly after the passage of a cold front."

2.32 Wulfsberg, K. N., "Apparent Sky Temperatures at Millimeter-Wave Frequencies," (AFCRL), AFCRL-64-90, Physical Sciences Research Papers No. 38, July 1964.

"Measurements of apparent sky temperatures taken over a one-year period at 15, 17 and 35 Gc are summarized. Sky temperature profiles for various meteorological conditions are presented as well as curves showing the percentage time distributions for various zenith angles. Such factors as absorption and radiation by oxygen and water vapor, extrapolation of the data to other geographical areas, and the relation between total attenuation of the atmosphere and sky temperature are discussed. A description of the radiometers and the calibration techniques are included."

2.33 Wulfsberg, K. N., "Sky Noise Measurements at Millimeter Wavelengths," (AFCRL), Proceedings of the IEEE, March 1964.

"The sensitivity of ground-based receivers operating above X-band and employing low-noise front ends will generally be determined by noise radiated by the atmosphere. Both water vapor and oxygen absorb and emit radiation in this part of the spectrum and in the absence of precipitation produce virtually all of the sky noise. Since the noise intensity is highly weather-dependent, statistical data on the noise levels is required in order to specify the long-term performance of systems operating at these frequencies and employing low-noise receivers. A program is underway at the Air Force Cambridge Research Laboratories (AFCRL) to obtain the sky noise statistics at 15, 17 and 35 Gc; the data presented here covers the months of February through July, 1963, and should be fairly representative of a full year's data."

2.34 Rogers, T. F., "An Estimate of Influence of the Atmosphere on Airborne Reconnaissance Radar Performance," (AFCRL), January 1953.

2.35 Barton, D. K., "Survey of Propagation Effects," Chapter 15 of "Radar System Analysis," (Raytheon Company), The Prentice-Hall Microwaves and Field Series, 1964.

The material presented in Chapter 15 provides much of the background for Barton's work associated with the millimeter-wave experiment design study.

2.36 Barton, D. K., "Reasons for the Failure of Radio Interferometers to Achieve Their Expected Accuracy," (RCA), Proceedings of the IEEE, Volume 51, No. 4, April 1963.

"The precision, long-baseline, microwave interferometer has been proposed as a means of overcoming atmospheric limitations which affect missile and satellite tracking systems. It has been stated that the fluctuating errors in angle due to tropospheric anomalies are reduced in direct proportion to the baseline length b when b is extended beyond a few thousand feet. Measurements made over short periods of time on fixed paths have tended to confirm this theory. On the other hand, it has been shown that tropospheric anomalies are not limited to any particular size, but extend with increasing intensity to very large sizes and long periods."

2.37 Barton, D. A., et al., "Report of the Ad Hoc Panel on Electromagnetic Radiation", Final Report, Air Force Systems Command, Air Force Systems Command Contract AF18(600)-1895, February 1963.

"Tropospheric bias errors are highly predictable using radiosonde or refractometer profiles; residual errors from 1% to 3% of the initial bias levels are commonly attained using procedures described in Section 3. Data to within one-half foot in range and 20 to 70 μ radians in angle can be expected at elevation angles above five degrees.

"Tropospheric fluctuation errors are not correctable using any known procedure, and will amount to a few tenths of a foot in range, and 10 to 50 μ radians in angle (depending on the baseline or aperture used for measurement), under normal weather conditions.

"The relationship between temporal and spatial correlation of tropospheric fluctuations has been investigated, based on data obtained by the National Bureau of Standards. The effect of short-period fluctuations is consistent with a drift of tropospheric anomalies across a fixed measurement path at the speed of the prevailing wind.

"In range instrumentation applications, where the beam is not fixed, the residual "bias" and long-term components will change as the beam moves and additional atmospheric rate errors will be generated, as shown in Figure 4-6. These errors will be proportional to the tangential velocity of the missile, and will typically be five to fifty times the errors measured for a fixed beam.

"The uncertainty in tropospheric path leads to errors equivalent to motion of the instrument on the ground. The motion of the "virtual source" typically amounts to several feet normal to the path and a few tenths of a foot along the path."

2.38 Blevis, B. C., "Losses Due to Rain on Radomes and Antenna Reflecting Surfaces," (Defense Research, Ottawa, Canada), IEEE Transactions on Antennas and Propagation," January 1965.

"As frequencies are increased above about 1 Gc, the presence of condensed water in the atmosphere has increasingly important effects on the propagation of radio waves. As a result, signal attenuation and enhancement of antenna noise by rain, fog, cloud, etc., have been of concern to designers of satellite communication systems. However, the effects of thin layers of water on radome and feed surfaces due to rainfall have been largely neglected.

"A brief theoretical study, summarized here, was undertaken to determine to what extent losses due to rain falling on a radome enclosing a large parabolic reflecting antenna would be expected to impair the performance of systems operating at frequencies about 2 Gc. Effects of increases in antenna noise temperature are not considered. Losses due to water layers on perfectly reflecting surfaces were also investigated in order to determine to what extent the problem would be alleviated if no radome were present. It is appreciated that in many circumstances these considerations may not be of any major importance in determining whether or not a radome is to be used.

"The values of the real and imaginary parts of the complex relative dielectric constant of water obtained at a number of frequencies between 380 Mc and 35 Gc by Grant, Buchanan and Cook have been used as the basis for calculations of the effects of rain water described here."

2.39 Grant, E. H., Buchanan, T. J., Cook, H. F., "Dielectric Behavior of Water at Microwave Frequencies," Journal of Chemical Physics, Volume 26, January 1957.

2.40 Gibble, D., "Effects of Rain on Transmission Performance of a Satellite Communications System," (Bell Telephone Laboratories), IEEE International Convention, March 1964.

"Results of measurements of sky noise during rain and snow are given. Measurements were made at Whippany, N. J., at 5350 Mc/s. Results are given as distribution curves of noise values for eight specific elevation angles.

"A method of estimating the thickness of the water layer on a radome during rainfall and the resulting increases in attenuation and apparent sky noise is given. Comparison with experimental results is made.

"The probability distribution of the received carrier to noise ratio of the earth station has been calculated for several typical satellite communication systems that use 6000 mile orbit, gravity gradient attitude controlled satellites. It is shown how this distribution curve can be used in designing a system so as to just meet noise and breaking objectives."

2.41 Giger, A. J., "4-Gc Transmission Degradation Due to Rain at the Andover, Maine, Satellite Station", (Bell Telephone Laboratories) Bell System Technical Journal, September 1965.

"The microwave link between a ground station and a communications satellite is normally very stable and essentially free from fading. Under conditions of rain or snow, however, the transmitted and received signals encounter extra attenuation and additional noise is introduced into the low-noise receiver on the ground. A good knowledge of such rain effects is important for the design of satellite ground stations which have to meet certain statistical requirements for transmission degradation. It is known that radome covered ground stations like Andover suffer more degradation during rain than uncovered stations. Some analytical work has been done by D. Gibble and B. C. Blevis to determine the effects of a water layer on radomes. Their theoretical work has been supplemented by an experimental technique applicable at existing satellite ground stations and to be described in this brief report. It consists of measuring the reduction of the noise power received from the strong and stable radio star Cassiopeia A during periods of rain."

2.42 Cady, W. M., Ed., "Radar Scanners and Radomes", M.I.T. Radiation Laboratory Series, Volume 26, Chapter 12, "Theory of the Reflection and Transmission of Electromagnetic Waves by Dielectric Materials", Leaderman, H., Turner, L. A., McGraw-Hill Book Company, New York, N. Y., 1948.

2.43 Evans, A., Bachynski, M. P., Wacker, A. G., "Propagation and Absorption in Planetary Atmospheres" in Volume IV of "The Radio Spectrum from 10 Gc to 300 Gc in Aerospace Communications", (RCA Victor Company) Research Report No. 6-400-3, July 1962.

"This report consists of two parts which deal with (Part I) Absorption of Electromagnetic Waves in the Atmospheres of the Earth and Other Planets and (Part II) Noise in the 10-300 Gc Frequency Range.

"In Part I, the theory of resonant absorption in gases is considered and the various factors affecting the width of the absorption bands discussed. The composition of the earth's atmosphere and constituents giving rise to absorption are treated in detail. Experimental measurements and theoretical considerations, including absorption and scattering in rain and fog are summarized. Absorption in the atmospheres of other planets is also discussed and the present state of knowledge with regard to planetary atmospheres and absorption spectra is outlined.

"Part II deals with the theoretical aspects of noise temperature. In particular, the limitation of the Rayleigh-Jeans law at these frequencies is pointed out and the validity of the concept of effective antenna temperature discussed. The various sources of noise and their relative importance are outlined."

2.44 Fukushima, M., Irige, H., "Preliminary Study of Spatial Distributions of Atmospheric Refractive Index from Aircraft Observations", (Radio Research Laboratories, Tokyo, Japan), Proceedings of the 1964 World Conference on Radio Meteorology, Boulder, Colorado.

"Various factors of the refractive index structure, such as scattering parameters, reflection layer characteristics and refractivity profiles are related to the mechanism of tropospheric propagation. There are two possibilities to derive refractive index structures: the one is derived from theoretical considerations of radio propagation experiments and meteorological data concerned, such as the study of Hirai et al (1963); the other one is derived from direct observations of the atmospheric refractivity, one of these observations is reported by Fukushima, Iriye and Akita (1962). But the agreement between the two above mentioned is not satisfactory.

"Now, in order to get further information of the refractive index structure of the lower troposphere, aircraft observations are carried out."

Crude description of the refractive index structure of the lower troposphere in the height of 1 to 3 kilometers has been presented which suggests some effect of topography or mountain waves, especially in the large-scale anomalies of the distribution of refractivity, but the confirmation must await further studies.

Concluding remarks deduced from the results of observation are as follows: (1) Mean square values of the deviation of refractivity from its average, $\Delta\overline{N^2}$, show some regional change, and the range of the seasonal variation was about 8 db. (2) Characteristics of "refractivity cloud" are summarized as follows: median value of the intensity and the scale is 2 N-units, and 600 meters and the ratio of the distributed region to the whole space is about 1/3 in summer, these values change to 2 N-units, 300 meters and 1/5 in winter. (3) Remarkable irregularities characterized by N-difference of 4 to 6 N-units at the two points separated in height by 10 meters were observed frequently at height of 1 to 2 kilometers where the vertical gradient of refractivity is steep and the atmospheric temperature lapse rate is great.

Elevated layers in summer and spring are considered as extreme cases of remarkable irregularities that are characterized by N-discontinuity of 20 - 40 N-units and the thickness is less than several tens of meters.

2.45 Maio, A. D., Castelli, J. P., Harneh, P. J., "Wavefront Distortion Due to Atmospheric Inhomogeneities", (AFCRL), Proceedings of the 1964 World Conference on Radio Meteorology, Boulder, Colorado.

"The dynamic effect of the problem created by wavefront distortion due to atmospheric inhomogeneities has been noticed by radio astronomers for over a decade. The development of high gain tracking antennas enabled the scientist to study discrete radio sources and atmospheric inhomogeneities were observed that caused the received signal to fluctuate strongly at low elevation angles.

"Radio astronomers have at times attempted to find the mechanism which produces this simple looking pattern. Efforts to relate the scintillations to atmospheric conditions have met with little success. Failure to obtain correlations may be due to choice of parameters or lack of atmospheric data, and the fact that this nuisance was tolerated while more pressing problems were solved. This is not surprising since meteorologists have for years tri d to fit propagation models to the complex nature of the atmosphere. It appears that the techniques of radio astronomy can be considered a tool for the study of these complexities. With ideal signals as a source, highly sensitive receivers and standard calibration techniques, coupled with established weather observations and in-flight refractometer measurements, a better understanding of the "blobby" structure of the atmosphere should be forthcoming. This paper presents some preliminary results and indicates to the meteorologist and radio engineer the type of data that is provided by radio-astronomical techniques.

"Stellar radiation at 1.2 Gc and 3.0 Gc was observed for a variety of elevation angles ranging from 0.5° to 4.0°. Several simple models for the fading mechanism are presented and rejected."

2.46 Wickerts, S., "An Investigation of the Semi-Fine Structure of the Refractive Index Field in a Coastal Area", (Royal Swedish Air Force), Proceedings of the 1964 World Conference on Radio Meteorology, Boulder, Colorado.

"In connection with a field-test during the autumn 1963, the structure of the atmosphere was studied along a path, 40 Km from the coastline out over the Baltic Sea 30 Km from the coast. At the same time as the meteorological measurements were performed, the field-strengths were measured in the Baltic Sea 200-300 Km from a transmitter, which was transmitting in a path that coincided with the first part of the meteorological test-path. The field-strengths were measured between the 1000 m and 13000 m elevation.

"The purpose of the field-test was to study the connection between the variations of the field-strength and the meteorological conditions. In this paper the meteorological problems will be described."

The author concluded "that the variations of the refractive index in the atmosphere depend mainly upon the variations of the humidity". The variations in refractive index are studied and the author further concludes "that there exists larger small-scale variations in the atmosphere than what was believed only a few years ago...in the near future, the microwave technique will present new possibilities to measure the fine-structure of the atmosphere.

2.47 Deirmendjian, D., "Complete Scattering Parameters of Polydispersed Hydrometeors in the λ0.1 to λ10 cm Range", (Rand Corporation), Proceedings of the 1964 World Conference on Radio Meteorology, Boulder, Colorado.

"This new theoretical investigation has two purposes: (a) to introduce a realistic size spectrum for the precipitation drops, including those found near the base of a cloud, and (b) to evaluate as exactly as possible all the rational scattering parameters that are necessary inputs for the formulation of the equivalent radiative transfer problem; in addition to the scattering and absorption coefficients, these parameters include polarization at any scattering angle, per unit volume of space with precipitation and/or cloud particles. Furthermore these quantities are evaluated over wavelengths as low as 1 mm, extending the range of previous studies.

"In part, we undertook this task because such parameters are not available in the literature. Previous investigations were generally limited to the determination of back-scattering and attenuation cross sections for single particles as a function of the size parameter. We hope that the new results presented here will lead to new research applications of passive and active microwave techniques, such as the use of bistatic systems. The radiative transfer problem arises when a continuous flux of microwave radiation is incident on a layer of hydrometeors suspended in a planetary atmosphere."

The differential and total scattering and absorption coefficients per unit volume were calculated using the full Mie series. The results in general, agree with previous theoretical estimates.

2.48 Doviak, R. J., Goldhirsch, J., Lombardini, P. O., "Electromagnetic Scattering from Electron Irregularities in an Inhomogeneous Electron Density Distribution", (Raytheon Company), Report No. FR-65-275, August 1965.

