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XPERIMENTAL PLAN FOR CONDUCTING IONOSPHERIC SCINTILLATION MEASUREMENTS USING ATS GEOSTATIONARY SATELLITES AT 136 AND 1550 MHz

W. E. Brown III
G. G. Haroules
W.I. Thompson III

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16. Abstract

An experimental plan for conducting ionospheric scintillation measurements using the geostationary Applications Technology Satellites at 136 MHz and 1550 MHz is presented. A remote unmanned data collection platform is proposed together with detailed design configurations and data collection and analysis procedures. The data collection platform provides a real time readout capability utilizing the ATS-1 or the ATS-3 satellites as a convenient radio relay link. A comprehensive literature search and bibliography are presented in support of the analysis which lead to the design of the remote data collection platform.

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PREFACE

This report presents an experimental plan for conducting ionospheric scintillation measurements using the geostationary Applications Technology Satellites (ATS) at 136 and 1550 MHz. Details of possible equipment configurations, data analysis procedures and an approach using an unmanned remote data collection platform are discussed. The proposed data collection platform contains a real-time readout capability using either the ATS-1 or the ATS-3 satellite as a radio relay link.

Several appendixes including a bibliography on ionospheric scintillation and the discussions of various mathematical and geophysical definitions and phenomena are also provided.

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LIST OF ABBREVIATIONS

AC: alternating current
A/D: analog-to-digital
ADPE: automatic data processing equipment
AEROSAT: aeronautical satellite
AIAA: American Institute of Aeronautics and Astronautics
AGARD: Advisory Group for Aerospace Research & Development (NATO)
AGC: automatic gain control
ALSEP: Apollo Lunar Surface Experiment Package
AM: amplitude modulation
AMP: amplifier
ASTRA: Application of Space Techniques Relating to Aviation (ICAO)
ATS: Applications Technology Satellite
BW: Bandwidth
cdf: cumulative distribution function
CFSTI: Clearinghouse for Federal Scientific and Technical Information
cm: centimeter (= 10^{-2}m)
CPU: central processing unit
CW: continuous wave
D/A: digital-to-analog
dB: decibel
DC: direct current
DDC: Defense Documentation Center
Det: detector
Diam: diameter
E: east
EIRP: equivalent isotropic radiated power
ESSA: Environmental Science Services Administration
f: frequency
FAA: Federal Aviation Administration (DOT)
Geograp: Geographic
Geomag: Geomagnetic
GHz: gigahertz, 10^9Hz
GMT: Greenwich Mean Time

IAA: International Aerospace Abstracts (AIAA)
ICAO: International Civil Aviation Organization
IF: intermediate frequency
INTELSAT: International Telecommunications Satellite Consortium
ITOS: Improved TIROS Operational Satellite (ESSA)
kHz: kilohertz (= 10^3Hz)
km: kilometer (= 10^3m)
KWIC: key word in context
LES-6: Lincoln Experimental Satellite - 6
LO: local oscillator
L-band: The portion of the radio frequency spectrum between 1000 MHz and 2,000 MHz (wavelengths between 30 and 15 cm)
m: meter
MHz: megahertz (= 10^6Hz)
MIX: mixer
ms: millisecond
mW: milliwatt (= 10^{-3}W)
N: north
NASA: National Aeronautics and Space Administration
NF: noise figure
NIMBUS: The name of a NASA meteorological satellite series
NOAA: National Oceanic and Atmospheric Administration
NTIS: National Technical Information Service
Osc: oscillator
PCM: pulse code modulation
PLACE: Position Location and Aircraft Communication Experiment
PLL: phase lock loop
PREAMP: preamplifier
Prob: probability
RF: radio frequency
S: south
S-band: The portion of the radio frequency spectrum between 2,000 and 4,000 MHz (wavelengths between 15 and 7.5 cm)
S.I. or SI: scintillation index
TIROS: Television Infrared Observation Satellite (NASA)
TSC: Transportation Systems Center
Univ: university

VCO: voltage controlled oscillator

VHF: very high frequencies. The portion of the radio frequency spectrum between 30 and 300 MHz (wavelengths between 10 and 1 m)

W: watt, West

Xtal: crystal

1. INTRODUCTION

The future designers of satellite communications systems for aircraft systems may be limited in their choice of modulation schemes on a particular carrier frequency because of ionospheric scintillation. Specifically, the Federal Aviation Administration (FAA) is responsible for the development of an aeronautical satellite (AEROSAT) system which will operate at approximately 1550 MHz (wavelength of 19.35 cm) and 1650 MHz for two way transmission of both voice and digital data.

The concept of the AEROSAT system when fully deployed is to employ four satellites of the same basic design in a nominally geostationary orbit, two for each oceanic coverage area (Atlantic & Pacific). Figures 1-1 and 1-2 show the coverage areas proposed. Each satellite will relay voice and digital data communications between suitably equipped aircraft flying within the coverage area and the designated ground facilities. In addition, an extensive experimental program is planned with the satellite system including air traffic control in conjunction with independent surveillance.

Those major parameters which must be calculated in specifying accurately the design of the AEROSAT are the radiated power of the satellite, the gain of the satellite antenna, the radiated power of the aircraft transmitter and the minimum gain of the aircraft antenna. These parameters must be accurately known together with the propagation losses resulting from multipath and scintillation effects if one is specifying an adequate power budget and desires to make allowances for a sufficient link margin. Thus the system designer who has been analyzing scintillation in terms of the fading rate and amplitude as a function of time of day, season, latitude and frequency must also assess the deterioration produced on the proposed system.

Scintillation is a natural phenomenon produced by irregularities at heights ranging from 200 to 600 km which can alternately increase the signal as well as produce deep fades which can disrupt a communications channel.