"Studies of electromagnetic weak scattering from irregularities of electron density have, for the most part, been made for cases in which these irregularities are stochastically embedded in media having uniform electron density distributions (Booker and Gordon, 1950; Villars and Weisskopf, 1954; Al'pert, 1960, Tartarski, 1961, Tai and Wait, 1962, Budden, 1965). Some studies have also been made of scattering from irregularities immersed in electron density distributions which are spatially slowly changing (Villars and Weisskopf, 1955; Gallet, 1955; Wheelon, 1960). In most of the above cases, the electron irregularities are assumed to be statistically homogeneous throughout the medium. Budden (1965) considered a model in which electron density irregularities are represented by a product of two functions; one deterministic and having a variation in the vertical direction, the other representing a statistically homogeneous process. He relates his analysis to the scintillation of radio signals received on the ground from satellites or radio stars, and he therefore specializes his study to the case in which small angles exist between the incident wave normal and the radius vector drawn from the scattering media to the receiver.

"The present work represents an extension of the above analyses in that forward scattering from electron irregularities, $\Delta N(x,y,z)$ are considered for the case in which ΔN is statistically inhomogeneous and embedded in media having a deterministic non-uniform electron density distribution, $N_o(x,y,z)$."

2.49 Krotikov, V. D., Troitskii, V. S., "Radio Emission and Nature of the Moon", Soviet Physics, Uspekhi, Published by American Institute of Physics, Volume 6, No. 6, May-June 1964.

"In somewhat more than a decade of the observation of the radio emission of the moon, important results were obtained, which disclose the nature and the physical conditions, not only of the outer cover, but also deep inside the moon, and cast light on its history.

"The purpose of the present review is to present not only as complete information as possible on the physical conditions of the moon, obtained by investigating the moon's own radiation, but also to describe the methods and analysis used to determine these conditions."

As the above summary implies, this is a very complete survey of experimental results concerning lunar radiation.

2.50 Krasilnikov, V.A., Tatarsky, V.I., "Atmosphere Turbulence and Radio Wave Propagation," (USSR Academy of Science, Moscow, USSR), in Monograph on Radio Wave Propagation in the Troposphere, Elsevier Publishing Company, New York, 1962. (See Tatarsky, V.I., "Wave Propagation in a Turbulent Medium," McGraw-Hill Book Company, New York, 1961.)

"The aim of this work is to consider the problem of the tropospheric radio-wave propagation far beyond the horizon and also of the fluctuations of the elements of the waves from the point of view of Kolmogorov-Oboukhov's local isotropy theory of turbulence. This theory has now been well developed, and numerous experimental investigations show that it satisfactorily describes the principal phenomena of the phase and amplitude fluctuations. This theory also gives the right order of value for the effective cross section of scattering in the transhorizon propagation. However, it is impossible to explain the fields observed beyond the horizon solely by means of this theory."

This paper, together with the book by Tatarsky, gives an extensive theoretical analysis of scattering phenomenon and also gives experimental results. The paper covers, in much less detail, the material in the book, and therefore, the paper is recommended to the individual interested in the results of the theory and in the experimental evidence. On the other hand, the book does clarify points that are not clear in the paper.

2.51 Stock, J., Keller, G., "Astronomical Seeing", in Telescopes, edited by Kuiper, G. P., Middlehurst, B. M., The University of Chicago Press, Chicago, 1960.

This article contains a good physical description of the causes of scattering in the atmosphere. The specific formulae presented are not really applicable to millimeter waves, however.

2.52 Manasse, R., "Maximum Angular Accuracy of Tracking a Radio Star by Lobe Comparison", (M.I.T., Lincoln Laboratories), IRE Transaction on Antennas and Propagation, January 1960.

"A general expression is derived for the maximum angular accuracy of tracking a radio star by lobe comparison (or monopulse). This angular accuracy depends on the input signal-to-noise ratio, the wavelength the time-bandwidth product of signal integration, and the effective length of the antenna aperture. The maximum angular accuracy can be obtained, approximately, by performing a simple correlation of odd and even components of the antenna output. Angular accuracy formulas for simple antenna dishes or for interferometers appear as special cases of the general result.

"The Appendix discusses the interferometer technique in more detail, and the angular accuracy for the data processing technique used by M. Ryle is compared with that obtained from the optimum processing."

2.53 Nicholson, P. F., "Atmospheric Refraction Considerations for the 150-Foot Paraboloidal Antenna at Sugar Grove", NRL Memorandum Report 1599, April 1965.

"Analyses of weather data collected over the past few years at Sugar Grove, West Virginia, show that certain simplifications are valid when computing radio refraction angles. An approximation to the classical equation for tropospheric refraction is cited which requires only the local surface weather conditions. Using the Sugar Grove environment, it is demonstrated that the above approximation will yield refraction predictions accurate to within a few seconds of arc for elevation angles greater than 10° and will maintain an accuracy better than 10 percent for elevations as low as five degrees.

"It is also shown that diurnal variations in refraction at Sugar Grove are relatively small in winter and that suitable mean values can be established. In addition, maximum and minimum bending are given for selected elevation angles based on all 1962 Sugar Grove weather data.

"Finally, the predicted values of refraction are compared to the main beam pattern of a 150-foot antenna."

2.54 Richer, R. A., Baverle, D. G., "Near-Earth Millimeter-Wave Radiometer Measurements", (Ballistic Research Laboratories), BRL Report No. 1207, December 1964.

"Radiometric measurements of the atmosphere and natural emissive and reflective features of the terrain at wavelengths of 8.58, 4.29 and 2.14 mm wavelengths are discussed. Characteristics of experimental radiometers operating at 1.45, 1.33 and 0.5 mm wavelengths are also given. The quantitative effects of weather on radiometric performance at these wavelengths are considered. The performance characteristics of low noise millimeter-wave radiometric antenna systems are investigated. The merits and shortcomings of various types of measurements with these radiometers are discussed.

"This paper was presented at the 1964 World Conference on Radio Meteorology at the National Bureau of Standards, Boulder, Colorado, September 1964, and was printed in the proceedings of that conference."

2.55 Hunt, W. T., "The Earth's Atmosphere at Millimeter Radio Wavelengths", (Wright Air Development Center), WADD TN 60-232, ASTIA AD 252, 126, November 1960.

2.56 Jordan, T., "Electromagnetic Theory", McGraw-Hill Book Company, New York.

2.57 Kerr, D. E., Ed., "Propagation of Short Radio Waves", (John Hopkins University), M.I.T. Radiation Laboratory Series, Volume 13, McGraw-Hill Book Company, New York, N. Y., 1951.

2.58 Lee, R., Waterman, A., "Some Millimeter Wave Propagation Measurements" (Stanford University), Contract AF 04(695)-353, Project 2274.

"There have been two aspects to the millimeter-wave propagation research conducted at Stanford so far -- one deals with absorption, the other with scattering.

"In the first, a set of measurements has been made of the absorption of solar radiation at 35 Gc. The procedure was similar to others used previously, involving a 5-ft parabolic antenna and a Dicke-type radiometer, but differed in details of the equipment and in maintaining a nearly daily record over a period of approximately five months. Results showed the effective vertical-incidence total atmospheric absorption to have a median value of 0.27 db. Typical clear- and cloudy-day values were 0.24 and 0.34 db respectively. During moderate rain the attenuation generally did not exceed 1.60 db, although in one severe storm it reached 6.72 db.

"The second aspect of the research program has dealt with line-of-sight propagation measurements, again at 35 Gc, over a 17-mile path. A CW signal has been transmitted and various combinations of spaced receivers have been used. Data, recorded on magnetic tape, have been analyzed by computing the autocorrelation and spectrum of a single received signal, and the cross correlation, with time lag as a parameter, between two signals received on spaced antennas. The results in general show the signal to consist of a constant component on which is superimposed a Gaussian-fluctuating component having variations of a fraction of a decible. The correlation between signals received simultaneously on spaced antennas generally drops to 0.5 at a spacing of around 20 ft. At a fixed antenna, the autocorrelation of the received signal envelope drops to 0.5 for a time lag of slightly less than 1 sec. Computed power spectra of the signal envelope show nearly all the energy to be contained in the region below 2 cps; on occasions there is a significant peak around 0.4 cps. With a fixed spacing (20 ft) between two receiving antennas, the time delay required for maximum cross correlation (usually around 0.8) is on the order of 1 sec. It varies by a factor of 4 or so, during the course of a day, and in a manner consistent with the variation in simultaneous cross-correlation coefficient and with the variation in width of the power spectrum. Other interrelations -- with the magnitude of signal deviations and with meteorological wind data -- present a less consistent picture."

2.59 Westinghouse Electric Corporation, "Navigation Satellite System", Volume 1, NASA Office of Space Science and Applications, Contract NASW-785, January 1964.

2.60 Kennedy, R., "Design Considerations for Ionospheric Channels", (Raytheon Company), BL-1039, July 1964.

2.61 "A Millimeter Communications Propagation Study", (Raytheon Company), BR-3011, June 1964.

This document is the solicited proposal to Goddard Space Flight Center upon which the award of the millimeter-wave experiment design study was based. All important technical information contained in this report has been included in the contract reports and therefore is now of little value.

3.0 Plasma Effects

3.1 French, I. P., Bachynski, M. P., "Plasma Effects in Aerospace Communications," Volume V of "The Radio Spectrum from 10 Gc to 300 Gc in Aerospace Communications," (RCA Victor Company), Research Report No. 6-400-3, July 1962.

"A review of the role of natural and artificial plasmas in aerospace communications is presented in this report. The theory applicable to antenna breakdown at high altitudes and methods of estimating the breakdown RF fields and powers for various microwave antennas, mainly in the frequency range above 10 Gc, is given. The ionized shock wave of a reentry vehicle is studied with special reference to the problem of propagating RF energy through it. The properties of antennas operating in ionized regions are considered, together with the passive microwave radiation emitted by plasmas which appears as noise at a receiver. An attempt is made to evaluate the role of other natural and artificial plasmas such as the ionosphere, aurora, rocket exhaust, nuclear reactors, and nuclear blasts, on communications."

The document is comprised of four chapters:

I. Breakdown Phenomena

II. The Plasma Sheath and Wake of a High Altitude Vehicle and Their Effect on Communications

III. Antenna Properties in Ionized Media

IV. Electromagnetic Radiation and Propagation in Various Natural and Artificial Plasmas

The important conclusions are to be drawn from Chapter I: (1) the breakdown field of an antenna increases with increasing frequency and has a minimum value of approximately 400 volts per centimeter (neglecting plasma effects) at the critical altitude for a frequency of 10 Gc; (2) the effect of the plasma is to reduce the breakdown field strength; (3) the pressure increase due to the buildup of the shock wave tends to shift breakdown conditions to higher altitudes; (4) the breakdown field of an antenna has been determined as a function of altitude under the influence of the ionization produced by a shock wave, for various velocities, nose-cone angles, and RF frequencies. Unfortunately, no quantitative data concerning (4) is contained in the report.

3.2 Bachynski, M. P., French, I. P., Cloutier, G. G., "Antenna Noise Temperature in Plasma Environment," (RCA Victor Company), Proceedings of the IRE, Volume 49, December 1961.

"The total noise power available at a receiving antenna on a hypervelocity space vehicle is determined by considering the engulfing plasma sheath as a uniform slab of plasma. The noise emission from the plasma is treated as a boundary-value problem which for this simple model can be completely solved. The effect of the hot vehicle surface and other external sources is included.

"The general conclusions are that for an isotropic plasma the main noise contributions result from the vehicle surface for RF frequencies well below the plasma frequency, from external sources for RF frequencies well above the plasma frequency, and from direct emission by the plasma for RF frequencies about the plasma frequency. The noise power from the plasma is the most significant and exhibits a pronounced peak at an RF frequency just above the plasma frequency.

"The effect of an anisotropic plasma sheath (due to auxiliary magnetic field carried by the vehicle) has been investigated for magnetic field orientations normal to and parallel to the plasma. The anisotropy completely alters the spectral characteristics of the available noise power resulting in several frequency regions of weak and intense noise emission."

3.3 Bachynski, M. P., Johnston, T. W., Shkarofsky, I. P., "Electromagnetic Properties of High-Temperature Air," (RCA Victor Company), Proceedings of the IRE, Volume 48, March 1960.

"This paper concerns the attenuation and phase characteristics of plasmas and, in particular, the electromagnetic properties of high-temperature air. It is shown that by a suitable normalization of the parameters the electromagnetic properties of plasmas may be universally represented in convenient form in either the complex dielectric coefficient plane or the complex propagation constant plane. Next, the electron number densities and electron collision frequencies for air ranging in temperature from 3000 to 12,000 K and in density from 10^{1} to 10^{-4} times the density at sea level are illustrated. The attenuation and phase constants for an electromagnetic wave traversing this medium have been evaluated for frequencies from 10^9 to 10^{11} cps. As an example, the above universal representation is applied to the stagnation region of a hypersonic vehicle in space."

3.4 Bachynski, M. P., Shkarofsky, I. P., Johnston, T. W., "Plasma Physics of Shock Fronts," (RCA Victor Company), RCA Research Departments No. 7-801-3, June 1959.

"A summary of fundamental physics associated with plasma formed by strong shock fronts is presented. The methods of quantum statistical thermodynamics, thermodynamics of real gases and aerodynamics are applied in order to determine the particle constituents and thermodynamic properties of a plasma created by a strong shock wave. This enables certain electrical and electromagnetic properties to be associated with the plasma. Variation of these plasma properties are given for air in thermal equilibrium. The effects of non-equilibrium i. e., relaxation phenomena, are discussed. Finally, measurement techniques for determining shock front plasma properties are considered."

3.5 Scharfman, W. E., Morita, T., "Voltage Breakdown of Antennas at High Altitude," (Stanford Research Institute), Proceedings of the IRE, Volume 48, November 1960.

"The factors influencing the power-handling capability of antennas at high altitude are considered in this paper. The physical mechanism involved, including the roles of attachment, free diffusion, ambipolar diffusion, and nonuniform field distribution in the breakdown process, is qualitatively described. These factors are illustrated by breakdown curves for various antenna configurations under both CW and pulse conditions. Normalized data -- useful for estimating breakdown fields when the conditions for scaling are fulfilled -- are presented.

"The effect of missile environment on breakdown characteristics is discussed, and an experiment that involves artificially introducing ionization near the surface of the antenna is described.

"Methods are then considered for increasing the power-handling capability, and typical results are given showing the increase in power that can be achieved."

3.6 Whitmer, R. F., "RF Breakdown Conditions in the Presence of the Plasma Sheath," and "Electromagnetic Effects of Re-Entry," Selected papers from the Symposium on Communications and Detection, Boston, December 1959, Published by Pergamon Press, 1961.

3.7 MacDonald, A. D., "High-Frequency Breakdown in Air at High Altitudes," (Dalhousie University, Halifax, Nova Scotia), Proceedings of the IRE, Volume 47, March 1959.

"The problem of microwave breakdown near antennas at high altitudes is considered in order to find limitations on transmission conditions. The fundamental processes are described briefly. The cw breakdown electric fields for frequencies of 100 mc, 3 kmc, 10 kmc, 20 kmc, and 30 kmc are computed on the basis of the available data on atmospheric composition. The maximum peak electric fields and powers for which pulses are almost completely transmitted are also computed for the same frequencies and for several pulse lengths. It is also shown that considerably more power per unit area of aperture can be transmitted at the higher frequencies. The validity of the assumptions on which the calculations are based is considered."

3.8 Langberg, E., Baldwin, K, Yos, J., "Radiation and Propagation of Telemetry Signals During Hypersonic Re-Entry," (AVCO), IRE Preceedings of the National Symposium on Telemetering, 1958.

"This paper contains an analysis of the propagation properties of thermally ionized air which are of interest in the design of a reentry telemetry system. It discusses first the simplifying assumptions which are used in the usual derivation of the plasma propagation constant. Next, a graphical solution is presented which relates aerodynamic parameters to electrical plasma parameters. Finally, the special problem of a stratified plasma is considered."

3.9 Huxley, L. G. H., "Free Path Formulas for the Electronic Conductivity of a Weakly Ionized Gas in the Presence of a Uniform and Constant Magnetic Field and a Sinusoidal Electric Field," (University of Adelaide, Australia), Australian Journal of Physics, Volume 10, 1957.

"A general free path formula is given for the drift velocity of electrons in a weakly ionized gas in a sinusoidal electric field. Most special cases of interest, including the magnetic deflection of an electron stream in a gas, are readily derivable from the general formula. The results find application in microwave and ionospheric studies of the motion of electrons in gases as well as in experiments on the magnetic deflection of an electron stream."

3.10 Lamb, L, Lin, S. C., "Electrical Conductivity of Thermally Ionized Air Produced in a Shock Tube," (AVCO), Journal of Applied Physics, Volume 28, July 1957.

"The electrical conductivity of shock-heated air at equilibrium temperature from 3500°K to 6200°K, and at densities of the order of 0.01 NTP, has been measured, using the shock wave-magnetic field interaction technique reported by Lin, Resler, and Kantrowitz. The experimental results indicated that the ionization process builds up quickly behind the shock front, and that the measured conductivity agrees quite well with calculated values based on the equilibrium degree of ionization, the electron diffusion cross sections for the molecular species available in the literature, and on a theoretical estimate of the scattering cross sections for oxygen and nitrogen atoms by Hammerling, Shine, and Kivel based on the Hartree potential with appropriate exchange and polarization terms."

3.11 Hochstim, A.R., Arave, R.J., "Various Thermodynamic Properties of Air," (Convair) Convair Report No. ZPH-004, June 1957.

3.12 Spitzer, L., Harm, R., "Transparent Phenomena in a Completely Ionized Gas," (Princeton University), Physical Review, Volume 89, 1953.

"The coefficients of electrical and thermal conductivity have been computed for completely ionized gases with a wide variety of mean ionic charges. The effect of mutual electron encounters is considered as a problem of diffusion in velocity space, taking into account a term which previously had been neglected. The appropriate integro-differential equations are then solved numerically. The resultant conductivities are very close to the less extensive results obtained with the higher approximations on the Chapman-Cowling method, provided the Debye shielding distance is used as the cutoff in summing the effects of two-body encounters."

3.13 Massey, H. S. W., Burhop, E. H. S., "Electronic and Ionic Phenomena," (University of London), Oxford University Press, London, 1952.

"There are very many directions in which research in physics and related subjects depends on a knowledge of the rates of collision processes which occur between electrons, ions, and neutral atoms and molecules. This has become increasingly apparent in recent times in connection with developments involving electric discharges in gases, atmospheric physics, and astrophysics. Apart from this the subject is of great intrinsic interest, playing a leading part in the establishment of quantum theory and including many aspects of fundamental importance in the theory of atomic structure. It therefore seems appropriate to describe the present state of knowledge of the subject and this we have attempted to do in the present work."

4.0 Channel Characterization

4.1 Bello, P. A., "Some Techniques for the Instantaneous Real-Time Measurement of Multipath and Doppler Spread," (Signatron), IEEE Transactions on Communication Technology, September 1965.

"The design optimization of digital communication systems using selectively fading transmission media such as HF and troposcatter requires knowledge of the selective fading characteristics of the media. A minimal characterization is provided by the gross channel parameters of multipath spread and Doppler spread. This paper presents several techniques which will allow the simultaneous measurement of multipath and Doppler spread in real time with a minimum of equipment complexity. The techniques are first divided into two classes depending upon whether measurements are made on in-phase and quadrature components of received carriers or on envelopes of received carriers. A further subdivision is made according to two different techniques of multipath spread measurement, one of which, called the SSB method, uses two transmitted carriers while the other, called the FM method, uses a frequency-modulated carrier. The envelope measurements are the simplest and should provide considerable help in any large scale testing of the selective fading properties of the HF and troposcatter media."

4.2 Bello, P.A., "On the Instantaneous Real-Time Measurement of Multipath and Doppler Spread," (ADCOM), IEEE First Annual Communications Convention, Boulder, Colorado, June 1965.

See Reference 4.1.

4.3 Bello, P.A., "Measurement of the Complex Time-Frequency Channel Correlation Function," (ADCOM), Radio Science Journal of Research NBS/USNC-URSI, Volume 68D, No. 10, October 1964.

"The time and frequency selective fading properties of radio channels may be characterized by evaluating the cross-correlation function between two received carriers as a function of their frequency separation. In practice such correlation functions have been measured using only the envelopes of the received carriers. Recent studies of the effect of time and frequency selective fading on digital data transmission have shown that envelope correlation information is insufficient for an accurate evaluation of system performance and that the complex envelope correlation function is needed. This paper presents an experimental technique for the measurement of the complex time-frequency correlation function of radio channels that uses independent frequency standards at transmitter and receiver. An analytical study is made of the theory of operation of this system and of the effects of instabilities of the frequency standards."

4.4 Watts, D.G., "Optimal Windows for Power Spectra Estimation," (Mathematics Research Center, United States Army, University of Wisconsin), MRC Report No. 506, ASTIA AD-607-822, September 1964.

"Two classes of optimal spectral windows are derived. These windows are compared with empirical windows used, e.g., Bartlett, Hanning, Parzen, and are found to be generally superior to them on a mean-square-error basis. Some of the considerations of bandwidth and resolution of spectral windows are discussed and clarified."

4.5 Blackman, R. B., Tukey, J. W., "Measurement of Power Spectra," (Bell Telephone Laboratories), Bell System Technical Journal; Part I, January 1958; Part II, March 1958.

"The measurement of power spectra is a problem of steadily increasing importance which appears to some to be primarily a problem in statistical estimation. Others may see it as a problem of instrumentation, recording and analysis which vitally involves the ideas of transmission theory. Actually, ideas and techniques from both fields are needed. When they are combined, they provide a basis for developing the insight necessary (1) to plan both the acquisition of adequate data and sound procedures for its reduction to meaningful estimates and (2) to interpret these estimates correctly and usefully. This account attempts to provide and relate the necessary ideas and techniques in reasonable detail."

4.6 Blackman, R. B., Tukey, J. W., "The Measurement of Power Spectra from the Point of View of Communication Engineering," (Bell Telephone Laboratories), Dover Publications, New York, 1958.

"If this account appears to be intended principally for communications engineers it is only because an adequate understanding of how (power) spectrum analysis works seems to demand some aspects of a communications engineering approach. (Even some of our colleagues, interested in digital computation, or in statistical techniques, rather than in communications engineering, have reluctantly come to agree with this statement.) This account is intended for all who know what they want to accomplish by spectral measurement and analysis (though perhaps nothing of how to accomplish it), and are concerned with how to do it, or with how to think about doing it, or with why it should be done in one way rather than another. Considerable mathematical detail is given, but as a guide and background to practice, rather than either for its own sake of for the sake of rigor.

4.7 Van Trees, H. L., Class Notes for Massachusetts Institute of Technology Course 6.576, (M.I.T.), Spring 1965.

4.8 Lebow, I. L., et al, "The West Ford Belt as a Communications Medium," (M.I.T., Lincoln Laboratories), Proceedings of the IEEE, Volume 52, No. 5, May 1964.

"A complete description of the communications properties of a dipole belt is given by its scattering function $\sigma(\tau, f)$, the scattering cross section of a differential volume located at propagation delay τ and Doppler shift f, evaluated over the entire common volume of the belt. A coarser description, but one which is sufficiently accurate if $\sigma(\tau, f)$ is well-behaved, is given by the two parameters, multipath spread L (the width of $\int \sigma(\tau, f) df$), and Doppler spread B (the width of $\int \sigma(\tau, f) d\tau$). This paper describes two experiments which were performed concurrently on the test belt: (1) a propagation experiment in which $\sigma(\tau, f)$ was measured, and (2) a communications experiment in which digital signals designed using estimate of B and L were transmitted and the performance of the system measured.

"Both experiments were performed using the West Ford sites described in Nichols, et al. The results may be divided into two phases. During the first 50 days after ejection, corresponding roughly to the period of belt formation, the scattering function was measured and the communications experiment performed. In general, the scattering function was well-behaved. Digital data were transmitted at rates from 20,000 bits/sec initially, down to around 100 bits/sec. PCM voice was transmitted during the first week. The performance of the digital communications was in good agreement with the expected theoretical performance of diversity signaling systems. After this first period, the belt density was generally too low to permit measurement of $\sigma(\tau, f)$. However, the spectrum of the signal received from the entire common volume $\int \sigma(\tau, f) d\tau$ was measured with results most applicable to physical belt studies. During this latter period the only communications signals have been teletype."

4.9 Gallager, R.G., "Characterization and Measurement of Time and Frequency Spread Channels," (M.I.T., Lincoln Laboratories), Technical Report 352, April 1964.

"This report deals with the characterization and measurement of channels in which the input waveform is subject to both additive noise and to time and frequency spreading. Part of the report is tutorial in nature and attempts to relate the wealth of mathematically oriented literature on spread channels, with both the underlying physical mechanisms and with the engineering concepts concerning spread-channel communication.

"Many spread channels are adequately characterized by any one of three functions of two variables: the scattering function, the tap-gain correlation function, and the two-frequency correlation function. These quantities are carefully defined and related by Fourier transform relationships. A number of interpretations are given for these functions, and the physical circumstances in which the functions provide meaningful characterizations of the channel are discussed.

"Techniques are given for measuring each of the above three functions. It is shown that the variance of these measurements approaches zero with the reciprocal of the measurement time. One of these techniques, using a chirp input signal to measure the two-frequency correlation function, appears to have definite advantages over the others, in terms of required measurement time and in ease of implementation. The analysis clears up some earlier paradoxes about measuring overspread channels and gives some insight into the relative merits of different input signals."

4.10 Green, P. E., Jr., "Radar Astronomy Measurement Techniques," (M.I.T., Lincoln Laboratory), Technical Report 282, December 1962.

"This report is a review of currently available techniques for studying the properties of objects of interest in radar astronomy, which are usually spread radar targets. The report is intended as a sequel to Lincoln Laboratory Technical Report 234 (Reference 4.11), in which R. Price has presented a rather complete treatment of the theory and methodology of the detection of such spread targets. Here we are interested in measurement (or estimation) rather than detection.

"Spread targets are defined to be those that produce an observable smearing of the echo in range, or an observable rate of echo fluctuation, or both. (Spread targets may or may not be at the same time extended targets, i.e., ones that fill the antenna beamwidth.)

"The approach taken here in presenting the available material on spread target measurements is to follow what happens to the various attributes (amplitude, delay, phase, frequency shift, polarization) of an incident signal upon reflection from such a target. Then the question is turned around by detailing the ways in which the study of these signal attributes by appropriate receiver processing can be used to infer target properties. In the case of such radar astronomy targets as rotating planets, these target properties might include range, velocity, shape, size, rotation vector, and surface characteristics. (The last of these may be studied either as average behavior over the target surface or as a function of location on the target surface.) The possible transmitted signals include simple (unity time-bandwidth product) signals, or complicated (large-TW) signals, including frequency-spaced sets of sinusoids. The receiver operations considered include processing of the echo signal received at spaced receivers (interferometry), and processing of separate components received at the same point (polarization), as well as the much more completely understood case of processing of the output of a single receiving antenna by various methods.

"The concluding section is a summary of presently available information on the variance of the error in making such measurements (including some very recent results obtained by M. J. Levin and R. Price).

"Much of this report consists of previous results that have not been placed in a connected story before. One topic that is new here is the extension of Manasse's study of radar interferometry to include the effect of target rotation, and the resulting motion of the diffraction pattern observed at the spaced radar receivers on earth."

4.11 Price, R., Green, P. E., Jr., "Signal Processing in Radar Astronomy and Communication via Fluctuating Multipath Media," (M. I. T., Lincoln Laboratory), Technical Report 234, October 1960.

"This study treats the detection and measurement of fluctuating targets that have appreciable depth. Although stated in radar terms, the results are equally applicable to communication problems in which the propagation medium has significant multipath spread and fluctuation rate.

"A signal received from such a target or channel is a perturbed version of the transmission, in which frequency and time (delay) spreads have been produced by multiple random modulation superimposed by the target (or channel) on the original modulation of the transmission. Special cases of the deep fluctuating target, namely the fluctuating point target and the very slowly fluctuating deep target, are also considered.

"A method of target measurement is discussed, in which a simple matched-filter detector is used to measure the <u>scattering function</u>; the scattering function describes the manner in which the transmitted power is redistributed in time and frequency upon reflection by the target. The ambiguity function of the transmission is shown to play a central role in such measurement. The amount of target time-frequency spreading, together with the behavior of the ambiguity function of the transmission, sets limitations on the fineness with which the scattering function can be measured. The relationship of the scattering function to physical and geometrical properties of the target is described, and is illustrated for the particular case of a uniform, rotating spherical target."

4.12 Kailath, T., "Sampling Models for Linear Time Variance Filters," (M.I.T., Lincoln Laboratory), Technical Report 352, May 1959.

"A large class of communication channels can be represented by linear time-variant filters. Different constraints can be imposed on these filters in order to simulate the actual operating conditions of such channels. The constraints permit the original filter to be replaced by another (simpler) filter that imitates the original filter under the operating constraints. These new filters need not resemble the physical channel at all, and need not be equivalent to the actual channel, except under the given constraints.