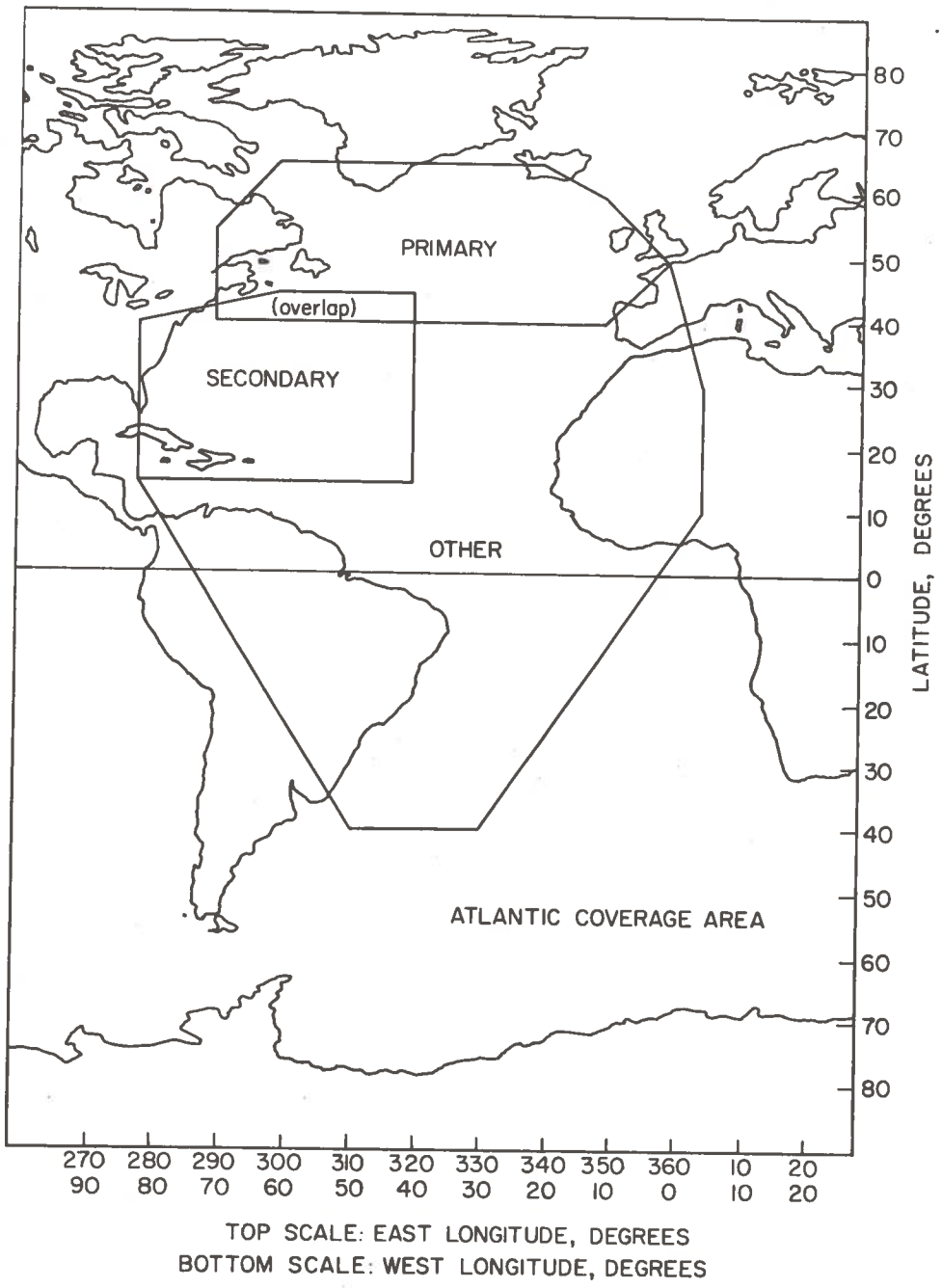

Figure 1-1. Map of Atlantic Coverage Areas for Proposed AEROSAT System

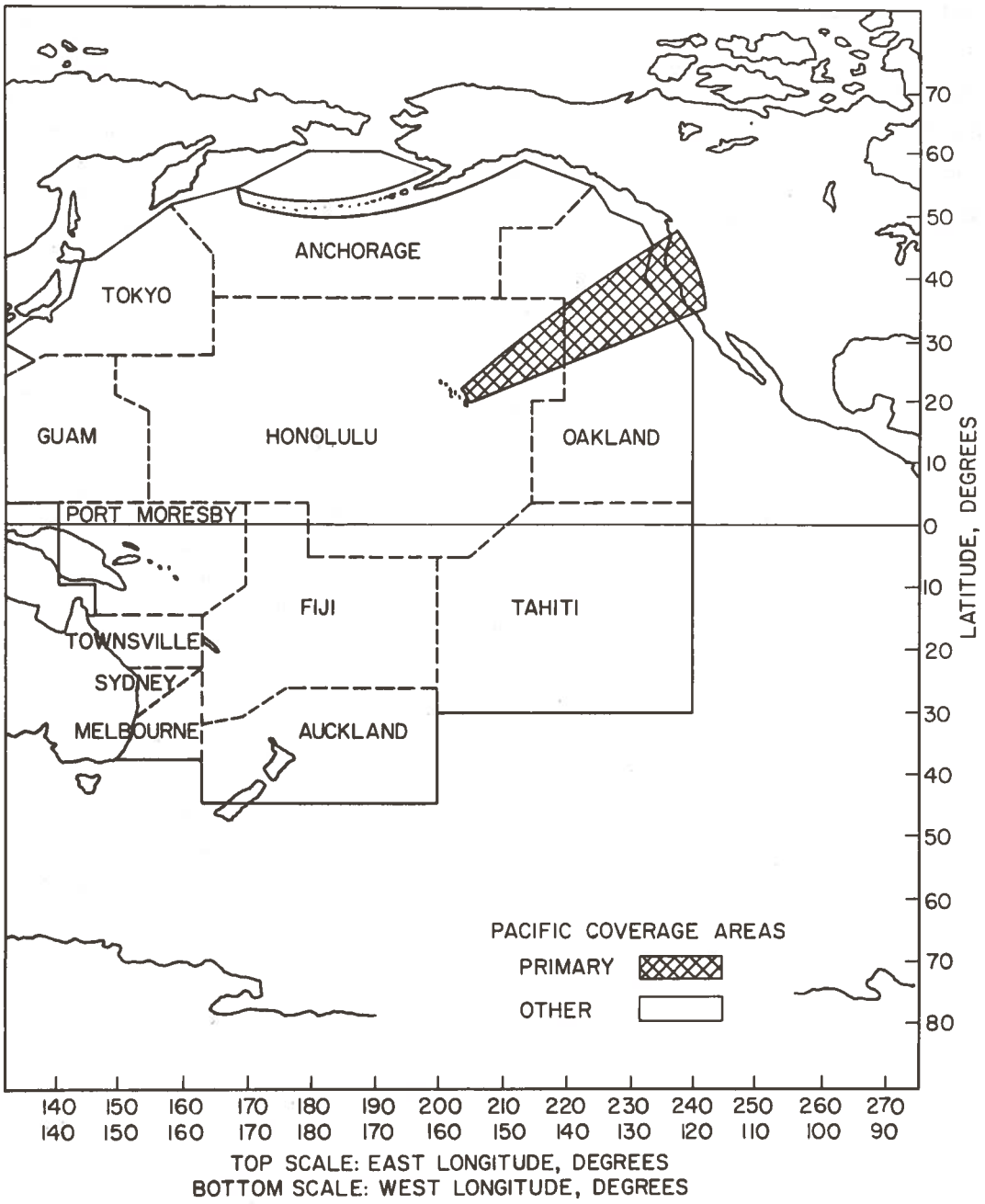

Figure 1-2. Map of Pacific Coverage Areas for Proposed AEROSAT System

Ionospheric scintillation is produced by the presence of small-scale irregularities within the ionosphere which introduce random phase changes in the wave front of a traversing electromagnetic wave. The phase of a radio wave emitted by a geostationary satellite transmitter will not be constant over the ground but will form an irregular pattern. This pattern appears to move as a consequence of ionospheric winds shifting the irregulatities. The result is that the phase and amplitude of the received signal will appear to fluctuate or scintillate.

2. REVIEW OF SCINTILLATION DATA

2.1 BACKGROUND

The VHF frequency of 136 MHz is heavily used in the satellite telemetry band. There exists as a result an abundance of signal amplitude data from earth satellites including synchronous satellites. However, most of the amplitude data is in the form of scintillation indexes. Some of this scintillation index data has been converted to cumulative amplitude probability distributions and has been made available in the literature. A comprehensive bibliography of this data is available as Appendix B of this report. A characterization of ionospheric scintillation is given in Appendix E.

This literature includes Aarons, Whitney and Allen (1971), Fremouw and Bates (1971) and Whitney, Aarons and Seemanns (1971). Most of the available data is in the form of amplitude distributions, seasonal dependences and fade depth-duration information. There is very little information on phase effects in transatmospheric propagation except for the work of Porcello and Hughes (1968) and Smith (1967).

Knowledge at 1550 MHz has been reported by several researchers: Golden (1970A,B,C), Maynard and Selin (1971), Wernlein (1970), Kissel (1970) and Crampton and Sessions (1971). The most comprehensive measurement program reported to date is the work of Crampton and Sessions.

Observations were taken at a large number of sites throughout the world. Table 2-1 lists the sites where scintillation observations have been made. Also included in the table are such items as the geographic and geomagnetic coordinates as well as the names of the researchers involved in the work. Appendix A defines several coordinate systems used in Table 2-1. A definition of scintillation indexes is given in Appendix D.

TABLE 2-1 LOCATIONS WHERE IONOSPHERIC SCINTILLATIONS HAVE BEEN OR ARE BEING MEASURED -- EMPHASIS ON 136 MHz AND 1550 MHz

Location	Investigator(s)	Comments
Huancayo, Peru Geomag: 02°N; 06°W Geograp: 13.5°S; 75°W	Mueller, 1970 Whitney, et al 1971	ATS-3; Scintillation Index(S.I.) 20% - 90%
Lima, Peru (Ancón, Peru) Geomag: 0°; 8°W Geograp: 11.6°S; 77.1W	Wernlein, 1970 Crampton & Sessions, 1971; Pomalaza, et al 1970	Fig. 9 Geophysical Institute of Peru
Accra, Ghana Geomag: 10°N; Geograp: 0°; 6°N	Allen, 1969 Koster, 1968	
Quito, Ecuador Geomag: 11N; Geograp: 0°; 78°W	Golden, 1970B	136.47 MHz; 1550 MHz
Hamilton, Mass. USA Geomag: 53.5°N Geograp: 43°N; 71°W	Mullen, et al 1969 NASA, 1970	Sagamore Hill Radio Observatory
Schenectady, NY, USA Geomag: 54°N Geograp: 42°50'53"N 74°05'15"W	General Electric, 1971	General Electric Radio & Optical Observatory
Westford, Mass. USA Geomag: 53°N; 2°W Geograp: 42.5°N 71.3°W	Brown, Haroules and Thompson	DOT/TSC/Westford Propagation Facility; using ATS-5
Thule, Greenland Geomag: 35.8°W; 89°N Geograp: 77°N; 69°W	Aarons, Whitney and Allen, 1971	
Narssarssuaq, Greenland Geomag: 36.6°W; 71°N Geograp: 61.2°N; 45°W	Aarons, Whitney and Allen, 1971	20° elevation angle to ATS-3
Gilmore Creek, Alaska, USA Geomag: 63°N; 270°W Geograp: 65°N; 147.5°W	Pope and Fritz, 1970	NOAA Control and Data Acquisition Station (20 km NE of College)
Churchill, Manitoba Canada Geomag: 69°N Geograph: 58°45'N 94°4' W Invariant Lat: 72°N	Rudin	L-Band 254.14 MHz Canada Dept. of Transport Dept. of Communication Research 6 ft diam parabola, BW = 30 kHz
Ottawa, Ontario Canada Geomag: 56°N Geograph: 45°N; 76°W Invariant Latitude: 58°N	Maynard	L-Band 30 ft diameter parabola BW = 100 kHz

2.2 AMPLITUDE DATA FROM RADIO STARS AT FREQUENCIES FROM 60 TO 400 MHz

Aarons, Allen and Elkins (1967) reported on the frequency dependence of radio star scintillation at the frequencies 30, 63, 113, 228 and 400 MHz. Their conclusions were:

a. With only a few exceptions, the exponent of the frequency dependence of scintillation index lies in the range 0-2.

b. Under conditions of weak scattering, and at high frequencies (113-400 MHz), the exponent of the frequency dependence of scintillation index η is close to 2, which is the expected theoretical value for Fresnel zone observations.

c. At the lower frequencies studied (30-113 MHz) frequent examples were found that were apparently characterized by strong scattering. For these conditions, the value of η was generally observed to be lower, and usually in the range 0-1.

d. In the portion of the spectrum between 30 and 63 MHz, for observations looking through the auroral zone, η was found to be centered about the value 1.

e. For some cases of very intense scintillation, the frequency dependence exponent approached zero, and on occasion became negative (i.e. scintillation index increased with frequency instead of the converse, which is normally the case).

f. Irregularity scale size of the order of 1 - 2 km are consistent with most of the measurements.

Chivers (1960) also discussed various aspects of the phenomenon of the scintillation of a radio star covering the frequency range 26 MHz to 408 MHz. His conclusions are:

g. The mean scintillation amplitude varies as the inverse square of the observing wavelength up to the point where the lower frequency index saturates at 100 percent (the scintillation index used). For zenithal observations on

26 MHz at the latitude of Jodrell Band (Geographic Latitude 53°N), a scintillation index of 100 percent is commonly obtained.

h. The rate of scintillations is independent of observing wavelength under weak scattering conditions, and for strong scattering, the rate increases with wavelength.

i. The probability amplitude distribution of small scintillations is a displaced Gaussian curve, and larger amplitudes have a Rayleigh distribution. Very intense scintillations have an irregular amplitude indicating the occurrence of non-statistical focusing and defocusing of the incident wave.

j. There is no significant cross-correlation between records of scintillations obtained simultaneously on frequencies differing in the ratio 3:1. Combining this with the results of other workers, it is clear that the fall in cross correlation with frequency separation is at least at a linear rate.

Table 2-2 summarizes most of the available data on the frequency dependence of ionospheric scintillation. As can be seen from the table, the data to date has not been conclusive as to the exponent of the frequency factor, if in fact one exists for all possible conditions.

Crampton and Sessions (1971) show a scatter diagram of the exponent of frequency dependence as a function of depth of VHF scintillation fading for each test run. These results show that the exponent of the frequency dependence decreases as the fading increases which is contradictory to the relationship experienced at high and mid-latitudes by Mullen et al (1969) and Allen (1968). Crampton and Sessions discuss the possible reasons for this departure from other measurements, however, a similar finding is indicated in the high latitudes by the study of Pope and Fritz (1970).

TABLE 2-2 COMPARISON OF FREQUENCY-DEPENDENCE RELATIONSHIPS OF IONOSPHERIC SCINTILLATION

Frequency Range	Scintillation Amplitude	Scintillation Rate	Comments and Citation
26 MHz - 408 MHz	$1/f^2$	independent of wavelength	See conclusions (vii) - (x) in section 2.3.2 from Chivers, (1960) Mid latitude
254; 1550 MHz	$1/f^2$	-	Maynard and Selin (1971) Ref. 5 in Golden, (1970B), auroral region
136; 1695 MHz	$1/f$	-	Pope and Fritz (1970), auroral. In general the S-band scintillation amplitudes were about 1/10 of the VHF scintillation amplitudes.
4; 6 GHz	$1/f^2$	-	Craft and Westerlund (1972), Hong Kong
?	$1/f$	-	Allen, (1968)
30; 63; 113;	$1/f^2$	-	Weak scintillations higher radio frequencies
228; 400 MHz	$1/f$	-	High levels of ionospheric activity and lower frequencies, Aarons, Allen and Elkins (1967) Mid-latitudes
136; 1550 MHz	$1/f^{0.78}$	-	Crampton and Sessions, (1971), equatorial
136; 1550 MHz	$1/f$ $1/f^{0.5}$	- -	summer solstice, equatorial autumnal equinox, equatorial Golden (1970B)

The real problem in trying to estimate frequency dependence over such a wide frequency region (136 - 1550 MHz) is that there is usually saturation of the lower frequency scintillation index before scintillation commences at the higher frequency. In other words, strong scattering occurs at 136 MHz and weak scattering occurs at 1550 MHz.

It thus may be concluded that frequency scaling of VHF data does not provide a reliable estimate for scintillation at L-band. Extensive measurements at 1550 MHz are urgently needed in order to provide useful system design information for aeronautical satellite systems.

2.3 AMPLITUDE SCINTILLATION DATA AT 136 MHz

A summary of available amplitude scintillation data at 136 MHz is presented in Table 2-3. Much of the amplitude-time information has been sponsored and reported by the Air Force Cambridge Research Laboratories and presented in cumulative form by Whitney, Aarons and Seemann (1971).

Data was collected at three different latitudes. The mid-latitude site was Hamilton, Massachusetts, the auroral site was Narssarssuaq, Greenland, and the equatorial site was Huancayo, Peru. The data collected at these sites was converted from scintillation index measurements over the indicated periods of measurement. Thus, to date there is only one source of digitized data at 136 MHz which has been converted into amplitude probability density distributions. This is item 4d at Hamilton, Mass. in Table 2-3.