"In this report, the constraints considered are those of finite input and output channel signals and finite channel memory. Other cases can be studied by similar methods. Methods of characterizing linear time-variant filters are investigated in order to determine the most convenient descriptions for the different constraints. These descriptions are used to obtain sampling theorems and models for the filter under the various constraints. The theorems are used to find the conditions under which a linear time-variant filter can be determined by input-output measurements only."

4.13 Kailath, T., "Channel Characterization: Time-Variant Dispersive Channels," (M.I.T., Research Laboratory of Electronics), Chapter 6 in "Lectures on Communications System Theory," E. Baghdady, Editor, McGraw-Hill Book Co., New York, 1961.

"We can regard the channel as a time-variant filter with additive noise superimposed on the output. In these general terms, of course, little of a specific nature can be said about the problem. But in communication systems there are certain additional constraints present: Signals are of finite time-bandwidth product, the channel is nearly linear, and so forth. Introducing these constraints into the problem should enable us to obtain restricted, but simpler, models for the filter -- models that are more useful for our purposes. These models will imitate the operation of the filter under the imposed constraints but may not bear any physical resemblance to the original filter and may not imitate the filter under other operating conditions. This chapter is devoted to methods of obtaining such models under the constraints of linearity and limited bandwidth or limited duration of channel memory. Some properties and methods of description and analysis of such models are also studied."

4.14 Brookner, E., "Synthesis of an Arbitrary Bank of Filters by Means of a Time-Variable Network," (Columbia University), IRE Convention Record, Part 2, 1961.

"Consideration is given to methods and systems for the synthesis of the transfer characteristic of a bank of arbitrary narrow-band filters. The synthesis methods involve: (1) the complex modulation of the input signals of a Fourier spectrum analyzer and (2) the filtering of the output of a real-time Fourier spectrum analyzer. The systems are based on the application of these methods to a real-time Fourier spectrum analyzer known as the Coherent Memory Filter (CMF) which is composed of a periodically time-variant delay-line feedback network. The synthesis methods allow wide flexibility of results: the synthesized bank can be comprised of filters possessing impulsive responses which may be either stationary or time-variant and need not all be identical. The necessary system changes for the synthesis of an arbitrary bank of comb filters are given.

"The systems presented for the synthesis have the following advantages over actual filter banks: (1) they give the output of the filter bank in real-time, (2) their decay time is a small fraction of the time constant of the filters being synthesized and (3) they synthesize the transfer characteristics of a continuum of filters covering the frequency band of interest. Another important feature of the systems is the ease with which they permit the change of the transfer characteristics of the filters being synthesized.

"Two methods are indicated for altering the characteristics of an existing bank of time-invariant filters to that of a completely different bank of time-invariant or time-variant filters.

"New results on the Fourier spectrum properties of the CMF are given."

4.15 Hannan, E. J., "Time Series Analysis," Methuen and Co., Ltd., London, and John Wiley and Sons, Inc., New York, 1960.

4.16 Bendat, J. S., "Principles and Applications of Random Noise Theory," John Wiley and Sons, Inc., New York, 1958.

4.17 Davenport, W., Root, W., "Random Signals and Noise," McGraw-Hill Book Co., Inc., New York, 1958.

4.18 Bergman, P. G., "Propagation of Radiation in a Medium with Random Inhomogeneities," (Columbia University), Physical Review, Volume 70, No. 7, October 1950.

"By means of the methods of geometrical optics, approximate formulae are being derived which correlate the statistical properities of the inhomogeneities of the transmitting medium with the fluctuations to be expected in the signal level of radiative energy. Through a further simplification of the formulae obtained, it is possible to predict the dependence of signal fluctuation on range without detailed knowledge of the statistical parameters of the "micro-structure" of the transmitting medium."

5.0 Communication System Performance

5.1 Sunde, E. D., "Digital Troposcatter Transmission and Modulation Theory," (Bell Telephone Laboratories), Bell System Technical Journal, Part 1, January 1964.

"In tropospheric scatter transmission beyond the horizon, the amplitude, phase and frequency of a received sine wave exhibit random fluctuations owing to variable multipath transmission and noise. The probability of errors in digital transmission over such random multipath media has been dealt with in the literature on the premise of flat Rayleigh fading over the band occupied by the spectrum of transmitted pulses. This is a legitimate approximation at low transmission rates, such that the pulse spectrum is adequately narrow, but not at high digital transmission rates. The probability of errors is determined here also for high transmission rates, such that selective fading over the pulse spectrum band must be considered. Such selective fading gives rise to pulse distortion and resultant intersymbol interference that may cause errors even in the absence of noise.

"Troposcatter transmission can be approximated by an idealized multipath model in which the amplitudes of signal wave components received over different paths vary at random and in which there is a linear variation in transmission delay with a maximum departure $\pm\Delta$ from the mean delay. Various statistical transmission parameters are determined on this premise, among them the probability distribution of amplitude and phase fluctuations and of derivatives thereof with respect to time and with respect to frequency. The probability of errors in the absence of noise owing to such fluctuations is determined together with the probability of errors owing to noise, for digital transmission by binary PM and FM. Charts are presented, from which can be determined the combined probability of errors from various sources, as related to the transmission rate and certain basic parameters of troposcatter links."

5.2 Sunde, E. D., "Intermodulation Distortion in Analog FM Troposcatter Scystems," (Bell Telephone Laboratories), Bell System Technical Journal, Part 2, January 1964.

"In broadband transmission over troposcatter paths, selective fading will be encountered with resultant transmission impairments, depending on the modulation method. An analysis has been made in a companion paper of such selective fading, based on an idealized model of troposcatter paths. It indicated that selective fading will be accompanied by phase nonlinearity which in a first approximation can be regarded as quadratic over a narrow band. A probability distribution for such quadratic phase distortion was derived. On the premise of quadratic phase distortion, the error probability owing to selective fading was determined for digital transmission by various methods of carrier modulation.

"The same idealized model and basic premise of quadratic phase distortion is used here to determine intermodulation distortion in FM for a signal with the statistical properties of random noise. An approximate expression for intermodulation noise owing to specified quadratic phase distortion has been derived, applying for any method of frequency pre-emphasis in

FM. In turn, median intermodulation noise as well as the probability distribution of intermodulation noise has been determined, as related to certain basic system parameters.

"A comparison is made of predicted with measured intermodulation noise in four troposcatter systems with lengths from 185 to 440 miles. The results indicate that phase nonlinearity owing to selective fading can be approximated by quadratic phase distortion, or linear delay distortion, over an appreciable part of the transmission band ordinarily considered for troposcatter systems, with a probability distribution that can be determined from certain basic parameters of troposcatter links, such as the length and antenna beam angles. However, to predict intermodulation distortion on any system, further experimental data than are now available are required on beam broadening by scatter.

"The present random multipath FM distortion theory is shown to afford a significant improvement over an equivalent single-echo theory that has been applied on an empirical basis to troposcatter systems."

5.3 Hatch, R.W., Bennett, S.B., Kinzer, J. P., "Results of the Telstar System Communication Tests," (Bell Telephone Laboratories), Bell System Technical Journal, Volume 42, No. 4, Part 2, July 1963.

"The results of the communications tests on the TELSTAR satellite system which have been conducted at the Andover earth station are presented. These tests have included successful transmission of telephone, television, and data signals. In addition, measurements of received carrier power, noise, transmission characteristics, linearity, data system errors, absolute delay, and Doppler shift have been made. The results are in good agreement with the expected performance."

This paper is particularly useful because actual data is presented on the amplitude of a 4,170 mc signal transmitted from a satellite to ground. Care must be used when interpreting the data to include the effects of both the satellite and ground antennae radiation patterns and possible tracking errors."

5.4 Hatch, R. W., Bennett, S. B., Kinzer, J. P., "Results of the Telstar System Communication Tests," (Bell Telephone Laboratories), Bell System Technical Journal, NASA SP-32, Volume 2, June 1963.

"The results of the communications tests on the TELSTAR satellite system which have been conducted at the Andover earth station are presented. These tests have included successful transmissions of telephone, television, and data signals. In addition, measurements of received carrier power, noise, transmission characteristics, linearity, data system errors, absolute delay, and Doppler shift have been made. The results are in good agreement with the expected performance."

5.5 Bello, P. A., Nelin, B. D., "The Effect of Frequency Selective Fading on the Binary Error Probabilities of Incoherent and Differentially Coherent Matched Filter Receivers," (ADCOM, Incorporated), IEEE Transactions on Communication Systems, June 1963.

"The presence of frequency-selective fading in a communication channel limits the maximum data rate capability of conventional communication systems. Surprisingly little analysis has been carried out to determine the effect of frequency-selective fading on digital (or analog) communication systems. This paper considers the effect of frequency-selective fading on the binary error probabilities of incoherent and differentially coherent matched filter receivers employing postdetection diversity combining. In the analysis it is assumed that the fading is slow enough so that over a few bits at least the channel transfer function remains constant. In addition, it is assumed that the amplitude and phase fluctuations on a received carrier have the same statistical character as those of narrow-band Gaussian noise.

"The general analytical results are specialized to the cases of frequency-shift keying using incoherent detection, and phase-shift keying using differentially coherent detection for the case of a Gaussian frequency autocorrelation function. For these special cases, signal-to-noise degradation curves are given as a function of the ratio of the binary data rate to the correlation (or coherence) bandwidth. Two types of FSK are considered, phase-continuous and phase-discontinuous. In phase-continuous FSK there is no discontinuity in the phase of the transmitted waveform at the mark-space or space-mark epochs. Such an FSK system results when the mark and space frequencies are obtained by frequency modulating an oscillator. In phase-discontinuous FSK phase discontinuities exist at the transition epochs. Such an FSK system results, for example, when the mark and space frequencies are derived by switching between two independent oscillators. An interesting result of the analysis is that the differentially coherent PSK system and the phase-discontinuous FSK system degrade considerably more rapidly with increasing (normalized) data rate than the phase-continuous FSK system.

"The existence of an irreducible error probability is demonstrated for the incoherent and differentially coherent matched filter receivers. Thus, in general, an increase in transmitter signal power cannot reduce the error probability below a certain value depending upon the ratio of data rate to correlation bandwidth and order of diversity. Theoretical curves of irreducible error probability are given for the incoherent FSK and differentially coherent PSK systems."

5.6 Lindsey, W. C., "Error Probabilities for Rician Fading Multichannel Reception of Binary and N-ary Signals," (Jet Propulsion Laboratories) IEEE Transactions on Information Theory, October 1964.

"Performance characteristics are derived for two different forms of multireceivers (the coherent and noncoherent) which are used with binary and N-ary signaling through the Rician fading multichannel. The coherent multireceiver is capable of perfectly measuring the channel amplitudes and phases whereas, at the other extreme, the noncoherent multireceiver implies a receiver which requires no channel measurement whatsoever. The multichannel model presumes that each transmission mode supports a specular or fixed component and a random or scatter component which fades according to the Rayleigh distribution. Heretofore, performance analyses of multichannel links have assumed that the fading obeys the Rayleigh law. This multichannel model is sufficiently general to include four practical types: the Rician and the Rayleigh fading multichannels, multichannels whose propagation modes do not fade, and those which simultaneously contain Rician and Rayleigh fading propagation paths or the so called mixed-mode multichannel.

"Error probabilities are graphically illustrated and compared for various multichannel models. It is found that the effectiveness of multichannel reception is highly dependent on the strength of the specular channel component relative to the mean squared value of the random channel component. In particular, multichannel reception is more effective when applied to the completely random multichannel. For special cases the error-rate expressions reduce to well-known results."

5.7 Lindsey, W. C., "Error Probabilities for Random Multichannel Reception of N-ary Signals," (Original Version of Reference 5.6)

5.8 Turin, G. L., "Error Probabilities for Binary Symmetric Ideal Reception through Nonselective Slow Fading and Noise," (Hughes Research Laboratories), Proceedings of the IRE, September 1958.

"One of two correlated, equal energy, equiprobable waveforms is transmitted through a channel during a given time interval. The signal is corrupted in the channel by slowly-varing, frequency-nonselective fading and by additive, Gaussian noise. On reception, the corrupted signal is processed by an ideal receiver, which guesses that the transmitted waveform was the one which it computes to be 'a posteriori' most probable. Expressions for the probability of committing an error in making such a guess are derived for both coherent and noncoherent receivers; these are studied in detail and some general trends and system design considerations are noted. In an illustrative example, the results are applied to binary frequency-shift keyed (FSK) systems with various pulse shapes and frequency separations."

5.9 Price, R., "Statistical Theory Applied to Communication Through Multipath Disturbances," (M.I.T., Lincoln Laboratory), Technical Report No. 34, September 1953.

"This work is concerned with the synthesis and evaluation of integrated communication systems constructed specifically to perform in the presence of channel disturbances of the form encountered in multipath propagation. In the communication system considered, information is conveyed from source to user by encoding it into electrical symbols at the transmitter and decoding it at the receiver. Statistical theory, including information theory, is used throughout the paper. Gross aspects of multiple-mode propagation and ionospheric scattering are discussed, and previous efforts to improve systems affected by these disturbances are reviewed.

"System capacities are computed for the transmission of band-limited white Gaussian signals through fixed multiple-mode disturbances, and the optimum spectral distribution of transmitter power is found. In general, presence of additional paths does not upset the message-handling capabilities of the channel if suitable wide-band signals are used. Quasi-stationary path fluctuations are considered, and a technique for measurement of the multipath characteristic by the receiver is suggested. Capacities are found for slow path delay fluctuations. Single-mode scatter propagation is considered as a complex multiplicative Gaussian process. The probability computing receiver is found analytically, and a physical realization is developed for small signal-to-noise ratios. Lower bounds to system capacity are found for a binary transmission through scatter. Incidental results are system capacities for a related multiplicative channel, and the capacity for a binary transmission through white Gaussian noise."

5.10 Corrington, M. S., "Variation of Bandwidth with Modulation Index in Frequency Modulation," (RCA Victor Company), Proceedings of the IRE, October 1947.

"Equations are derived for the carrier and side-frequency amplitudes which are obtained when a carrier wave is frequency-modulated by a complex audio signal. The bandwidth occupied by such a frequency-modulated wave is defined as the distance between the two frequencies beyond which none of the side frequencies is greater than 1 per cent of the carrier amplitude obtained when the modulation is removed.

"Curves are given to show the amount this bandwidth exeeds the extremes of deviation for a range of modulation indexes from 0.1 to 10,000, for sinusoidal, square, rectangular, and triangular modulation. For more precise definitions of bandwidth, curves are also given for side-frequency amplitude limits of 0.1 per cent and 0.01 per cent of the carrier-wave amplitude. For complex modulation the total bandwidth can be estimated by computing the bandwidth that would be required by each audio-frequency component, if it were on separately, and adding the results."

6.0 Millimeter System Application

6.1 Smith, I. D., "Role of Millimeter Waves in Deep Space Telecommunication Systems," (Raytheon Company), NTC 66, May 1966.

"Deep Space Telecommunication Systems may be operating in the 1.0 mm to 10.0 mm band by 1975. Extension of the present millimeter-wave component technology shows some promise of the much needed increases in channel capacity per pound of spacecraft equipment and offers ample spectrum space to handle the anticipated increase in deep space traffic.

"Using typical space-to-earth communication link requirements, this paper compares millimeter-wave (94 Gc) solutions with S-band solutions; and assumes, for both frequency bands, that extensions in the present component technology will take place. Spacecraft equipment weight, trade-offs and earth terminal antenna array cost trade-offs are featured in this comparison.

"An account is given of the effects of the earth's atmosphere on propagation of millimeter waves and the importance of geographic location of the millimeter-wave earth terminal is discussed. Realistic penalties in atmospheric attenuation and sky temperature as a function of elevation angle are given."

6.2 "Final Report for Millimeter-Wave Satellite Communications Systems Study," (Raytheon Company) for COMSAT Corporation, Raytheon Report No. FR-66-52, February 1966.

"These are the final results of a study performed by Raytheon's Space and Information System Division for the Communications Satellite Corporation to define the utilization of millimeter-wave (10 to 100 gigacycle) frequencies in satellite communication systems.

"A review of the standard communication channel characteristics is followed by a discussion of the specific effects of the atmosphere on the 10-100 gigacycle band within the limits of our present understanding. Using these estimates of the propagation effects as a base, typical system applications are presented which show the potential of millimeter waves. For these typical systems applications, key subsystems are broken out and discussed in terms of their hardware implementation. The gap between the present component state-of-the-art and the hardware requirements is indicated. Finally, a system development plan is presented which shows when a millimeter-wave satellite communication system could become operational and also shows how the various communication/propagation experiments fit into the development schedule. Also in this plan specific areas of system study and component development are recommended."

6.3 Meisels, M., "NASA Sets Deep-Space Microwave Specs," (Microwaves Magazine), Microwaves, January 1966.

"Deep-space communication systems for the mid-70's cannot be built with today's hardware. More powerful RF sources, large antennas and more sophisticated signal-processors must be developed to handle the data from planetary and stellar probes on NASA's drawing boards.

"The communication systems and the necessary hardware are already being planned at NASA's new Electronics Research Center, Cambridge, Massachusetts. But with 10 years of lead time at their disposal, NASA scientists are first designing an R&D program to provide the hardware needed rather than committing themselves to a specific system."

6.4 Dees, J. W., Derr, V. E., Gallagher, J. J., Wiltse, J. C., "Beyond Microwaves," (Martin Company), International Science and Technology, November 1965.

"New explorations of the relatively unused mm/sub-mm waveband indicate its value for communications, radiometry, and spectrometry. From the adjoining spectrum come extensions of optical and microwave techniques that are combined in almost a new discipline. Microwave power sources are hard to scale down to shorter wavelengths. Borrowing from the optical region, certain molecular transitions produce useful coherent radiation with gas lasers. Good sensitivity to mm/sub-mm radiation is now shown by cryogenic detectors and superheterodyne receivers. The radiation is collimated and guided by quasi-optical devices like horns, lenses, beam waveguides. While deep-space communication applications look promising, not enough is known yet about absorption of mm/sub-mm radiation by planetary atmospheres. Vastly improved spectrometers, using mm-wave equipment, are aiding studies of the interaction between radiation and matter."

6.5 Altshuler, E. E., "Earth-to-Space Communications at Millimeter Wavelengths," (AFCRL), AFCRL-65-566, Physical Sciences Research Papers, No. 125, August 1965.

"It is expected that with the exploration of outer space, a requirement for high data rate earth-to-space communication channels will arise. A program to investigate the feasibility of using the millimeter-wave region of the spectrum for this application is presented. The theory of atmospheric attenuation resulting from losses due to absorption, scattering and refraction processes is reviewed and used to estimate propagation losses produced by atmospheric gases, clouds and precipitation. Curves of total atmospheric attenuation and noise level as a function of meteorological parameters and antenna elevation angle are also presented.

"A series of experiments designed to obtain as much information as possible on the limitations imposed by the atmosphere on millimeter-wave propagation is considered. Although experiments using natural celestial bodies such as the sun, moon, planets and galaxies as radio sources are emphasized, those which would utilize aircraft, rockets and satellites are also mentioned. Finally, the characteristics of a recently installed precision 29-ft antenna designed to operate at 35 Gc (λ =8.6 mm) with a traveling-wave maser as a preamplifier for the radiometer are outlined along with the specific experiments for which this antenna system will be used."

6.6 Gordon, J. P., "Optical Communication," (Bell Telephone Laboratories), International Science and Technology, August 1965.

"The ubiquitous laser has been characterized by the more skeptical as a solution looking for a problem. And indeed some of the proposed problems have been outlandish. Not so communications, however. Although a lot of the early talk about the advantages of unlimited bandwidth was probably not to the point, lasers have additional characteristics that make them well worth exploring for communications applications. For instance, their high directionality and monochromaticity can be real advantages for secure communications and radar-type work. Although for ultrareliable communication we should put the system out in space or into a pipe, there are useful things that can be done in both these environments. Whether lasers will turn out to have any real economic advantage is the crucial question, of course. Certainly the experimental systems developed so far do nothing a millimeter-wave system couldn't. But the technology for manipulating coherent light is young, and in a few years we may have the answers."

6.7 DuWaldt, B. J., "Research on the Suitability of Millimeter Wavelength Systems for Space Application," (Aerospace Corporation), WESCON, August 1965.

"Aerospace Corporation is conducting an investigation into the suitability of millimeter wavelength systems for space and missile applications. At the initiation of the project, it was felt that a key issue in the question of practicality would be resolved by the construction and operation of a large aperture ground-based antenna operating from a sea-level site. A 15-foot steerable reflector was specified for operation up to 300 Gc, but with initial operation at 94 Gc. The pointing control system was specified for an overall peak error of 30 seconds of arc in an inertial coordinate system, for tracking speeds from 0.001 to 3.0 degrees per second. The antenna has been operating with a 3.2 millimeter radiometer since December, 1963. Performance has been evaluated in operation as a radio telescope. Measurements were taken during the lunar eclipse of 30 December, and radiometric data is being taken on the earth's atmosphere, the sun, the moon, and Venus."

This report describes the rationale for establishing their Space Radio Systems Facility which is essentially the following:

(1) The possibilities for practical uses of the millimeter spectrum, it appeared, could best be explored by using millimeter components in some instrument which would have requirements on it similar to those placed on radar and communications equipment.

(2) The practicality of millimeter systems would depend to a large extent upon the ability to build relatively large antennas with extremely fine tolerances on pointing control and boresight stability.

(3) It also was evident that basic propagation data should be gathered.

(4) A millimeter instrument could be used to fill an important spectrum gap in radio astronomy observations. Moreover, such an instrument could have unusual resolution capability.

This report also discusses the various operational activities performed at Aerospace such as measurements of atmospheric absorption, communications experiments, radiometric mapping of the moon and radiometric observations of the sun and Venus. The report supports the validity of the Von Vleek-Weisskopf equations for water vapor absorption.

6.8 Johnson, R. E., "The Millimeter-Wave Compromise," (Sylvania), Space/Aeronautics, July 1965.

"The vast frequency region between 30 and 300 Gc, bypassed in the rush to exploit optics, offers potential tracking accuracies and communications bandwidths approaching the ideals of lasers without many of the penalties. Full use, however, awaits the design of better generators and receivers."

6.9 King, D. D., "Long Waves or Short - Perspectives on the Millimeter Region," (Aerospace Corporation), IEEE Spectrum, May 1965.

"The newly accessible spectrum between microwaves and optics invites a blending of classical and quantum techniques for a variety of applications. To estimate the potential of millimeter waves, we must assess the effect of a few critical parameters on the basic functions of transmission, generation, and detection. A comparison of spectral regions in these broad terms may lack specific appeal, but it also has more general validity. After considering the three basic functions, we shall cite an example in communications to introduce a numerical comparison."

6.10 King, H. E., "Research and Experimentation on Space Applications of Millimeter Waves," (Aerospace Corporation), BSD and SSD Contract AF 04(695)-269, October 1, 1964.

"The planning, engineering and installation phases of the Space Radio Systems Facility (SRSF) have been concluded during this reporting interval. The facility is established for research and experimentation on space applications of millimeter waves. The SRSF consists of a 15-foot antenna with its associated servo control system, digital data processing equipment and radiometer and receiving equipment. A brief description of the instrumentation is given; observations made to date, and future plans are outlined. (Detailed descriptions are reported in separate technical documentary reports.) Observations at 3.2 mm wavelength (94 Gc) include the lunar eclipse of December 30, 1963, radiometric maps of the moon, measurements of the sun and Venus, and atmospheric measurements.

"A description is given of the proof-of-performance tests performed by the contractor to demonstrate compliance with contractual specifications. Surface tolerance of the 15-foot reflector for all antenna attitudes, in sunlight, partial shading, 20 mph wind, and including human error is measured to be 0.0036 in. rms. Other significant tests included are thermal measurements, tower tests, subreflector tests and the establishment of the principal axis of the parabola.

"Installation and checkout of the SRSF are described, including the control penthouse, antenna, servo system, digital data processing equipment, radiometer and receiving equipment and boresight station."

6.11 Meyer, J. W., "Millimeter-Wave Research: Past, Present and Future," (M.I.T., Lincoln Laboratory) Technical Report No. 389, May 1965.

"This report is the edited transcript of a seminar given at Lincoln Laboratory on 2 March 1965. The cyclicity of interest in millimeter wave research is traced from the time of Hertz, when investigations of this part of the electromagnetic spectrum began. The waxing and waning of millimeter wave research are traced as exciting new fields are discovered which diverted the interest of physicists. Each re-emergence of millimeter wave research has been more robust, often because the results of the diversions were important to improved techniques. Early millimeter wave apparatus is described. The narrative of the development of a millimeter wave radar for the detection of the moon relates the opening of this spectral region to radar astronomy. Other applications are mentioned, along with future possiblities. A chronology, a list of large millimeter wave antennas, and a bibliography of review papers are included."

6.12 Krassner, G. N., Michaels, J. V., "Introduction to Space Communication Systems," McGraw-Hill Book Company, New York, 1965.

"This book presents an encompassing, unified introduction to space communication systems which covers the broad scope of its elements, rather than the details of its many complex subsystems. This book is addressed primarily to space-system engineers and to communication specialists seeking coordinated information of the many interrelated technical disciplines and interfaces which characterize space communication systems. It also can serve as a source of fundamental information for technical administrators and civilian and military users, as well as for engineers and scientists in related fields. Sufficient theoretical material and equation derivations are presented to introduce new techniques and concepts at the senior or graduate engineering student level. The authors wish to stress the potential of this book toward fulfilling the textbook requirements of rapidly expanding University aerospace curricula.

"This chapter (Chapter 4) examines those radio transmission and noise properties that influence the selection of operating frequencies for space applications. For systems operating in an earth-space mode, analysis gives rise to bands of optimum frequencies whose extremes are determined by the propagation anomalies of the earth's atmosphere and by the perturbation effect of external noise sources. These bands are called radio "windows". The limits of these windows are not rigorously defined, insofar as the limiting phenomena vary considerably with atmospheric, galactic, and solar activity."

This book is useful because it presents, in one place, much of the basic information needed to estimate absorption and refraction at radio waves. It is a good elementary discussion of propagation problems.

6.13 Warren, F.G.R., Bachynski, M.P., Moody, H.J., French, I.P., "General Description of Phase I Study and Phase II Program," Volume I of "The Radio Spectrum from 10 Gc to 300 Gc in Aerospace Communications," (RCA Victor Company), Research Report No. 6-400-3, July 1962.

"A survey of the state of development and of knowledge in the frequency range 10-300 Gc, with particular reference to possible uses in aerospace communications, is described. Information contained in Volumes II to VII is summarized, the subjects covered being:

Vol. II - Generation and High Level Amplification of Millimeter Waves. (See Reference 7.12)

Vol. III - Components, Transmission Techniques and Materials. (See Reference 7.13)

Vol. IV - Propagation and Absorption. (See Reference 2.43)

Vol. V - Plasma Effects in Aerospace Communications. (See Reference 3.1)

Vol. VI - System Considerations. (See Reference 6.14)

Vol. VII - Applications (SECRET). (See Reference 6.15)

"The program for the second part of the study is discussed. Proposed experimental work covers four areas. These are studies of :

1. Millimeter wave detectors
2. Beam transmissi on techniques
3. Interaction of antennas with plasmas in this frequency region
4. Millimeter wave components using plasmas."

6.14 Warren, F.G.R., Moody, H.J., "System Considerations in Aerospace Communications," Volume VI of "The Radio Spectrum from 10 Gc to 300 Gc in Aerospace Communications," (RCA Victor Company), Research Report No. 6-400-3, July 1962.

"This volume discusses systems considerations for millimeter-wave applications to aerospace communications. A list of possible space communications missions with distinctly different systems requirements is given in Chapter I. Chapter II discusses various effects in millimeter wave propagation for aerospace applications, including atmospheric attenuation, Faraday rotation and Doppler effects, and presenting modified propagation monograms. Chapter III analyzes the problem of beam acquisition between cooperating stations. It is concluded that no method is any faster than simultaneously scanning with both antennas provided the required scan rates can be realized. Chapter IV describes various types of active and passive relaying satellites and Chapter V discusses noise considerations in aerospace systems. Chapter VI presents some calculations of radiative cooling in space systems. In the final Chapter, some predictions of the future application of millimeter and submillimeter waves are presented along with a discussion of the areas in which further research and development are required before these applications can be realized."

6.15 French, I. P., Shkarofsky, I. P., Bachynski, M. P., Warren, F. G. R., Moody, H. J., "Application of Millimeter Waves," Volume VII of "The Radio Spectrum from 10 Gc to 300 Gc in Aerospace Communications," (RCA Victor Company), Research Paper No. 6-400-3, July 1962. Volume VII is classified SECRET.

6.16 Fisch, J., "Wideband Quadriphase Modulated Digital Data Transmission System," (Republic Aviation) 9th NATCOM.

"A microwave digital data link employing differentially coherent quadriphase keying has been developed for aerospace applications. The system has been operated with digital data at 40 megabits per second, and tested with simulated PCM data at rates up to 1000 megabits per second. Among the novel features of the system are high-speed acquisition techniques for synchronizing coherent RF detectors, digital clocks, and word sequence generators. Microwave circuits include wideband solid-state modulators and demodulators and TWT amplifiers. Digital data processing circuits include differential coders and code base conversion in encoding and decoding to achieve maximum data rates by quadriphase (or octal) coding."