Cumulative amplitude distribution of ATS-5 (1550 MHz) and INTELSAT I (136 MHz) signals were collected at Ancón, Peru. This data was reduced from strip chart data manually. The conclusion to be drawn from the 23 hours of data reported to date is that a proper physical interpretation of scintillation cannot be deduced from these data due to the restricted sample size (Crampton and Session, 1971). The relative severity of microwave scintillation

TABLE 2-3 SUMMARY OF PROPAGATION DATA AVAILABLE AT 136 MHz -- EMPHASIS ON SYNCHRONOUS SATELLITE DATA

Location Name	Type(s) of Data	Satellite	Reference(s)
Huancayo, Peru	1. S.I. 20% to 90%, Fig. 8	ATS-3	Mueller, 1970
	2. S.I. - cumulative distribution function (cdf), Fig. 9	ATS-3	Whitney, Aarons, and Seemann 1971
	3. 9381 hrs. Fig. 11, S.I. cdf (6 Jan. 1968 - 30 Apr. 1970)	"	"
	4. S.I. - cdf (5 Jan. 1968 - 30 Apr. 1969)	"	"
	5. S.I. - cdf (5 Jan. 1968 - 30 Apr. 1969) Day - Night - All hours, Fig. 14	"	"
	6. Fading Range vs month, Fig. 15 (1 Jan. 1968 - 30 Apr. 1970; 9245 hrs)	"	"
Lima, Peru (Ancón) Ancón Satellite Tracking Station	1. cdf from manual data reduction of strip chart data Elevation Angle: 49-52°	INTELSAT I (Early Bird)	Crampton and Sessions, 1971 Pomalaza, et al, 1970
	2. cdf for runs on 29 Sept., 6, 8, 10, Oct. 1970, Figs. A-1 - A-5		
Hamilton, Mass. USA Sagamore Hill Radio Observatory	1. S.I. - cdf (11 May 1967 - 30 Apr. 1968) Day - Night - All Hours	INTELSAT II F3 F3 (Canary Bird)	Whitney, Aarons and Seemann, 1971
	2a. S.I. - cdf; 1745 hrs (11 May 1967 - 9 Aug. 1967)	"	Whitney, 1969, Fig. 7 NASA, 1970, Fig. 6-1 Aarons, 1970
	2b. Fade depths; Distribution of 3 and 6 dB fades, Fig. 8	"	Whitney, 1969

TABLE 2-3 (CONTINUED)

Location Name	Type(s) of Data	Satellite	Reference(s)
Hamilton, Mass. USA (Continued)	3. Strip chart recording; 1 1/2 hrs 7 Aug. 1965, Fig. 4-11	INTELSAT I (Early Bird)	Allen, 1969
	4. 37° Elevation Angle over a propagation path intersecting an invariant latitude of approximately 54°	ATS-3	
	4a. 15 minute sample of strip chart and a corresponding amplitude distribution. Fig. 2	"	Aarons, Whitney, and Allen, 1971
	4b. 16 May 1970; 0130 - 0630 UT "Worst Case", Fig. 5	"	"
	4c. 15,750 hrs S.I. - cdf 9 Nov. 1967 - 31 Oct. 1969, Fig. 4	"	"
	4d. 35.5 hrs digitized - cdf, Fig. 7	"	Whitney, Aarons and Seemann, 1971
	4e. 1296 hrs - S.I. -cdf, Fig. 6	"	"
	4f. strip chart, 15 Oct, 1970 (412; 137.35; 136.47 MHz) 0300-0600 GMT; Figs. 11-37	"	General Electric, 1971
Schenectady, NY USA General Electric Radio & Optical Observatory	1. Experimental VHF satellite-to-aircraft comm. link with a jet over the N. Atlantic. A strip chart for the entire flight is included in the reference.	ATS-3	General Electric, (1970) Note: there is also a tape recording to go along with the strip chart

TABLE 2-3 (CONTINUED)

Location Name	Type(s)	Satellite	Reference(s)
Thule, Greenland	1. Fading period and amplitude for 21, 22, 23 Oct. 1968, See Fig. 7 of the present report	ATS-3	Aarons, Whitney and Allen, 1971
Narssarssuaq, Greenland	1. 20° Elevation Angle Intersection with invariant latitude at 350 km level was 63° on the average; Fig. 15	ATS-3	Aarons, Whitney and Allen, 1971
	2. S.I. - cdf; Fig. 8 Mean Distributions	ATS-3	Whitney, Aarons and Seemann, 1971
	3. S.I.- cdf; Fig. 13 17 Sept. 1968 - 14 Aug. 1969 All Hours - Day Hours - Night Hours	"	"
	4. 7635 hrs (Sept. 1968 - Apr. 1970) S.I. - cdf; Fig. 10	"	"
Gillmore Creek, Alaska, USA NOAA Control & Data Acquisition Station	1. 1700 MHz too. 22 Feb. 1970; three times; strip chart data	ESSA-9 ITOS	Golden, 1970C
	2. Description of amplitude scintillations	TIROS-9 NIMBUS	Fremouw, 1967
	3. S.I., 137 MHz and 1695 MHz	ITOS-1	Pope and Fritz, 1970

effects points out again the urgent need for further experimentation in this area.

It was found that the equatorial VHF fade duration statistics generally were about the same as those observed at higher latitude stations. One significant finding in the equatorial data was that at low fade depths (2 dB or less), the durations are about the same at L-band. However, as the depth of fade increases, the VHF fades tended to be considerably longer than L-band fades for the same length of time.

2.4 SUMMARY OF PERTINENT MEASUREMENTS

A comprehensive bibliography is presented in Appendix B. Tables 2-4 and 2-5 present a visual presentation of pertinent amplitude scintillation measurements reported by various workers. Caution should be used when consulting these tables since different types of measurements are recorded.

TABLE 2-4 COMPARISON OF SEVERAL VARIOUS EXPERIMENTS BETWEEN FREQUENCIES OF 254 AND 6295 MHz

Frequency/ Wavelength	Location	Measurement Instrumentation	Researcher	Comments
250 MHz 1.2 m	Churchill	12 ft Diam. 17 dB at a rate of 55% efficiency	Rudin	Analog tape - Ottawa-Data - LES-6
"	Ottawa	30 ft Diam 25 dB at a rate of 55% efficiency	Maynard	No data available
1.550 GHz 19.35 cm	Ancón	4 ft Diam. 23 dB at a rate of 55% efficiency	Crampton et al 1971	23 hrs - hand reduced - ATS-5
"	Westford	10 ft Diam. 31.2 dB at a rate of 55%	Brown	70 hrs - Aug. - Dec. 1971 - ATS-5
"	Churchill	6 ft Diam. 27 dB at a rate of 55%	Rudin	Analog tape - Ottawa - ATS-5
"	Ottawa	30 ft Diam. 41 dB at a rate of 55%	Maynard	No data avail. - ATS-5
4 GHz 7.5 cm	Many Sites	Standard Communication satellite earth stations Diam. > 30 ft 49 dB at a rate of 55%	Craft et al	Envelope of fading 8 dB peak-to-peak. INTELSAT satellites.
6 GHz 5 cm	Many Sites Longonot Kenya	Standard communication satellite earth stations. Diam. > 30 ft 49 dB at a rate of 55%	Craft et al Skinner et al 1971	Amplitude fading up to 4 dB in carrier level

TABLE 2-5 CHART OF VARIOUS MEASUREMENTS OF IONOSPHERIC SCINTILLATION FROM SEVERAL AREAS AND RADIO FREQUENCIES. ○ -99%; □ -99.5/99.9%; ◇ -99.99%; △ -PEAK TO PEAK FLUCTUATIONS; ⬡ -MAXIMUM FADING

Site; Source; See Tables 2-3 and 2-4 for information on measurements.	Signal Level Below Median (dB)* -1 -2 -3 -4 -5 -6 -7 -8 -9 -10 -11 -12 -13 -14 -15 -16 -17 -18	
Ancón; Crampton & Sessions, 1971, INTELSAT I, 136 MHz		Equatorial (± 20° N/S)
Huancayo; Whitney, Aarons, Seemann, 1971, ATS-3, 136 MHz		
Huancayo; same, 136 MHz		
Ship, Apollo-13 Kuegler, (1970), 136 MHz		
Ancón; Crampton & Sessions, (1971), 1550 MHz, ATS-5		
Several Sites; Craft and Westerlund, 1972, 4 GHz		
Several Sites; Craft and Westerlund, 1972, 6 GHz		
Longonot, Kenya; Skinner et at, 1971, 6.295 GHz		
Ascension Island; Christiansen 1971, 2.2 GHz, ALSEP		
Hamilton; Aarons et al., 1971, 136 MHz, ATS-3		Mid Latitude 20-45°N
Hamilton; Whitney 1971, 136 MHz, INTELSAT IIF3		
Hamilton; Whitney, et al., 1971, 136 MHz, ATS-3		
Ottawa; private communication 1550 MHz, ATS-5		
Westford; 1550 MHz, ATS-5		
Narssarssuaq; Aarons, et al. 1971, 136 MHz		High Lat. >45°N
Narssarssuaq; Whitney, et al. 1971, 136 MHz		
Churchill; private communication, LES-6, 254 MHz		
Churchill; private communication, ATS-5, 1550 MHz		

*Except where noted by △ or ⬡.

3. DESCRIPTION OF PROPOSED SCINTILLATION MEASUREMENT PROGRAM

3.1 BACKGROUND

To successfully implement a reliable satellite communication system as that proposed for the AEROSAT System the propagation anomalies which may affect performance must be delineated and characterized. Several different types of modulation have been proposed for the AEROSAT system, and in order to make intelligent system design decisions the channel must be characterized for each of the proposed modulation methods.

This chapter will outline the first steps of a suggested measurement program. A brief description of the DOT/TSC/Westford Propagation Facility will be given as an example of the receiver and data processing equipment that would be involved. A description of the methods and equipment that should be used in making remote measurements will also be outlined. Typical remote sites will be tabulated as will a suggested schedule for implementation of the first steps of the measurement program.

3.2 PROPOSED MEASUREMENT PROGRAM

3.2.1 Phase I Measurement of Amplitude Scintillations of a Continuous Wave (CW) Signal

Some signal level variations are accountable for and may be calculated (i.e. changes in spacecraft altitude due to its orbit or variations in aircraft antenna gain relative to satellit line-of-sight). However, the fluctuations (or scintillations due to ionospheric variations) must have their amplitude-time statistics determined and documented.

The probability density and the probability distribution functions of a CW signal's amplitude should first be determined. Though there are other statistical methods these are the most often used and easiest to perform and provide complete statistical data of the random effect observed. The data should first be analyzed in short segments to allow the ability to separate times of no

scintillation from periods of heavy scintillation and to ensure statistical stationarity of the median signal level changes. Then the periods of light and moderate scintillation should be established. It should thus be possible to identify the periods of light, moderate and heavy scintillation during a given run of several hours duration. This will give some physical feeling for when and how severe the scintillations were before the time history of the data run is lost in the calculation of the cumulative probability for the whole time period.

When the amplitude-time statistics due to the ionospheric scintillations are determined, the circuit parameters for the receiver's phase locked loop may be determined, and reliability and precision of phase lock may be calculated.

The statistics will also give an indication of the reliability of a voice channel. Moreover, the statistics will serve as a guide as to the possible message length or to the redundancy that needs to be incorporated in a message of a certain length in order to provide the necessary reliability. The statistics of the rapid scintillations will indicate if there is a more favorable bit size that will not be influenced by the rapid scintillations. The statistics of scintillation when known would have an impact on the design of codes for the channel.