6.17 Cohen, D., "A Kilomegabit Data Encoding and Transmission System," (Airborne Instruments Laboratory), Seventh National Communications Symposium, 1961

"A digital data encoding and transmission system is described that can provide kilomegabit transmission rates. The technique involves the storing of a long time sample of an analog signal, simultaneously sampling the signal at a number of time positions, and converting each sample into digital form by parallel circuitry.

"Digital outputs are frequency-multiplexed onto a number of separate channels, each bit modulating a separate channel of either a single or a multiplicity of RF carriers.

"Receivers detect and demodulate each bit in a separate channel and reclock the signals. Shaped and reclocked signals are reconverted to analog levels and the waveform is reconstituted by means of delay-line decoder techniques."

In this basic discussion of a kilomegabit transmission system, a typical application mentioned is the transmission of high resolution video pictures from satellites and manned spacecraft to ground read-out stations during short acquisition intervals. The modulator method chosen minimizes the dispersion effects in the transmission of wide band analog signals through the atmosphere. The kilomegabit system which can handle 100 Mc bandwidth analog signals might use 20 Mc bandwidth digital channels thus requiring 50 such channels. At present there is no single transmitter at 10 kilomegacycles and above which can insure reception of kilomegabit data over a space-earth link. Therefore the modulation system described using 50 channels lends itself well to the use of parallel transmitters. The multiplicity of channels divides the system down into a number of lesser but still complex problems. The repetitive nature of the system indicates that feasibility can be demonstrated by the construction of only a few channels. As in any large electronic system, the reliability problem exists. With the channelizing method, loss of the channel reduces the resolution in the video signal but the system can continue to operate. The number of quasi-parallel channels form a redundancy that increases reliability in spite of the increased numbers of components.

Propagation experiments are required to determine statistically the coherence bandwidth as a function of zenith angle. Since coherence bandwidth affects the number of parallel channels required, it has a heavy bearing on the complexity of the kilomegabit system.

6.18 Drake, F. D., "Optimum Size of Radio Astronomy Antennas," (National Radio Astronomical Observatory), Proceedings of the IEEE, January 1964.

"It is well known that economy may be achieved in the building of a radiotelescope if an array of many small collectors is constructed, rather than a single large collector. Such arrays have an added advantage in that the geometrical arrangement of the antennas may be adjusted so as to give an optimum antenna response pattern for the prime problems to be studied. This note shows that an optimum size for each antenna in such an array can be determined from cost considerations alone."

The methodology for determining optimum sizes of astronomy antennas was applied to the design of arrays of receiving antennas for deep space telecommunications (Reference 6.1) and satellite communication systems (Reference 6.2).

6.19 Schrader, J. H., "Receiver System Design for Arraying of Independently Steerable Antennas," (Langley Research Center), IRE Transactions on Space Electronics and Technology, June 1962.

"This paper considers the problem of arraying independently steerable antennas for use in deep-space communications systems. It describes the basic design of a receiver capable of utilizing all the signal power received on a number of antennas without requiring that the signals be phase coherent. The results of this study indicate that for very large aperture systems, the array approach offers both economical and technical advantages over the single-reflector approach."

6.20 Eberle, J. W., "An Adaptively Phased, Four-Element Array of Thirty-Foot Parabolic Reflectors for Passive (Echo) Communications Systems," (Ohio State University), IEEE Transactions on Antennas and Propagation, March 1964.

"A description is given of an adaptively phased receiving antenna array consisting of four independently steered thirty-foot parabolic reflectors capable of operation to 15 Gc. The array has been designed as a research tool to demonstrate the principle of adaptively phasing the signals from independent array elements to achieve the same performance as would be obtained from a single equivalent aperture. The initial operating frequency has been chosen at 2270 Mc so that the array may be used in communication experiments using Echo I and Echo II passive satellites."

This report is helpful in designing antenna systems which will automatically restore loss in the antenna gain of very large millimeter-wave antennas by compensating with self-adaptive antenna techniques for the observed random phase variations due to the fluctuations in the transmission media. The report contains the mathematics which describe the summation of signals in the receiver. It also contains some interesting cost relationships for large S-band antennas such as: (a) cost versus diameter, (b) cost/square foot versus diameter, and gain versus frequency for various antenna diameters.

This report is the follow-on to Reference 6.19. It describes an active installation at Ohio State University of four thirty-foot antennas operating at S-band. Description including block diagrams are given on: (a) the monopulse tracking system, (b) the acquisition system and (c) signal acquisition system.

6.21 Schrader, J. H., "A Phase-Lock Receiver for the Arraying of Independently Directed Antennas," (Langley Research Center), IEEE Transactions on Antennas and Propagation, March 1964.

"This paper describes a phase-lock receiver designed to accomplish the arraying of four independently steerable antennas and provides some measured performance data. The results indicate that the performance of such an array will be comparable to that of a single antenna with the same aperture and a conventional phase-lock receiver."

This report is a follow-on to Reference 6.19. Based on the limitation that the gain of a fully steerable antenna is on the order of 70 db primarily, because of the atmospheric distortion of the wavefront, and the inability to maintain proper reflector surface tolerances, an adaptive array system was designed which shows how these limitations can be overcome. Of the three primary areas of consideration: (1) the antenna array configuration, (2) the antenna control system, and (3) the receiving and detection system, this report deals with the design of the latter, a UHF system, which was constructed and evaluated by NASA.

6.22 Breese, M., Colbert, R., Rubin, W., Sferrozza, P., "Phase-Locked Loops for Electronically Scanned Antenna Arrays," (Sperry Gyroscope Company), IRE Transactions on Space Electronics and Telemetry, December 1961.

"This paper describes the ATHESA (Automatic THree-dimensional Electronic Scanned Array) technique for achieving very high antenna gain for deep-space communication systems. Phase coherence over a band of frequencies is established on reception automatically and continuously for either stationary or moving targets by phase-locking the signals from antenna elements separated by many wavelengths to a reference antenna element."

6.23 "Final Report - Two-Way Communicator," (Raytheon Company). RADC-TDR-63-373, Contract AF 30(602)-2574, June 1964.

"The Two-Way Communicator is a portable M-band (50 to 70 Gc) transceiver specifically designed for secure air-to-ground communications. This was developed for the Rome Air Development Center by the Raytheon Company under Contract AF 30(602)-2574.

"The objectives of this program were to design and build a communications equipment suitable for air-to-ground operation for ranges up to ten miles. The purpose of the equipment is to provide a means for evaluating the use of the higher portion of the microwave spectrum to provide a two-way secure communication link for relaying land instructions to an aircraft during adverse conditions. Specifically, the following operational problems were to be investigated using this equipment. (a) Fidelity of propagation (b) Utilization of narrow beam transmission and reception (c) Hand-held operation in an aircraft.

"It was a further objective of the program to deliver the working equipment within a 90 day period."

7.0 Millimeter Antennas and Components

7.1 The Bell System Technical Journal (Bell Telephone Laboratories), Volume 44, September 1965. (4 papers)

Four papers in this report (See Reference 7.1a-7.1d) deal with system design concepts for all-weather earth station satellite communication antennas. Although these papers were written with C-Band (4 Gc) operation in mind, the concepts presented are useful in developing all weather antenna configurations for the millimeter-wave frequencies. In fact, these papers include the results of 15:1 scale model antenna tests performed at 60 Gc.

7.1a Cook, J. S., Giger, A.J., "All-Weather Earth Station Satellite Communication Antennas."

"The successful TELSTAR and Relay satellite experiments have led to consideration of the equipment and techniques that might be incorporated in future commercial and military satellite communication systems.

"The experiments re-emphasized two facts that had been recognized for some time: (1) that worthwhile improvement in the earth station receiver sensitivity could be obtained by elimination of the antenna radome and (2) that an important practical improvement would be brought about by the location of the communication and tracking equipment on a platform that does not move with the antenna.

"These improvements can be achieved by special design of the antenna itself, as indicated in the subsequent papers in this issue. Here the major considerations which motivated that work are reviewed."

7.1b Giger, A. J., Turrin, R.H., "The Triply-Folded Horn Reflector: A Compact Ground Station Antenna Design for Satellite Communications."

"An antenna suitable for ground stations of satellite communications systems is described. The antenna has very good low-noise properties, high aperture efficiency and excellent broadband characteristics. It can be operated without a radome and allows the location of all communications and tracking equipment in a stationary room on the ground. Called the "triply-folded horn-reflector antenna," it is derived from the well-known conical horn-reflector antenna by folding the horn three times to bring its apex into a stationary position on the ground. Plane reflectors are used in the folding process and the propagation in the antenna is based on the principles of geometrical optics.

"The paper describes electrical tests on an antenna model at frequencies of 60 and 11 Gc and presents results of hydrodynamic tests which were performed to study the behavior of the antenna in high wind."

7.1c Cook, J. S., Elam, E. M., Zucker, H., "The Open Cassegrain Antenna: Part I - Electromagnetic Design and Analysis."

"The open Cassegrain antenna combines an asymmetric Cassegrain reflector system with antenna rotation about two non-orthogonal axes. The compact configuration provides well-controlled radiation with full hemispheric coverage.

"A comprehensive analysis of the antenna geometrical and radiation characteristics has been made, and an experimental antenna with 40-inch aperture, operating at 60 Gcs, has been constructed and measured electrically. Agreement was obtained between the computed and measured characteristics of the antenna and its components. By computation, it is found that the aperture efficiency of the experimental antenna is 70.4 per cent, the antenna efficiency (neglecting ohmic loss) is 65 per cent, and based on measured sub-reflector radiation patterns, the noise temperature due to spillover at the main reflector is less than 4°K."

7.1d Denkmann, W. J., Gegling, F. T., Pope, D. L., Schwarz, A.O., "The Open Cassegrain Antenna: Part II -- Structural and Mechanical Evaluation."

"The mechanical features of a preliminary concept for an open Cassegrain antenna are discussed briefly. In the analysis, emphasis is given to the upper rotating structure, where the major problems are the provision for an efficient back-up structure for the main reflector and the selection of a suitable subreflector support structure. The philosophy and method of approach are described in detail. Representative deflection results are given for both gravity and wind loading. Other mechanical considerations pertinent to this configuration are discussed in general. The structural implications of exposed operation, in particular those due to wind, are considered at some length. The mechanical feasibility of this configuration is demonstrated by the current results."

7.2 Hogg, D. C., Semplak, R. A., "An Experimental Study of Near-Field Cassegrainian Antennas." (Bell Telephone Laboratories), Bell System Technical Journal, Volume 43, November 1964.

"The near-field Cassegrainian antenna is a double-reflector system that employs, in its simplest form, confocal paraboloids. Unlike the standard Cassegrain which employs a hyperboloidal subreflector illuminated by a spherical wave, the near-field device is fed by a uniform phase front. Experimental data on noise performance, gain and radiation patterns have been obtained at a frequency of 6 Gc using two 16-foot paraboloids (focal length-to-diameter ratios of 0.375 and 0.25) in both standard and near-field configurations.

"Using the shallow antenna, zenith noise temperatures of 10°K and 6°K were obtained for the standard and near-field systems, respectively; at an elevation angle of 10° the antenna temperatures were 50°K and 20°K. Using the deep secondary reflector, zenith noise temperatures of 4°K were obtained for both configurations; at 10° above the horizon, however, the standard Cassegrain has an antenna temperature of 30°K and the near-field device 13°K. In all cases, the antenna efficiencies are not far above 50 per cent. Discussion of noise produced by various methods of mounting subreflectors is included. Since noise produced by transmission lines and antenna environment is closely related to these experiments, it is discussed in detail in appendices."

7.3 Kott, M. A., "A Variable Beamwidth Millimetric Wave Antenna," (John Hopkins University), IEEE Transactions on Antennas and Propagation, November 1964.

"A preliminary investigation of a millimeter wavelength antenna based upon the optical zoom lens system is presented. The antenna consists of an axial lens system of four elements and possesses a beamwidth that can be continuously varied over a range of 7.7 to 1 at 140 Gc and 5.3 to 1 to 70 Gc by the proper axial motion of its lens elements. An analysis based upon both visible and microwave optics is presented which provides approximate expressions for the beamwidth and gain variations in terms of the positions of the lenses of the system."

7.4 Feldman, N. E., "Communication Satellite Output Devices," (Rand Corporation), Microwave Journal, November and December 1965.

"A communication satellite operating at microwave frequencies is not constrained to the use of a vacuum tube for generating an output signal. Various semiconductor devices are also available and, although they are subject to certain limitations, they offer advantages which make their use attractive in some applications.

"The relative ability of semiconductor devices such as tunnel diodes, transistors and varactor diodes, and vacuum tube amplifiers such as triodes, klystrons, amplitrons and TWT's to generate signal power efficiently at frequencies of 1-10 Kmc and power levels of 0.1-100 watts is the primary concern of this paper."

7.5 Nichols, L., Edwards, R., Krahn, H., "Millimeter-Wave Generators," (Raytheon Company), Electro-Technology, September 1964.

"Millimeter Waves - the vast region between 30 Gc and the infrared wavelengths - have properties which have value quite beyond the additional communications capacity they provide. For example, millimeter-wave generating and transmitting equipment is characteristically of small size, making compact hardware possible. Millimeter waves can be directed in very narrow beams, increasing efficiency and precision. And, because they attenuate rapidly in the atmosphere at certain frequencies, they can be used for "safe" communication in circumscribed areas.

"Use of millimeter waves has been impeded by difficulties in the development of millimeter-wave generators. The small component-size characteristic of these wavelengths is a major advantage in equipment, but a serious problem in generator design. As wavelengths go down, the tube designer finds himself working with impractically small anodes, cathodes, delay lines. Such parts are fragile and very difficult to machine and assemble. Another problem is that as parts become smaller their ability to dissipate heat decreases. Thus, as frequency goes up, power output (in general) goes down.

"Ways to circumvent these problems are being found. Peak pulse power levels of 100 Kw at 100 Gc are now possible. In continuous-wave operation, several watts at 50 Gc can be obtained. But above 150 Gc, power outputs are measured in mere milliwatts.

"We have been talking so far about scaling lower-frequency klystron-and magnetron-type devices for millimeter wavelengths. There is another approach: use of "unconventional" devices which operate on completely different principles. Examples are the tornadotron, the ferrite generator and the maser. Although use of these devices at millimeter wavelengths is still experimental, they promise to fill the gap between scaled-down conventional millimeter-wave generators and coherent infrared generators.

"The authors discuss the operation of the linear-beam (klystron-type) and crossed-beam (magnetron-type) generators, and the principles of frequency scaling. They review the important unconventional approaches. Throughout this article, the authors evaluate: they analyze, compare, and predict performance. (It should be noted, however, that the field is continually changing, and it is possible that some of the very latest achievements have not been recorded here.)"

7.6 Simmons, A., Giddings, O., "Ferrite Devices for the 3 mm Band," (TRG, Inc.), WESCON, August 1964.

"Ferrite circulators, isolators, switches and attenuators have been designed and built to operate over a 5% band in the neighborhood of 3.2 mm. The basis of operation of these devices is Faraday rotation. The advantages of using the Faraday rotation principle in the millimeter-wave region are: (1) magnetic fields of relatively small magnitude are needed, just enough to saturate the ferrite; (2) the physical configuration, that of a ferrite rod centered in a circular tube, is simple and lends itself to the precision required; (3) ferrite material with no special properties other than low loss and large $4\pi M_s$ can be used. Disadvantages of the configuration used are the frequency sensitivity with the ferrite mounted in circular waveguide, and the relatively long structure, in terms of wavelength.

"The desired ferrite devices have been built by proper connection of two basic devices: a dual-mode transducer and a ferrite rotator, with addition of suitable loads and resistive cards. The design and construction of a relatively broadband transducer from two orthogonal rectangular waveguides to circular waveguide has been carried out, and 45° and 90° rotator designs developed. These have been assembled to make up a number of devices whose characteristics will be described."

7.7 Jaskolski, S. V., Ishii, K., "Millimeter-Wave Generation Employing a Packaged Microwave Tunnel Diode," (Marquette University), WESCON, August 1964.

"Experimental results are presented which show that inexpensive, commercially available, packaged microwave tunnel diodes can generate millimeter-wave frequencies, in excess of presently accepted theoretical resistive cutoff frequency limits. Through the use of a specially designed waveguide circuit, a maximum frequency of 42.39 Gc was generated with a D4168D X-band tunnel diode whose resistive cutoff frequency was 21.74 Gc. The experimental results are theoretically verified employing an analysis which re-defines the tunnel diode equivalent circuit. In so doing, the existence of negative resistance above the classical resistive cutoff frequency is illustrated. Circuit diagrams and circuit design equations are presented, along with design considerations of the actual tunnel diode waveguide mount."

7.8 Forster, D. C., "Mid-1964 Review of Available Millimeter-Wave Sources," (Hughes Research Laboratories), WESCON, August 1964.

"Power levels and efficiencies of millimeter-wave sources have been increased by several orders of magnitude in the past few years. In this paper, a qualitative description of conditions which limit the performance of the various types of sources is presented. A survey of available sources is presented with various types broken down into four major categories: (1) low power backward-wave oscillators, (2) low power klystrons, (3) high power CW sources, and (4) pulsed sources."

7.9 Heney, J. F., "Some New Results with High Power Millimeter-Wave Tubes," (Hughes Research Laboratories), WESCON, August 1964.

"Recent advances in the art of high power millimeter-wave tubes provide unique solutions to many system design problems. At 6 mm, an oscillator-amplifier chain is capable of up to 1 Kw of average power output. At 3 mm, a similar series of tubes will provide a CW output of more than 100 w. These tubes are relatively low voltage, lightweight units with efficiencies between 10 and 20%. Bandwidths are of the order of 10% and life has been measured up to many thousands of hours. These tubes find direct application in the area of high resolution radars, plasma penetration problems, and space communications."

7.10 Teich, W. W., "New Approaches to Millimeter Wavelength Devices," (Raytheon Company), Electronics, May 1962.

"Many design approaches to tubes for generating and amplifying millimeter and submillimeter wavelengths are under investigation. Some of the more promising versions are discussed in this survey, including one structure that has generated a few milliwatts at 420 Gc."

7.11 Wade, G., "Low-Noise Amplifiers for Centimeter and Shorter Wavelengths," (Raytheon Company), Proceedings of the IRE, May 1961.

"A number of new techniques for detecting signals at centimeter and shorter wavelengths are making possible far better noise performance than ever before attainable. Over the past ten years, noise temperatures have been reduced from around 3,000°K to less than 5°K. The low-noise devices which are currently competitive or which show future promise include traveling-wave tubes, parametric amplifiers, tunnel diodes, masers, photon counters and photsensitive detectors. This paper discusses the various techniques for attaining low noise and summarizes the achievements relative to each technique.

"Effective noise reduction in traveling-wave tubes is accomplished by making the beam flow through an extended low-velocity region. Noise temperatures as low as 250°K have been measured on traveling-wave tubes at S-band. Low noise has been attained in parametric devices using both electron beams and semiconductor diodes. Some of the lowest noise temperatures measured on any unrefrigerated microwave amplifiers are those for electron-beam parametric amplifiers. Refrigerated semiconductor-diode parametric amplifiers have given even lower noise temperatures. The tunnel-diode amplifier is the most recent negative resistance microwave device. It seems to have limitations as far as extremely low-noise performance is concerned, but nevertheless it is a good competitor for many low-noise applications. So far, the maser is the best in microwave low-noise amplification. Intrinsic maser noise temperatures of a few degrees are readily attainable. Photon counters and photosensitive detectors are inherently even quieter and give promise of considerable future potential."

7.12 Shkarofsky, I. P., Brannen, E., "Generation and High Level Amplification of Millimeter Waves," Volume II of "The Radio Spectrum from 10 Gc to 300 Gc in Aerospace Communications," (RCA Victor Company), Research Report No. 6-400-3, July 1962.

"The results of a study of the state-of-the-art in generation and amplification of power at frequencies in the range 10 to 300 Gc are given. Chapter I describes the principles of the various conventional tubes (klystrons, magnetrons, forward and backward wave amplifiers and oscillators, etc.) which have been used in this frequency range. Characteristics of tubes which are commercially available are given, as well as of developmental types on which information is available. Chapter II deals with generation of millimeter waves and higher frequencies by means of high voltage electron beams using unconventional techniques. Chapter III covers some other miscellaneous or suggested approaches to the generation of millimeter wave frequencies."

7.13 Moody, H. J., Davidson, A. J. S., Warren, F. G. R., Evangelatos, T., Wever, J., "Components, Transmission Techniques and Materials," Volume III of "The Radio Spectrum from 10 Gc to 300 Gc in Aerospace Communications," (RCA Victor Company), Research Report No. 6-400-3, July 1962.

"This volume discusses transmission lines, components and properties of materials at millimeter wavelengths. The various types of transmission lines are reviewed with emphasis on their properties at millimeter wavelengths. Components for rectangular waveguide and for beam type transmission lines are discussed. Special detectors such as dielectric and superconducting bolometers as well as free carrier absorption and photo-conductive detectors are included. Some properties of materials that have been studied at millimeter wavelengths, ferromagnetism, anti-ferromagnetism, ferroelectricity and anti-ferroelectricity are discussed. Low noise amplifier devices, masers, parametric amplifiers and low noise traveling wave tubes are reviewed and the limiting noise temperature at high frequencies is presented. A thorough discussion of antennas and antenna systems, i.e., scanning antennas, is included.

"The use of a germanium point contact diode as a modulator was described. At 35 Gc the diode can give 100% modulation with an insertion loss of 2 db. The diode can modulate several hundred milliwatts of carrier power with a response time less than 3 nanoseconds. A PIN diode modulator for use in the 67-77 Gc frequency range was also described. It has been operated at 120 Gc, also. The modulation depth dropped to .707 of its d.c. value as a modulating frequency of 50 Kc. An attenuation of 11 db was obtained with a d.c. current of 15 ma.

8.0 Millimeter Circuits

8.1 Ippolito, L. J., Allen, W. K., Prillanon, C., "Traveling Wave Tube Development for a Serrodyne Re-Entrant Amplifier," (Goddard Space Flight Center), Report No. X-625-65-47, April 1965.

"Program objectives were to study serrodyne techniques and determine TWT characteristics to incorporate in serrodyne re-entrant amplifiers. Investigations included the upper limit of serrodyning, optimum modulation methods and the necessary sawtooth generator circuits. Tube properties studied were amplifier intermodulation, noise figure, and overall design for optimum re-entrant amplifier characteristics.

"Sawtooth generation and use for TWT modulation is difficult at rf frequencies. Instead, the fundamental and the second and third harmonics of a sawtooth waveform may be combined and used to modulate the TWT drift tube. This simplifies the generation problem but modulation becomes difficult due to drift-tube pole-piece capacitance. While this capacitance can be reduced by a factor of four, waveform amplitude is decreased when coupled to the TWT. Also, waveform distortion is encountered when its amplitude is varied after initial tuning.

"The most practical technique is to modulate the input and output helices and the drift tube separately. This uses the TWT as a mixer for all three harmonic frequencies with the input signal. By properly adjusting modulation-frequency amplitude and phase, frequency shift is obtained with carrier and sidebands down 16 db with respect to the desired output frequency.

"Theoretical studies show that infinite carrier and sideband suppression may be obtained with three modulation-voltage amplitudes having approximately 7:1:1 ratios, the first number denoting the fundamental and the second and third representing second and third harmonic amplitudes. Translation loss is about 5.4 db, indicating the presence of other sidebands not considered. Other ratios give superior suppression, but translation loss always exceeds 5.4 db.

"In practical experiments, three-frequency modulation was applied as described, the fundamental (30 Mc) to the drift tube and 60 Mc and 90 Mc to the input and output helix. Three-element modulation was necessary due to waveform distortion and amplitude reduction that arose when trying to modulate the drift tube along with the three frequencies combined. Carrier and second-sideband suppression below the desired sideband were measured at 18 and 20 db, respectively. Modulation-voltage amplitudes were 34:5:5, close to those determined theoretically. When the re-entrant loop was closed, the desired sideband was translated and underwent 14 db of gain. Analysis showed that lower conversion loss would be obtained with three -- than with two -- frequency modulation, the decrease in loss being calculated at 4 db, and this was verified experimentally.

"Finally, a TWT mixer was fabricated to achieve larger frequency translations, consisting of an input helix centered at 6 Gc, and intermediate helix with local-oscillator input at 10 Gc, and an output helix optimized for operation at the cross-product frequency of 4 Gc. Data are given for different combinations of frequency, to determine bandwidth and output linearity.

At the optimum operating point, input-signal gain was 10 db at the new output frequency. This is another approach to achieving large frequency shifts."

8.2 Cagnon, R.R., McCoskey, C.D., "Spacecraft Transponder with Re-Entrant Mode TWT Amplifier," (TRW Space Technology Laboratories), Presented at International IEEE Convention, March 1965.

"This paper describes a new type communication satellite transponder with extremely wide bandwidth capability. The transponder makes use of a traveling wave tube operated in the re-entrant mode (i.e., frequency translating the output signal and re-amplifying it in the same TWT to achieve direct RF to RF conversion and amplification.) The transponder is of the linear translator type and has the advantage of being essentially independent of the type of modulation. The particular configuration developed uses the re-entrant loop as an intermediate amplifier with a low noise preamplifier to establish the system noise figure and a power amplifier to improve dc to RF conversion efficiency. A discussion of the basic gain, noise figure, and output power requirements for a communication satellite transponder is presented and the developed system shown to be consistent with these requirements.

"Emphasis is placed on the re-entrant loop amplifier as the unique portion of the transponder. Measurements pertinent to the selection of a TWT for re-entrant operation and their effect on re-entrant loop operation are discussed. These include power-in/power-out, intermodulation distortion, and gain suppression. Test results for the re-entrant loop are presented showing performance with single and multiple signals.

"The wide bandwidths available suggest multiple access systems as an application for the re-entrant transponder. The choice of an operating point for the loop TWT when used to amplify several carriers is discussed in relation to permissible intermodulation distortion. It is shown that the re-entrant amplifier can be considered as a means of achieving direct wideband RF to RF conversion, and thus replace several separate IF amplifiers for multiple access systems.

"Some alternate transponder configurations using the re-entrant loop and areas for further investigation are suggested."

8.3 Viterbi, A.J., "Acquisition and Tracking Behavior of Phase-Locked Loops," (Jet Propulsion Laboratories), External Publication 673, July 1959.

"This work represents an investigation of frequency acquisition properties of phase-locked loops for a variety of reference-signal behavior and loop configurations. Results are obtained concerning the frequency pull-in and tracking behavior (for both constant and linearly varying reference frequencies) of various loop filter transfer functions.

"The general approach involves solution of the non-linear differential equation which describes the system behavior, using analog and graphical methods. The terminology adopted in the text is the one in general use for closed-loop systems and servomechanisms. However, the application of phase-locked loops to the filtering of noisy signals has generated an alternate terminology in which the loop noise-bandwidth is the key parameter."

8.4 Frazier, J. P., Page, J., "Phase-Lock Loop Frequency Acquisition Study," (General Electric Company), IRE Transactions on Space Electronics and Telemetry, September 1962.

"The ability of a phase-lock loop using a proportional plus integral control filter to acquire a noisy signal when the local oscillator is being swept was determined empirically by means of a low-frequency, GEESE, model of such a system.

"The effects of the damping factor and natural frequency on the frequency acquisition properties of linear loops (as distinguished from a loop in which the IF signal is limited) are considered in this study. In addition, consideration is given to a loop in which the IF signal is "hard" limited and the loop designed to maximize the sweep rate under the constraint that the probability of acquisition is equal to or greater than 90 per cent for a given SNR.

"The rms phase jitter in the output signal was measured as a method of verifying the standard analytic approach to predicting phase jitter.

"The results of the study are as follows:

1. The range of damping factors from 0.5 to 0.85 yields near optimum acquisition performance.

2. Although a drop in loop gain produces lower phase jitter for a given $(S/N)_{IF}$, it degrades the over-all ability of the loop to acquire and track a signal.

3. A "hard" limiter in the IF can be effectively used as a gain control to enhance loop performance.

4. Using an empirical formula derived from experimental results the VCO sweep rate for 90 per cent probability of acquisition can be predicted accurately, given the $(SNR)_{IF}$ and loop parameters."

8.5 Jaffee, R., Rechtin, E., "Design and Performance of Phase-Lock Circuits Capable of Near-Optimum Performance Over a Wide Range of Input Signal and Noise Levels," (Jet Propulsion Laboratory and California Institute of Technology), IRE Transactions on Information Theory, March 1955.

"Phase-lock loops provide an efficient method for detection and tracking of narrow-band signals in the presence of wide-band noise. This paper explains how minimum-rms-error loops may be designed if the input-signal level, input-noise level, and a specification for transient performance are given. However, the system performance of such loops departs rapidly from the best obtainable performance if either the signal or the noise levels are different from the design levels, and if no compensating changes are made in the loop. A marked improvement results if the total input power is held constant, regardless of signal or noise levels. It will be demonstrated that a fixed-component loop preceded by a bandpass limiter yields near-optimum performance over a wide range of input signal and noise levels."