3.2.2 Phase II Measurement of Coherent Amplitude Scintillations and Phase Variations of CW Signal

The analysis of the coherent amplitude scintillations should be performed as outlined in Phase I for incoherent amplitude measurements. In all probability, the operational AEROSAT System will employ phased locked receivers in the airborne receivers in order to remove Doppler frequency and acceleration modulation on the received signal. This will also allow narrow-band operation in order to improve the signal-to-noise ratio as much as possible.

In addition to removing the Doppler influences it may be necessary to track phase changes in the received signal due to ionospheric scintillation effects. The proper phase lock loop

bandwidth has to be established such that the deleterious propagation effects are tracked out but the modulation is not tracked out.

3.2.3 Phase III Measurement of Phase-Modulated Signal with Three Coherent Tones

The accomplishment of Phases I and II should provide the necessary information for implementing an experimental communication system through the spacecraft. A set of coherent tones may be used to measure phase dispersion across a typical operational bandwidth. This would be necessary for implementing a ranging system or for wide-band coherent communication channels.

At first a modest arrangement of audio tones would be implemented. Again the data from this measurement would be analyzed as outlined in Phase I.

3.3 EQUIPMENT CONSIDERATIONS FOR SCINTILLATION MEASUREMENTS

To appreciate the possible receiving equipment required, a brief description of the receiving station at the DOT/TSC/Westford Propagation Facility in Westford, Massachusetts will be given.

The receiving system is a two element phase coherent interferometer which is completely operated under computer control. The data processing, analysis and display is done in real-time as the interferometer is being operated.

The receiving system is capable of making several different scintillation measurements, many of them simultaneous. They may be categorized as incoherent and coherent (phase locked or synchronous) in various combinations with the two antennas. The various modes are described below.

The incoherent measurements are signal strength as measured by the envelope detector in the second or third intermediate frequency (IF) amplifier. The IF detector in the telemetry receivers may be preceded by a narrow-band (2.5 kHz) or intermediate-band (30 kHz) filter. The detected voltage is direct coupled to a stabilized operational amplifier with a 1 MHz bandwidth. This provides an output voltage proportional to the input power. With

this detector it is possible to obtain a dynamic range of 25 dB with a 0.1 dB error starting at the system noise level. The linear 10 MHz signal from the telemetry receivers is also fed to a combination of vector voltmeters. The vector voltmeters down convert the signal to 20 kHz and then the signal is envelope detected. The radio frequency (RF) bandwidth at 20 kHz is 1 kHz. The vector voltmeters provide a direct current (DC) output voltage (2 ms rise time) over a 12 dB dynamic range with a 0.1 dB error. The 10 MHz output from each telemetry receiver is split, and one output from each receiver is fed to individual vector voltmeters. This provides a measure of the signal strength as received at each antenna. The other halves of the individual receiver's 10 MHz outputs are added together and fed to a third vector voltmeter. This provides a means to calculate the correlation between the signals received by the two antennas.

Coherent measurements are also made using the telemetry receivers. Each receiver is phase locked to the carrier at the second IF (the two receivers share a common second local oscillator (LO)) and provide coherent detection of the carrier amplitude. The detected coherent carrier amplitude is direct coupled to a stabilized operational amplifier with a bandwidth of 1 MHz. This coherent detection of the carrier amplitude has a 12 dB dynamic range with a 0.1 dB error from the loop lock threshold. This coherent carrier amplitude and the incoherent carrier detection discussed above operate with the receiver's automatic gain control (AGC) off in order to insure true linearity.

It should be pointed out that various types of coherent and incoherent modulation could be demodulated if they existed. However, the present scintillation measurements only involve a CW signal from the ATS-5.

A simplified block diagram of the interferometer system is shown in Figure 3-1. The figure shows the overall organization of the receiving system. The central processing unit (CPU) controls the antenna pointing through the antenna control station. The receiver electronics are also under computer control such that

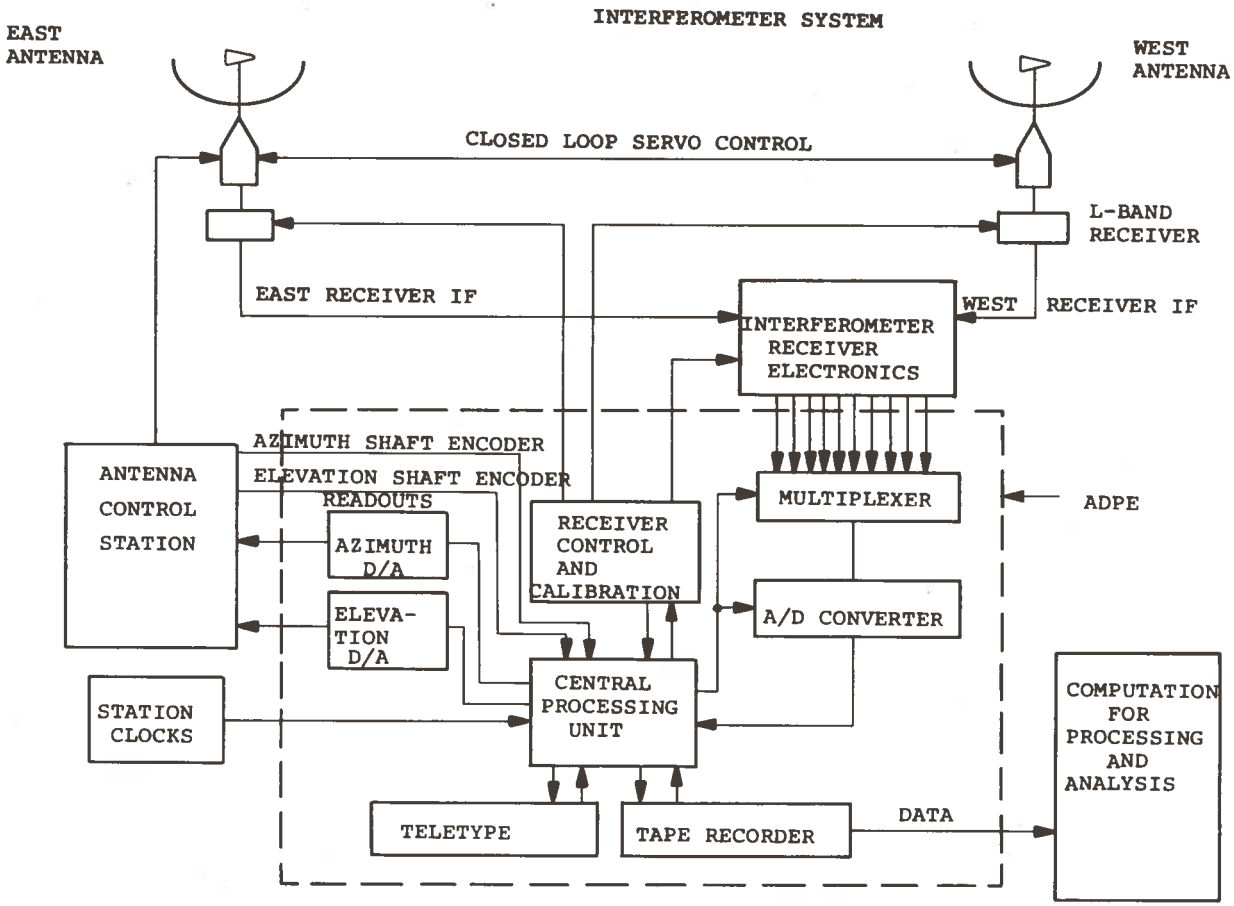

Figure 3-1. Simplified Block Diagram of Interferometer System

the automatic calibration can be made. The major portion of the computer control is devoted to data acquisition and processing. Preliminary analysis of the data is also performed continually to assure the data is of acceptable quality.

Figure 3-2 presents a simplified block diagram of the L-band interferometer system used in conjunction with the ATS-5 spacecraft for making scintillation measurements. The first conversion is performed at each antenna and the signal is returned at 30 MHz to the IF telemetry receivers of the East and West antennas. A LO reference signal of approximately 250 MHz is sent to each antenna's RF electronics package. Control Functions are also sent to the RF package. The control functions may be performed automatically or manually. A switchable set of delay lines is incorporated into the East antenna's IF cable. This unit compensates for differences in IF cable length as well as the path difference across the interferometer aperture. Consequently, when the IF signals from the East and West antennas are combined they have each traveled through the same overall path length (i.e. they have experienced the same time delay).

The various outputs of the 30 MHz telemetry receiver are digitized and the digital word from the analog to digital (A/D) converter is combined with the West antenna A/D converter to form a computer word. The 10 MHz receivers (vector voltmeters) are multiplexed into one A/D converter (each reading is a computer word). The multiplexer is twenty channels and may also be used to sample data from the telemetry receivers. The low speed A/D converter works at a 30 Hz rate and the high speed converter works at a 250 kHz rate.

The first LO is controlled by a frequency synthesizer at 60.222 MHz to provide a 1520 MHz LO signal. A common 250 MHz signal is generated, split and sent to the individual antenna's RF electronics for final multiplication to 1520 MHz. The second LO is a crystal oscillator unit serving both telemetry receivers. The third LO is common to the three vector voltmeters operating at 10 MHz. Tuning the third LO allows the narrow band third IF to be

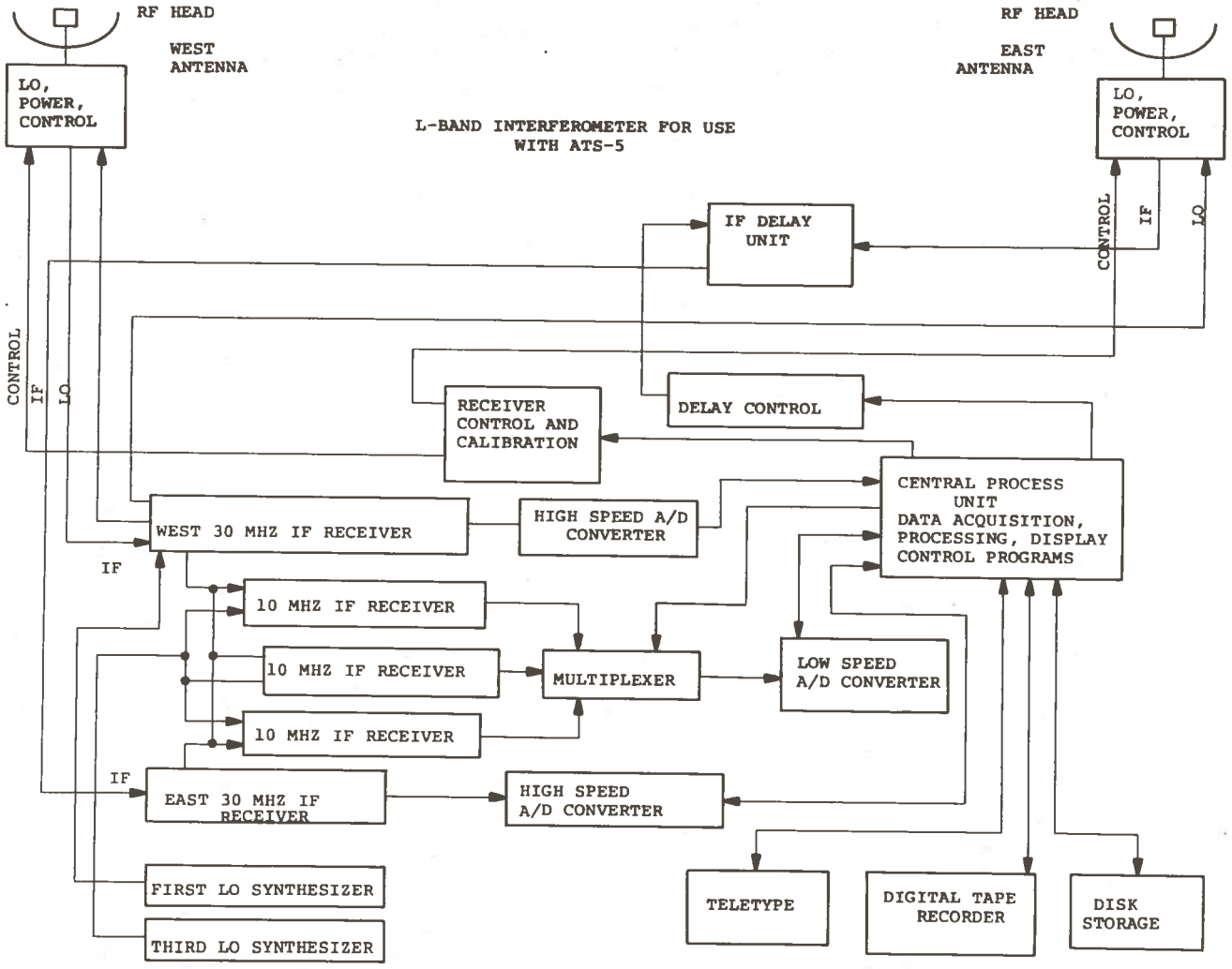

Figure 3-2. Simplified Block Diagram of L-Band Interferometer for Use with Applications Technology Satellite-5 Spacecraft

tuned within the wider bandwidth of the telemetry receivers. This is often used to check the spectral composition of the signals with complex modulation on them.