9.0 Millimeter Experiment Ground Facilities

9.1 Keane, L. M., "The AFCRL 29-Foot Millimeter-Wave Antenna," (AFCRL), AFCRL-65-726, Special Report No. 34, October 1965.

"A general description of AFCRL's new 29-foot parabolic antenna is given. This antenna, designed for operation at 35 Gc, has Cassegrain feed optics and a precise reflecting surface supported on an elevation over azimuth mount. Design parameters include a gain of 67.5 db at 35 Gc and a pointing capability of better than ±1 arc min under 30-knot wind loads, normal solar loading, and peak accelerations of $.012°/sec^2$. The servo system was designed primarily to track objects traveling at sidereal rates. A limited satellite tracking capability should exist, however.

"Emphasis is given to engineering aspects of the tower, mount, drive system and reflector assembly, which should provide efficient RF operation and extreme precision in pointing."

9.2 Hoffman, L. A., Wintroub, H. J., Garber, W. A., "Propagation Observations in the 3.3 Millimeter-Wave Window," (Aerospace Corporation), Presentation to Millimeter-Wave and Far Infrared Conference, Estes Park, Colorado, August 1965.

"Aerospace Corporation has been investigating millimeter wavelength systems for space applications for several years. The major instrument for these investigations is the 4.57 m (15-ft) precision paraboloidal antenna that was constructed for operation at millimeter wavelengths down to 1.0 mm. The full dish is effective at 1.46 mm (205 Gc/s), yielding a value of D/λ greater than 3000.

"In addition a millimeter-wave system for the transmission and reception of an information-modulated carrier, including typical television material, has also been constructed. A baseband width of about 4 Mc/s is used to frequency modulate a 3.2 mm Klystron to a modulation index of 2.5. The propagation path is 450 m above sea level at the transmitter and traverses an 18.95 Km path to the receiver, which is at an elevation of 39 m atop a two-story building in El Segundo, California. The elevation angle is approximately 1.17 degrees when corrected for curvature and refraction."

9.3 Hoffman, L. A., "Propagation Factors at 3.2 Millimeters," (Aerospace Corporation), Presented to Tenth Symposium of the Advisory Group for Aerospace Research and Development at Rome, Italy, October 1965.

See Reference 9.2

9.4 Tolbert, C. W., Straiton, A. W., Krause, L. C., "A 16-Foot Diameter Millimeter Wavelength Antenna System, Its Characteristics and Its Application," (University of Texas), Technical Report No.1, Grant NsG-432, March 1964.

"The 16-foot diameter antenna system at the Electrical Engineering Research Laboratory of The University of Texas has characteristics suited for the spectroscopic measurement of millimeter wavelength emission and absorption of the bodies of the solar system and of galactic and extragalactic sources."

9.5 Lynn, V. L., Sohigian, M. D., Crocker, E. A., "Radar Observation of the Moon at 8.6 mm Wavelength," (M.I.T., Lincoln Laboratory), Technical Report 331, October 1964.

"The experimental, pseudo-CW radar used to detect the first lunar echoes at millimeter wavelengths is described. This system, with a peak-power output of 12 watts, has been used to obtain preliminary mapping of the moon at a wavelength of 8.6 mm with resolution in angle only.

"Approximately 85 per cent of the reflected power can be attributed to diffuse scattering. This component appears to follow the Lommel-Seeliger Law although there are insufficient data to define the distribution accurately. For the positions observed, there was no significant difference in reflection between the maria and the continents, within limits of approximately ±2 db.

"The total radar cross section of the moon at 8.6 mm wavelength was determined to be 7 ±2 per cent of the geometric cross section."

9.6 Fitzgerald, W. D., Lynn, V. L., Keeping, K. J., "Experimental Evaluation of a 1000-Wavelength Antenna," (M.I.T., Lincoln Laboratory), NEREM Record, November 1962.

"The recent demands of space surveillance and space communications have greatly increased the need for very high-gain, narrow-beam antennas. Until recently, this need has been fulfilled by increasing the physical aperture of reflectors operating at wavelengths of 3 cm or longer. However, in the space environment, essentially free from the previously imposed atmospheric limitations, the higher frequencies of the millimeter band can improve gain and beamwidth with relatively small structures, while simultaneously permitting extremely wide bandwidths, relatively unused spectrum, small size of waveguide components and reduced interference.

"Following this reasoning, the M.I.T. Lincoln Laboratory initiated a program of millimeter-systems development. In conjunction with this effort, a 28-foot diameter antenna, operating at 8.3 mm, has been installed and tested."

9.7 Weiss, H. G., "The Haystack Experimental Facility," (M.I.T., Lincoln Laboratory), Technical Report 365, September 1964.

"A new ground station for space communications, radar and radio astronomy research has recently been completed at Tyngsboro, Massachusetts. This installation, which is named Haystack, employs a 120-foot diameter fully steerable antenna enclosed in a metal space-frame radome. Advanced design and construction techniques have been developed to achieve a reflector with a very precise parabolic contour. The antenna will operate very efficiently at wavelengths of 3 cm and will also provide a useful capability at wavelengths as short as 8 mm. The antenna incorporates a "plug-in" equipment room behind the reflector which makes it possible to conveniently utilize the antenna for a variety of both active and passive experiments. At the highest operating frequency, the half-power width of the antenna beam will be less than 0.02°. To provide appropriate control for this very narrow antenna beam, a general-purpose digital computer has been integrated into the facility. The RF configuration of the antenna is compatible with the use of high-power transmitters and cooled, low-noise receiving equipment. A versatile 1-Mw average power, high-voltage supply has been provided for energizing transmitting equipment. This new installation will provide a unique capability in the microwave portion of the spectrum for communications, radar and radio astronomy."

10.0 Miscellaneous

10.1 "Opportunities for Participation in Space Flight Investigation," (Office of Space Science and Applications), NASA, Washington, D. C., January 1965.

"In conducting the Nation's program of scientific investigations in space, the National Aeronautics and Space Administration seeks the participation of the most competent scientists and tries to conduct the investigations which will contribute the most to the advancement of our scientific knowledge. This is the fourth in a series of announcements designed to inform the scientific community of the opportunities for manned and unmanned flight missions. The opportunities listed in this document are necessarily tentative and are subject to change for scientific, technological or fiscal reasons. Copies of this announcement are sent to an extensive list of potential investigators in universities, industry, NASA field centers, and other government agencies. The announcement is also distributed to scientists in other countries both directly and through their national space organizations."

10.2 "Performance Requirements, Electrical Power Subsystems," GSFC Specification No. ATS S2-0120, April 1965.

10.3 "Spacecraft Communications Subsystem," GSFC Specification No. ATS S2-0130, December 1964.

10.4 "Spacecraft Telemetry and Command Subsystem," GSFC Specification No. ATS S2-0140, December 1964.

10.5 "Spacecraft Interface Specification for Advanced Technology Experiments," GSFC RFP 233-621671-16, September 1964.

11.0 Bibliographies

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Session I: Atmospheric Propagation

1. Wintroub, H. J., Garber, W. A., Hollman, L. A., "Propagation Observations in the 3.2 Millimeter Wave Window," (Aerospace Corporation). (See Reference 9.2)

2. Mondloch, A., "Observations of Short-Term Fading at Millimeter Wavelengths," (Sylvania Electronic Systems). (See Reference 2.12)

3. Chang, S. Y., Lester, J. D., "Radiometric Measurement of Atmospheric Absorption at 600 Gc," (Department of Army, Frankford Arsenal).

4. Williams, R. A., Chang, W. S. C., "Observation of Solar Radiation from 50 Microns to 1 Millimeter," (Ohio State University).

5. Hayes, R. D., "Total Vertical Atmospheric Attenuation Measured from 40 to 140 Gc," (Georgia Institute of Technology).

6. Weibel, G., Dressel, H. O., "Propagation Studies in Millimeter Link Systems," (Zenith Radio Corporation and General Telephone and Electronics Laboratory).

Session II: Spectroscopy

1. Sakai, H., Vanasse, G., "Direct Determination of the Transfer Function of a Far-Infrared Spectrometer,"(AFCRL).

2. Geick, R., Perry, C. H., "Solid-State Studies by Means of Fourier Transpose Spectroscopy," (Spectroscopy Laboratories).

3. Valkenburg, E. P., Derr, V. E., "A High-Q Fabry-Perot Interferometer for Water Vapor Absorption Measurements in the 100 to 300 Gc Frequency Range." (Martin Company).

4. Frenkel, L., Woods, D., "On the Absorption of Millimeter Waves by H_2O and Its Mixtures with Atmospheric Gases Between 100 and 300 Gc," (Martin Company).

5. Knapp, P. H., Martin, D. H., "Submillimeter Spectra Using an Arc Harmonic Generator," (University of London).

6. Varga, A. J., Lucovsky, G., Fisher, S. J., "Far Infrared Absorption in Mn Doped GaAs." (Philco Applied Research Laboratory).

7. Gallagher, J. J., Cupp, R. E., Strauch, R. G., Derr, V. E., "Millimeter Wave Electric Resonance Spectroscopy," (Martin Company).

Session III: Generation

1. Forster, D. C., "High Power Sources at Millimeter Wavelengths," (Hughes Research Laboratory).

2. Day, W. R., Noland, J. A., "The Millimeter Wave, Extended Interaction Oscillator," (Sperry Electronic Tube Division).

3. Petroff, M. D., "Millimeter Wavelength Power Generation Utilizing the Phreatron Effect," (National Engineering Science Company).

4. Treacy, E. B., "The Two Cone Resonator," (A.W.V. Physical Laboratory, Sydney, Australia).

5. McFarlane, R. A., "Gas Laser Technology in the Far Infrared," (Bell Telephone Laboratories).

6. Hughes, W. E., Kremenek, C. R., "Zero Field Millimeter Maser," (Westinghouse Aerospace Division).

7. Rosenbaum, F. J., Jeffers, W. Q., "The Effect of Non-Uniform Population Distribution in Masers," (McDonnell Aircraft Corporation).

8. Wade, G., "The Free Electron Maser," (Cornell University).

9. Phillips, R., Enderby, C., "Recent Developments in the Ubitron," (General Electric Company).

10. Sells, V., Choo, F. C., Brannen, E., Froelich, H., "Generation of Millimeter Waves with a Racetrack Microtron," (University of Western Ontario, Canada).

11. Salisbury, W. W., "Generation of Infrared and Visible Light by Free Electrons," (Varo, Inc.)

12. Yamashita, E., Baird, J. R., "Theoretical Analysis of a Tunnel Diode in a Microwave Structure," (University of Illinois).

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1. Anderson, J. R., "A Standing-Wave Indicator for Millimeter Waves," (TRG, Inc.)

2. Taub, J. J., Cohen, J., "Several New Quasioptical Waveguide Filters for Millimeter and Submillimeter Wavelengths," (Airborne Instruments Laboratory).

3. Stern, R. A., "TR_{01} Cross-Guide Isolator," (U. S. Army Electronics Laboratories).

4. Peyton, B., Arams, F., "Dielectric-Waveguide Resonance Isolators: Performance, Material Considerations and Application to Millimeter Masers," (Airborne Instruments Laboratories).

5. Heller, G., "Use of Band Edge Properties of Antiferromagnetic Materials in Switching Millimeter Waves," (Brown University).

6. Eiber, G., Gaddis, T., Barnes, F., "Millimeter Wave Tunnel Diode Oscillating Mixer and Harmonic Generator," (University of Colorado).

7. Bauer, R. J., Cohen, M., Cotton, J. M., Packard, R. F., "Millimeter and Submillimeter Wave Semiconductor Diode Devices," (Advanced Technical Corporation).

8. Aoki, T., Azuma, S., Ishii, S., "Broadband and High Efficiency Thermistor Mounts for Millimeter Wavelengths," (Hitachi Electronics Company, Japan).

9. Andrews, J. M., Jr., Strandberg, M. W. P., "Thermal Microwave Phonons," (M.I. T.).

10. Anderson, D. B., August, R. R., "Applications of Microphotolithography to Millimeter and Infrared Devices," (Autonetics Divsion, North American Aviation).

11. Salati, O. M., "Report on NASA Millimeter Wave Survey," (University of Pennsylvania).

Session V: Post Deadline Papers

1. Okamura, S., "Millimeter and submillimeter Wave Research in Japan," (University of Tokyo, Japan).

2. Harrison, R. I., Zucker, J., "Hot Carrier Microwave Detectors," (General Telephone and Electronics Laboratory).

3. Haddad, G. I., Krumm, C. K., "Paramagnetic Materials for Millimeter and Submillimeter Wave Detection," (University of Michigan).

4. Coleman, P. D., Akitt, D., Jeffers, W., "Water Vapor Gas Laser Operation at 123 Microns Wavelength," (University of Illinois).

5. Flesher, G. T., Muller, W. M., "Submillimeter Gas Laser," (GM Defense Research Laboratories).

6. Langenberg, D. N., Scalapino, D. J., Taylor, B. N., "Josephson-type Super Conducting Tunnel Junctions as Generators of Microwave and Submillimeter Wave Radiation," (University of Pennsylvania).

7. Gilbert, J., Vaillancourt, R. M., "A Saturation Effect Spectrometer," (Armament Research and Development Establishment, Quebec, Canada).

8. Coleman, P. D., Degenford, J. E., "A Quasi-Optics, Perturbation Technique for Measuring Dielectric Constants in the Millimeter and Submillimeter Region," (University of Illinois).

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1. Coleman, P. D., "State-of-the-Art: Background and Recent Developments -- Millimeter and Submillimeter Waves." (See Reference 11.3)

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3. Tischer, F. J., "The Groove Guide, a Low-Loss Waveguide for Millimeter Waves."

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6. Baird, J. R., Coleman, P. D., "Bunching an Electron Beam by Deflection Modulation."

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"Subject classifications include classical and quantum electronics, harmonic generation optical frequency pumping and mixing, waveguide and optical transmission systems, resonators and detectors. At the end of each section, a few critical evaluation remarks are made on the work in progress and the prospects of success in the near future.

"A fairly comprehensive list of some 157 references dating from 1959 is listed by year and subject title. While substantial progress has been made, especially in technology, in the last few years, the submillimeter wave problem appears as formidable as ever and no breakthrough idea has yet been recognized."

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3.0 Plasma Effects

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The document is comprised of four chapters:

I. Breakdown Phenomena

II. The Plasma Sheath and Wake of a High Altitude Vehicle and Their Effect on Communications

III. Antenna Properties in Ionized Media

IV. Electromagnetic Radiation and Propagation in Various Natural and Artificial Plasmas

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