Figure 3-3 presents a simplified block diagram of the L-band equipment located at each antenna. The RF feed package consists of a RF switch, a bandpass filter and a transistor preamplifier. The amplified signal is fed to a mixer-IF preamplifier located behind the main reflector. The RF switch directly at the input allows a calibration signal to be substituted for the antenna's signal. The calibration signal is a coherent CW signal generated back in the electronics van and fed to each antenna through a cable of known loss. The bandpass filter is a three cavity filter which provides 45 dB image rejection and 60 dB out-of-band rejection ahead of the transistor amplifier.

The mixer is a double balanced unit with conversion loss of 5 dB, and the IF preamplifier has a gain of 30 dB with a 1.5 dB noise figure. The IF passband is flat from 20 MHz to 49 MHz. This fact allows operation over most of the bandpass of the ATS-5 or operation near 1550 MHz and also at the beacon frequency of 1565.814 Mhz. The operating bandwidth of the LO multiplier allows operation from 1520 to 1540 MHz.

A simplified block diagram of the L-band telemetry receiver is shown in Figure 3-4. The receiver is essentially a double conversion receiver with provisions for various types of coherent and incoherent demodulation. A third conversion to 20 kHz is also included to permit narrow-band operation. The 20 kHz is also fed to a wave analyzer when necessary. The linear 10 MHz is also fed to a spectrum analyzer for display and measurement. When the AGC amplifier is in the manual position it provides manual RF gain control. Also the gain of the first IF amplifier may be independently controlled. This allows almost perfectly linear operation over any 30 dB signal range. When the receiver is under AGC the operation is linear within 3 dB over a 90 dB dynamic range from threshold.

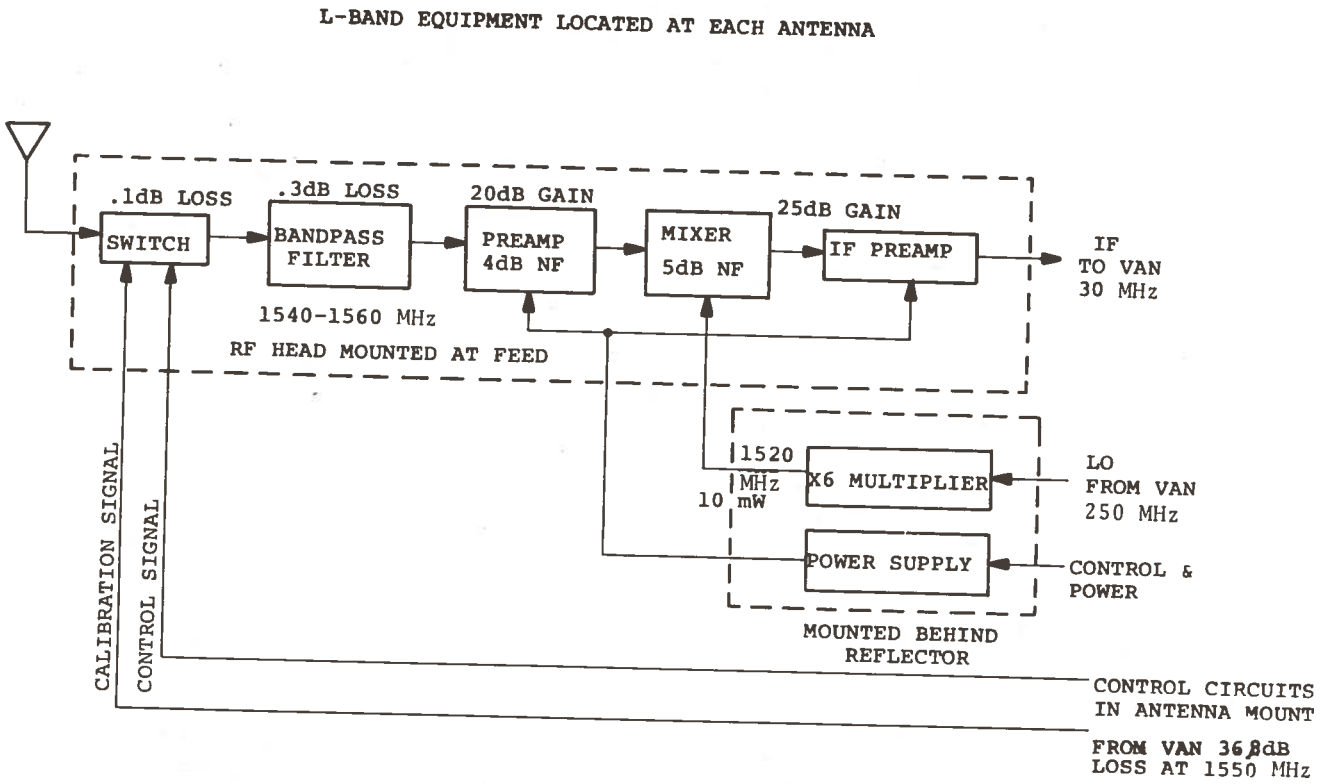

Figure 3-3. Simplified Block Diagram of L-Band Equipment Located at Each Antenna

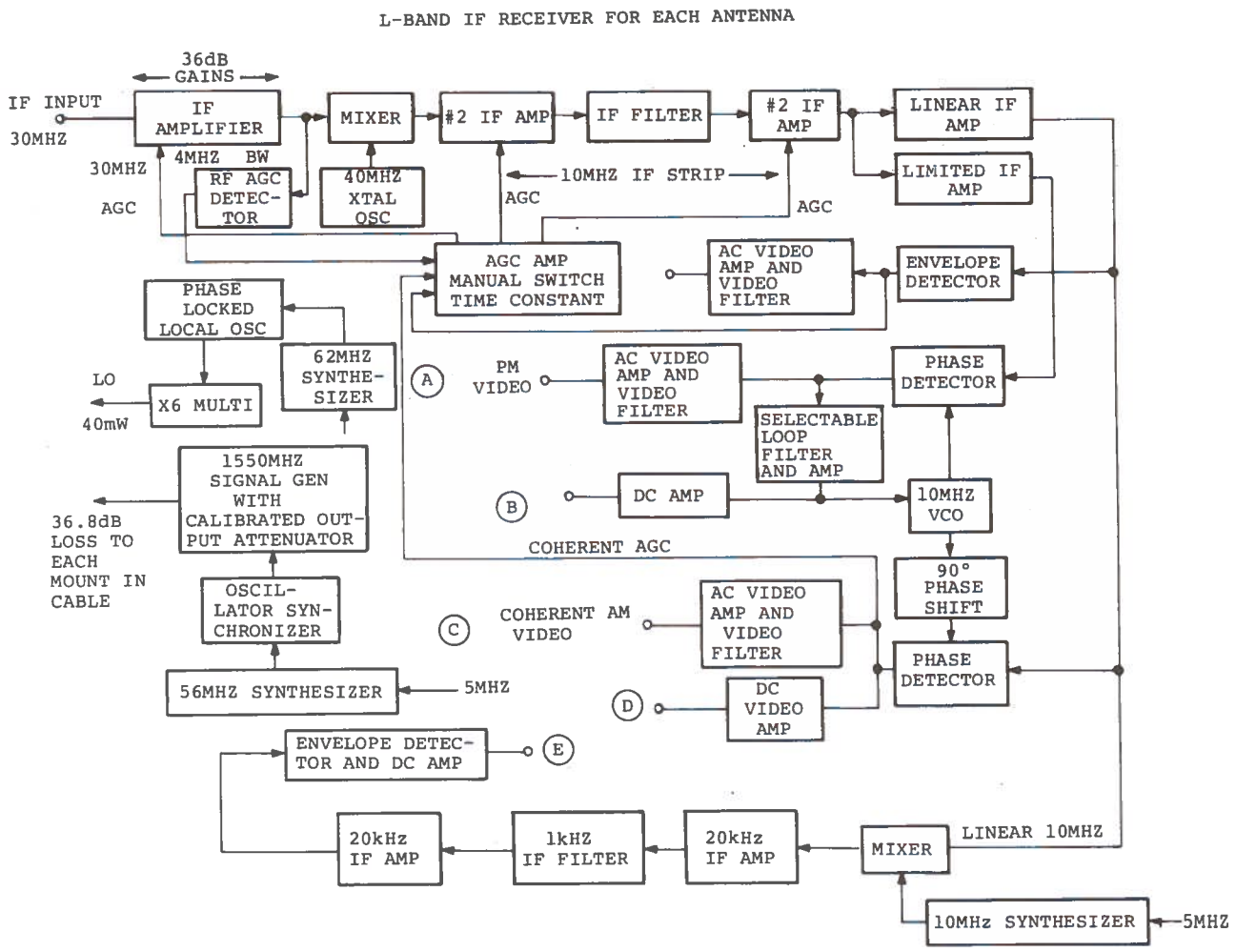

Figure 3-4. Block Diagram of L-Band Receiver for Each Antenna

Either 2.5 kHz or 30 kHz crystal filters may be plugged into the second IF. Outputs A, C and F provide alternating current (AC) video demodulated signals while B, D, E and G provide DC demodulated signals. Each of the DC amplifiers is a stabilized operational amplifier.

Automatic data acquisition and processing is done on-site in real-time using an Hewlett-Packard 2114B computer. The data acquisition program used with the ATS-5 signal continuously digitizes the detected signal and incorporates the absolute calibration into the measurements. Since the pulsed signals are sampled many times, a faithful replica of the pulsed signal is stored in the computer. The individual samples of the pulse have an absolute accuracy of 0.1 dB.

The replica of each pulse is analyzed to find its maximum values. The procedure for finding the maximum of the pulse is such that several values leading up to the maximum and several values following the maximum are checked in order to ensure the value selected as the maximum is in fact the maximum. This procedure prevents the noise peaks on the leading edge of a pulse from being picked as the maximum value of the pulse.

The peak values are then stored in a table with two hundred entries corresponding to the possible signal strength. The table covers a 20 dB dynamic range with 0.1 dB steps. Data may be added to the table for a period of time as short as 10 seconds or as long as 45 minutes.

At the end of the time interval that has been selected by the observer the values in the table are used to calculate the probability density function of the data for that particular time interval. The probability density may be typed out on a teleprinter for a hard copy, or plotted to illustrate the signal's behavior during the observing period. The table of signal strengths is also stored. Consequently, at a later time the tables may be combined and a probability density function for a much longer segment of time may be calculated. Each time a density function is

is calculated it is also possible to calculate cumulative probability distribution functions.

The use of two independent receiving systems allows equipment problems to be quickly identified in the data since the two receivers are operated with the same calibration. When variations appear in both receiving systems the chances are that the variations are real and not equipment malfunctions. The procedure of taking data in short runs of 10 to 20 minutes makes it possible to separate the periods of scintillation from the quiet periods before all the short runs are combined to form a long continuous data run.

3.4 PROPAGATION MEASUREMENTS AT REMOTE SITES

One of the significant accomplishments of a satellite communication system such as AEROSAT will be to provide communications to aircraft flying over remote regions of the earth. At present reliable worldwide coverage is not enjoyed. In order to insure reliable communications over wide expanses of the earth, propagation measurements of scintillation must be made at remote sites. The establishment of complete field stations for these measurements is not necessary. A much more sensible approach is to install a simple receiving station and relay the measurement back to a main test facility.

At the main facility the extensive data processing and analysis is performed, not only of the data collected at the remote site but also of the data collected at the main facility itself. Data from remote sites and the main site should be processed simultaneously. One of the important items that has to be established is whether scintillations are likely to be encountered simultaneously on an uplink and a downlink. By measuring two paths simultaneously the reliability of the ground-to-spacecraft-to-aircraft link can be evaluated. Consequently, by processing the main station's data in real-time a more realistic appreciation for the system problem will be achieved.

Eventually, tests should be run whereby a signal or set of signals is transmitted from the main station and then received by both the remote station and the main station. The remote station's data should be continually relayed back to the main station. An experimental test such as this will permit a complete characterization of the system link in real-time. Experimental set-ups such as this would very quickly allow evaluation of the several possible modulation techniques.

At present, a single remote test station is being considered for use in conjunction with the equipment at the DOT/TSC/Westford Propagation Facility. The remote station can be controlled by a VHF radio relay link to perform several different measurements. The results of these measurements are then relayed back to the Westford site where they will be analyzed concurrent with the measurements at the main site. The overall system concept is illustrated in Figure 3-5 and pictorially in Figure 3-6.

A functional block diagram of the remote measuring station is shown in Figure 3-7. Coded control signals are sent to the ATS-1 or ATS-3 satellites at 149.2 MHz and re-transmitted at 135.6 MHz to the remote station. The VHF signals are received by a 10-turn helix and decoded by the VHF receiver. The decoded instruction is sent to the Central Processing Unit (CPU) to initiate the the particular measurement desired, which is made using the L-band receiver. The measurement may, for example, consist of making one measurement or several (i.e. 100) measurements very quickly. The L-band receiver is a typical superheterodyne receiver. Provision is made for inserting a calibration signal in the antenna transmission line. In the beginning, a simple A/D converter will be used to encode the detected signal.

The measurements are processed and reformatted for use in modulating the VHF transmitter. The pulse code modulated (PCM) data is transmitted by the VHF transmitter to the ATS-1 or ATS-3 spacecraft. The VHF signal is retransmitted by the spacecraft to the VHF receiver at Westford. The retransmitted data at 135.6 MHz has the proper control coding such that the VHF receiver at the

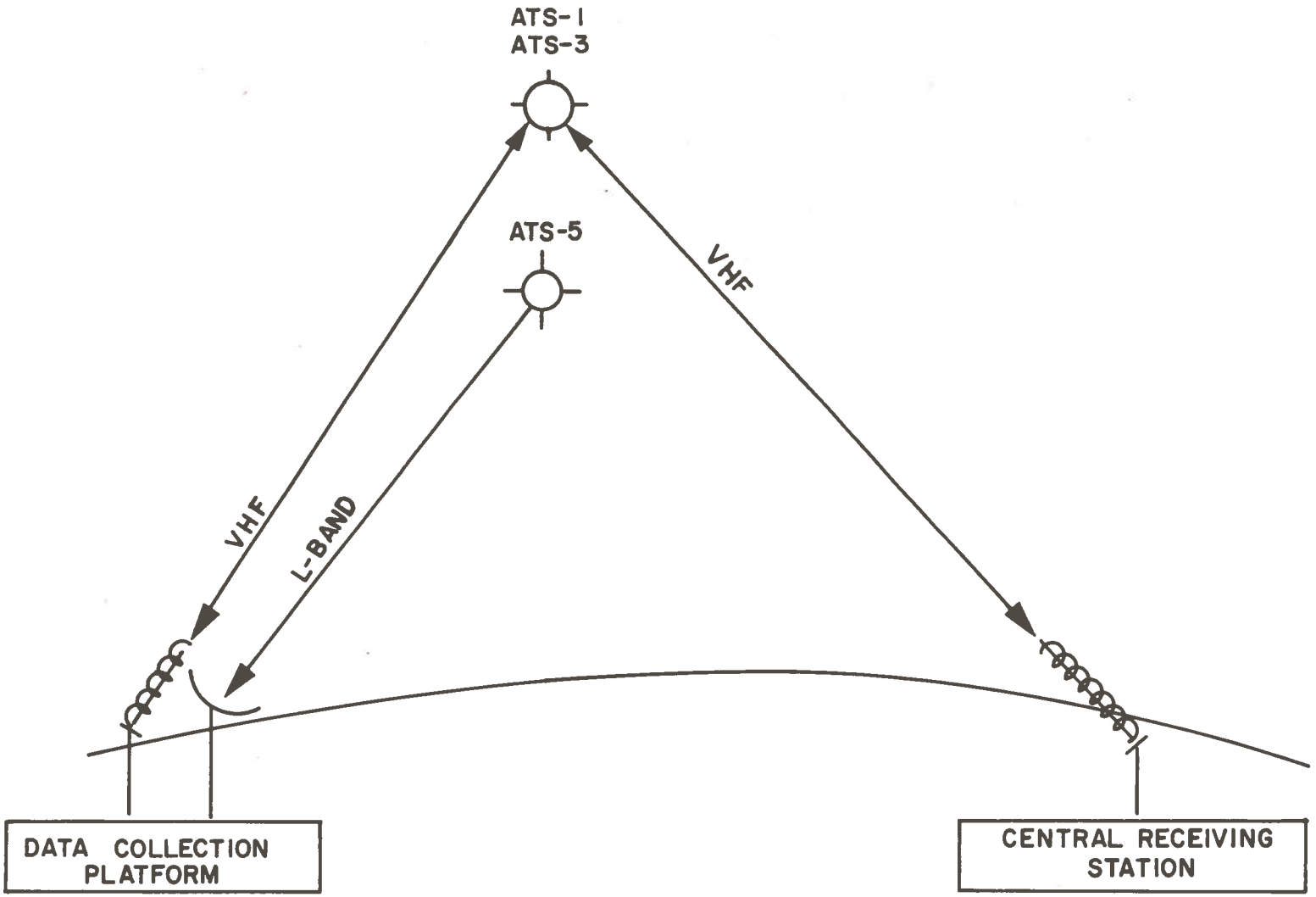

Figure 3-5. Overall System Concept of Remote Scintillation-Measurement Technique

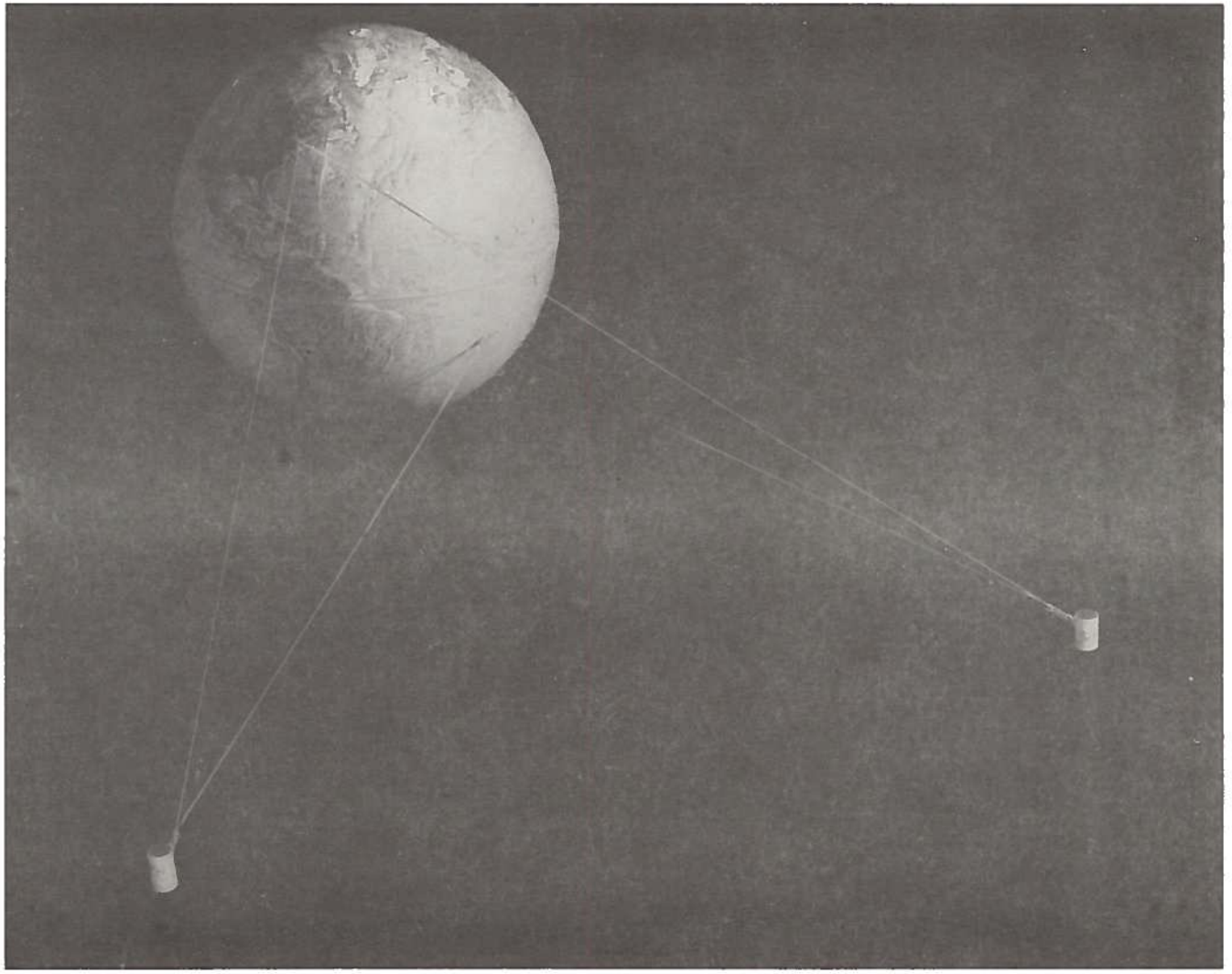

Figure 3-6. Pictorial Representation of Remote Scintillation-Measurement Technique Using ATS Satellites after General Electric (1971)

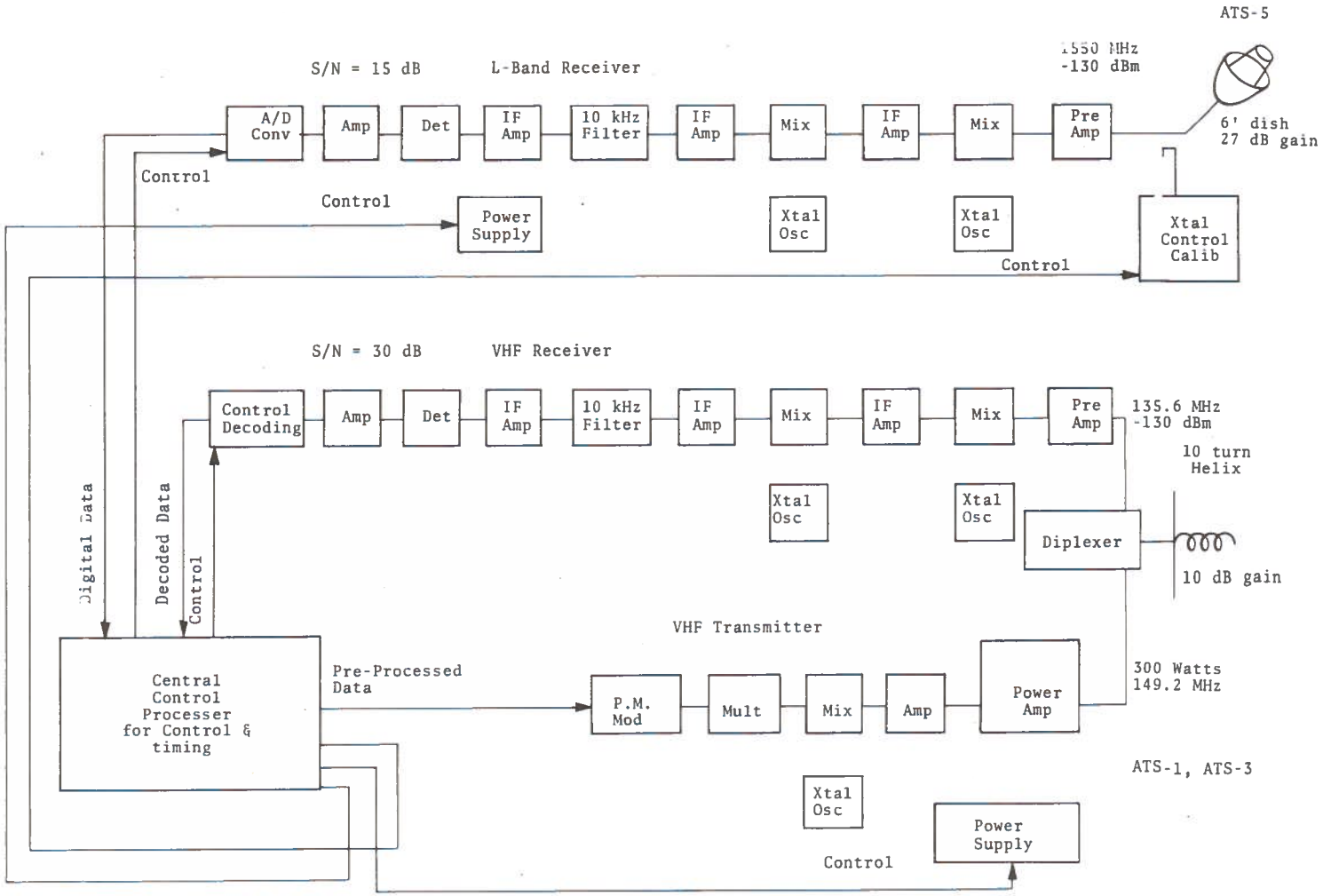

Figure 3-7. Functional Block Diagram of Remote-Measuring Platforms

remote site will ignore it while the VHF receiver at Westford will decode the data and route it to the data processing computer at Westford.

3.5 POSSIBLE REMOTE SITES

Table 3-1 lists possible remote sites to be considered in placing the remote data collection platform.

TABLE 3-1 SITES TO BE CONSIDERED FOR IONOSPHERIC SCINTILLATION-MEASUREMENT PROGRAM

Location & Site Name	Geomagnetic Lat. Long. (degrees*)	Geographic Lat. Long. (degrees)	Elevation Angle (degrees) ATS-5	Elevation Angle (degrees) ATS-F**	Remarks
Auroral Site: Goose Bay Labrador	63N 12E	53N 61W	14	27	Air Force Cambridge Research Laboratories
Alternate: Gander, Newfoundland	57N 20E	47N 54W	16	33	Canadian Department of Transport
Mid-Latitude Site: Westford, MA, U.S.A. Westford Test Facility	53N 2W	42.5W 71.3W	29	32	DOT Transportation Systems Center
Equatorial Site: Ancon, Peru (Near Lima) Ancon Satellite Tracking Station	0 8W	11.6S 77.1W	55	55	Geophysical Institute of Peru and NASA Goddard Space Flight Center
Near Equatorial Site: Hawaii	20N 90W	21N 156W	15	-	Univ. of Hawaii, Honolulu
Oakland CA	40N 60W	38N 122W	40	8	Coast Guard Station

*Figure 11-2 in Valley (1965), Handbook of Geophysics, Chapter 11, The Geomagnetic Field, McGraw-Hill, New York.
**Figure 3-61 in E. Clausen, T. Lerner, E. Rupp and H. Winter, (1970), PLACE Final Report, Report No. 6225-950002 on Contract No. NAS 5-21101, Bell Aerospace Co., Buffalo, NY.

3.6 IMPLEMENTATION STEPS FOR PROPOSED SCINTILLATION-MEASUREMENT PROGRAM

The initial steps of a scintillation measurement program are outlined below:

Task I-0: Measurement of CW Signal Incoherent Amplitude

Task I-1 Install and checkout station receiver equipment.

Task I-2 Initiate preliminary measurements to evaluate correct system performance.

Task I-3 Interface receiver equipment with data acquisition and data processing equipment.

Task I-4 Evaluate overall system operation including RF equipment, data acquisition equipment, data processing equipment and the data presentation equipment to be sure that the system is in optimal and final form.

Task I-5 Develop overall system calibration.

Task I-6 Initiate uniform and consistent data taking program.

Task I-7 Evaluate reliability of data acquisition system ulilizing systematic checks taken during data runs.

Task II-0: Measurement of CW Signal Coherent Amplitude

Task II-1 Check out the phase lock loop (PLL) characteristics using laboratory test equipment.

Task II-2 Install PLL electronics in existing RF electronic equipment.

Task II-3 Check out receiving equipment using PLL.

Task II-4 Initiate preliminary measurements.

Task II-5 Interface PLL receiver equipment with data acquisition, data processing, and data display equipment.

Task II-6 Evaluate overall system performance and establish system calibration to insure system is in optimal and final form.

Task II-7 Develop overall system calibration.

Task II-8 Initiate uniform and consistent data taking program.

Task II-9 Evaluate reliability of data taken with systematic checks taken during data runs.

Task III-0: Measurement of PM Signal with Tone Codes

Task III-1 Use the range tone configuration that is finally decided upon by the AEROSAT Joint Programs Office if possible. Determine availability of such equipment

as necessary considering engineering models, etc. as possible sources.

Task III-2 Acquire range tone equipment and make necessary arrangements with other parties involved.

Task III-4 Evaluate all equipment and their interfaces.

Task III-5 Establish overall system calibration.

Task III-6 Initiate data taking program.

Task III-7 Evaluate reliability of data acquisition system utilizing systematic checks taken during data runs.

In the course of designing this experimental program it was realized that the cost of fully implementing manned remote sites would be prohibitive. The L-band scintillation experiment program must therefore take advantage of unmanned automatic ground responders for the remote sites. A scheme of automatic ground responders using the ATS-1 and ATS-3 satellites at VHF (136 MHz) has been successfully carried out and reported by the General Electric Co. (General Electric, 1971) for several sites around the world.

Other considerations were that the data could be quickly reduced at all sites and be computer compatible. This flexibility of operation assures immediate data reduction so that recommendations could be forwarded to the designer's avionics systems operating with satellites.

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APPENDIX A: COORDINATE SYSTEMS FOR IDENTIFYING POINT ON OR ABOVE EARTH'S SURFACE

A.1 GEOGRAPHIC COORDINATE SYSTEM

Geographic coordinates are coordinates defining a point on the surface of the earth, usually by latitude and longitude. Terrestrial latitude is angular distance from the equator, measured northward or southward through 90° and labeled N or S to indicate the direction of measurement. Terrestrial longitude is the arc of a parallel, or the angle at the pole, between the prime meridian and the meridian of a point on the earth, measured eastward or westward from the prime meridian through 180°, and labeled E or W to indicate the direction of measurement.

Examples of geographic coordinate systems are given in Figures 1-1 and 1-2 and Figures A-1 and A-2.

A.2 GEOMAGNETIC COORDINATE SYSTEM

The geomagnetic coordinate system is a system of spherical coordinates based on the best fit of a centered dipole to the actual magnetic field of the earth. Figure A-1 is a view of the geomagnetic coordinates. The geomagnetic latitudes, with an idealized dipole having its north pole near Thule, Greenland, fail to represent the trajectory of energetic particles and from comparisons of observations at various sites, also fail to represent high-latitude scintillation observations (Allen, 1965; Aarons, Whitney, and Allen, 1971).

A.3 INVARIANT-LATITUDE COORDINATE SYSTEM

The coordinates of the invariant latitude system utilize a dipole field corrected by higher order terms which are obtained by earth's magnetic field. A figure showing the invariant latitude coordinate system for Epoch 1969.75 is presented in Figure A-2. This figure came from ASTRA (1971). Invariant coordinate systems are also discussed by Aarons, Whitney and Allen (1971).

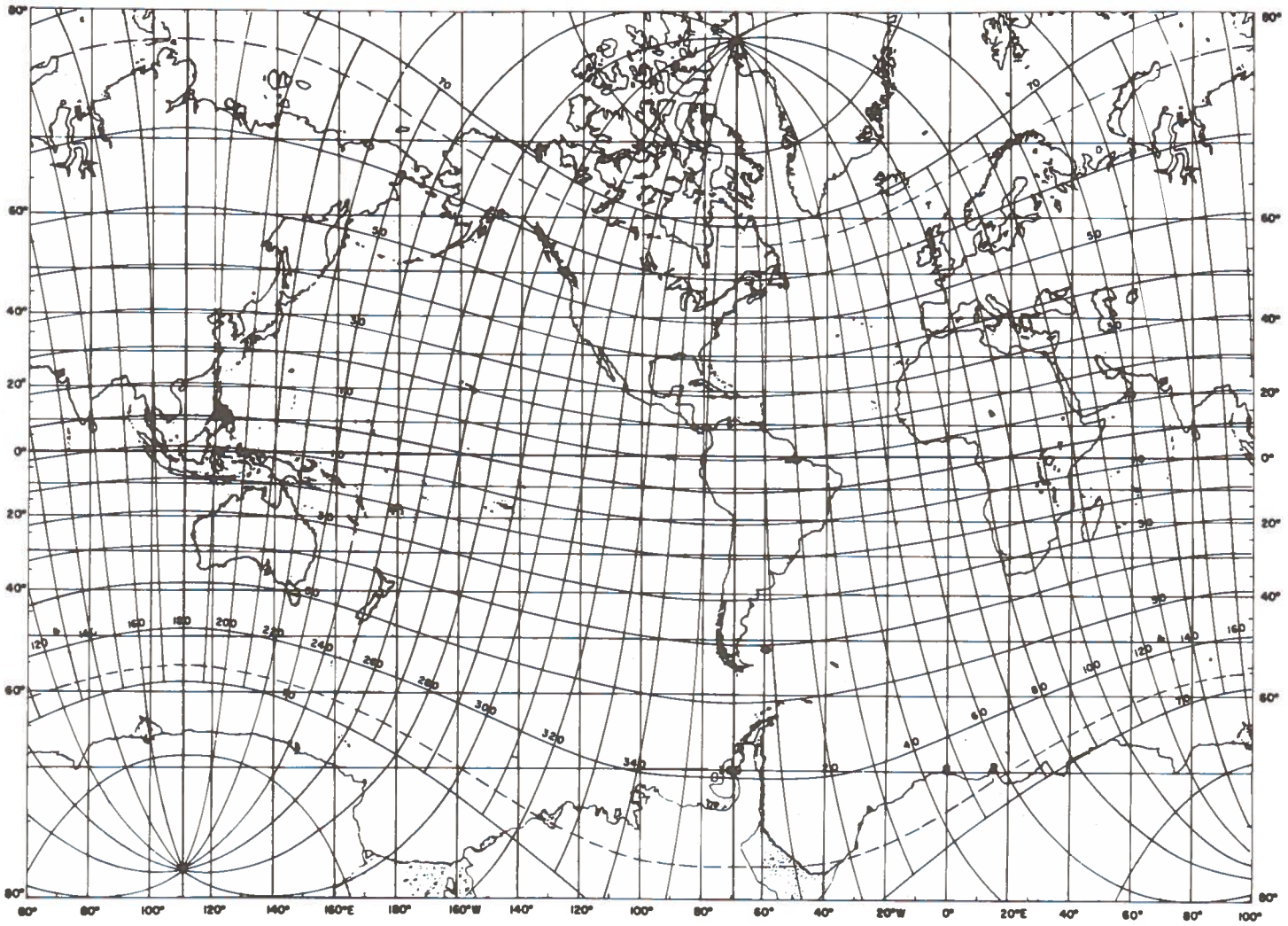

Figure A-1. Geomagnetic Coordinates (Centered Dipole Field) Superimposed on Geographic Mercator Projection, from Chernosky, Fougere, and Hutchinson (1965), After Vestine (1947)

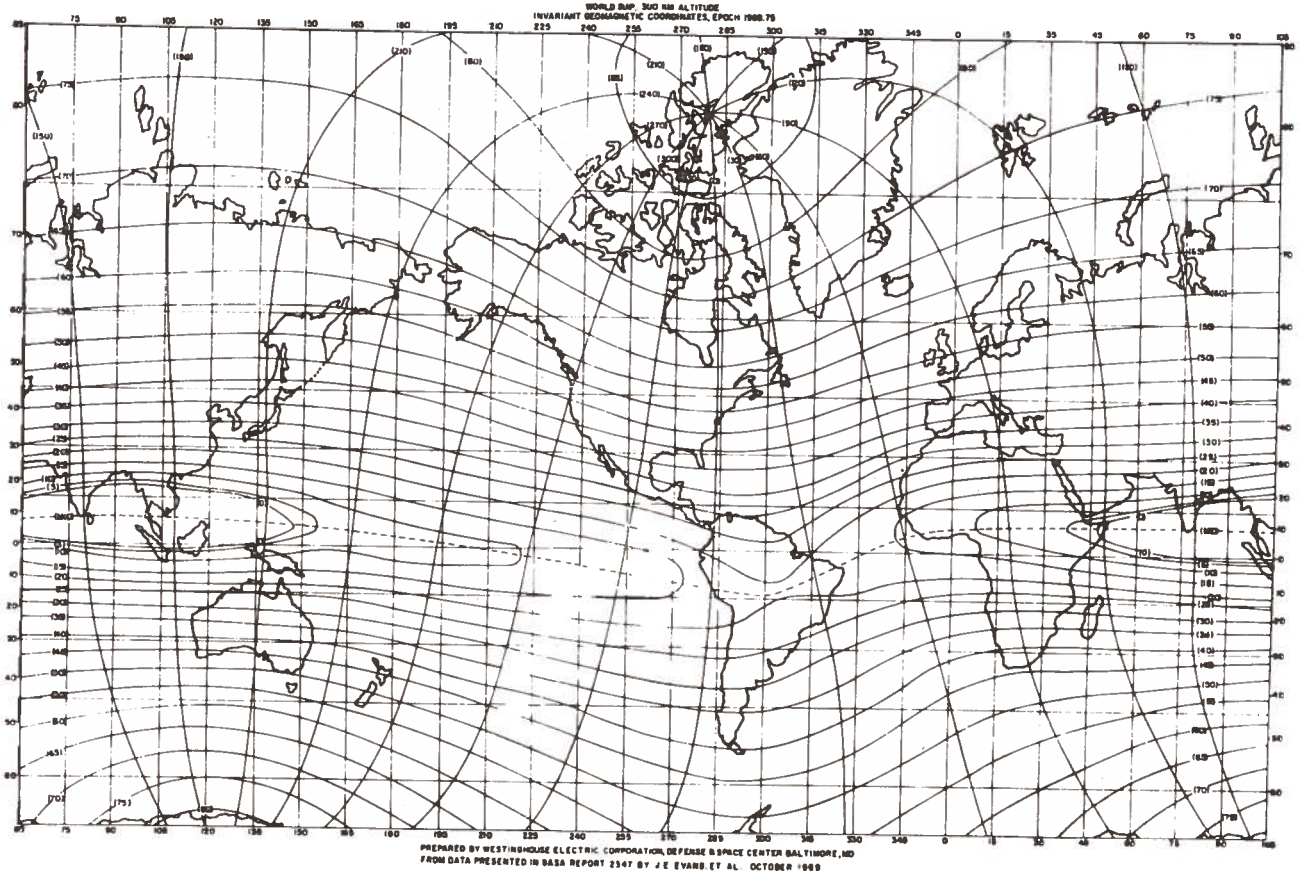

Figure A-2. World Map, 300KM Altitude, Invariant Coordinate System (Epoch, 1969.75)

A.4 SUMMARY

Invariant latitudes at a standard height of 350 km seem to best order the observations of scintillations. Geomagnetic latitudes, however, are still used on occassion because of the vast amount of material analyzed in this simpler coordinate system; geomagnetic coordinates are a good first approximation to most of the data. (Aarons, Whitney and Allen, 1971).

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APPENDIX B: IONOSPHERIC SCINTILLATION BIBLIOGRAPHY

B.1 BACKGROUND

This bibliography was compiled as a result of an exhaustive literature study to support analytically the investigation of current knowledge on scintillation phenomenon. The application of this data has been to supplement experimental programs producing scintillation data from satellite experiments. The basic material deals with radio wave propagation through the earth's atmosphere as it pertains to satellite communication with emphasis on ionospheric scintillation.

The accession number listing gives the following information: local accession number (in this case A-XXX, AERO-XXX etc.); authors (up to 80 characters); title of journal; volume number; inclusive page numbers; NASA, DDC or NTIS accession number (See Table B-1) if known; report number; contract number; corporate source; and location of corporate source.

The author index lists alphabetically all authors given, and as much of the title as space permitted. The negative key word list is an alphabetical listing of the letters and words. The index is an arrangement of the title of a document such that a key word is printed in the center of the page. In general, the shorter the title - the longer the work in the document. In a few instances some key words were added to titles to enrich the entry.

TABLE B-1 SOURCES OF TECHNICAL INFORMATION WITH THEIR ACCESSION-NUMBER SYMBOL OR ABBREVIATED TITLE

SYMBOL	SOURCE
AXX-XXXXX	International Aerospace Abstracts (IAA) Published semimonthly by American Institute of Aeronautics and Astronautics, 750 Third Avenue, New York, NY 10017* (See NASA, 1970 in Section B.6).
AD XXX-XXX ATI	Defense Documentation Center (DDC), Cameron Station, Alexandria, VA 22314 Channels and Forms for DDC Users to Order Copies of Technical Reports - July 1968. For Hard Copies, as follows.

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400 000 - 464 929	X	
464 930 - 489 999		X
490 000 - 492 999	X	
493 000 - 499 999		X
AD-600 000 Series		X

TABLE B-1 (CONTINUED)

SYMBOL	SOURCE
CC or ISI	Current Contents in such fields as: Engineering and Technology; Physical Sciences; A Service of the Institute for Scientific Information, 325 Chestnut St., Philadelphia, PA 19106. Original Article Tear Sheet Service (OATS).
CFSTI or PB XXX-XXX NTIS**	Clearinghouse for Federal Scientific and Technical Information** (CFSTI), National Bureau of Standards, Springfield, VA 22151.
NXX-XXXXX ORNXX-XXXXX#	Scientific and Technical Aerospace Reports Published semimonthly by: NASA Scientific and Technical Information Facility, P.O. Box 33, College Park, MD 20740. (See NASA, 1970 in Section B.6).
Sm. Inst.	Publications Distribution Section, Editorial and Publications Division, Smithsonian Institution, Washington, DC 20560.
SOD (see Supt. Docs.) Supt. Docs. or SOD	Superintendent of Documents, U.S. Government Printing Office Washington, DC 20402.
TIP (see AD)	
Univ. Microfilms	University Microfilms, 300 N. Nebb Road, Ann Arbor, MI 48106.
X00-00000	Unclassified report in the NASA Information System available to United States Government Agencies and United States Government Contractors only.
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*Note: The symbol # following the accession number indicates that the document is available in microfiche form.

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KENT,G.S.	(1966B)	A2189	SOME STUDIES OF NIGHTTIME F LAYER
KING,G.A.M.	(1971)	AERO10	THE IONOSPHERIC F-REGION STORMS
KISSEL,F.J.	(1970)	A979	L-BAND PERFORMANCE CHARACTERISTICS
KLASS,P.J.	(1971)	SATT162	AEROSAT SPECIFICATIONS DELINEATED
KLOBUCHAR,J.A.	(1969)	A1884	A SURVEY OF SCINTILLATION DATA AND
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KORFKER,W.L.	(1970)	A2737	STUDIES OF EQUATORIAL IONOSPHERIC
KOSTER,J.R.	(1960)	A776	SCINTILLATION, SPREAD F AND TRANSE
KOSTER,J.R.	(1963)	A2234	SOME MEASUREMENTS OF THE IRREGULAR
KOSTER,J.R.	(1966)	A2617	STUDIES OF THE EQUATORIAL IONOSPHE
KOSTER,J.R.	(1966A)	A2232	SOME STUDIES OF NIGHT-TIME F LAYER
KOSTER,J.R.	(1966B)	A2189	SOME STUDIES OF NIGHTTIME F LAYER
KOSTER,J.R.	(1967)	A2279	STUDIES OF THE EQUATORIAL IONOSPHE
KOSTER,J.R.	(1968A)	A2621	EQUATORIAL SCINTILLATIONS AT LEGON
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KRATZER,D.L.	(1970)	A983	L-BAND ATS-5/ORION/S.S. MANHATTAN
KUEGLER,G.K.	(1969)	A2708	EQUATORIAL SCINTILLATIONS EXPERIEN
KUEGLER,G.K.	(1970)	A2707	EQUATORIAL SCINTILLATIONS EXPERIEN
LABROUSSE,J.	(1971)	SATT154	GROUND ACQUISITION OF THE DIGITAL
LANSINGER,J.M.	(1967)	A1128	AURORAL ZONE RADIO STAR SCINTILLAT
LARSON,A.G.	(1967)	A2788	PRELIMINARY RESULTS ON THE WAVELEN
LAWRENCE,R.S.	(1964)	A220	A SURVEY OF IONOSPHERIC EFFECTS UP
LEADABRAND,R.L.	(1967)	A2788	PRELIMINARY RESULTS ON THE WAVELEN
LEINBACH,H.	(1970)	A2766	EFFECTS OF POLAR CAP ABSORPTION EV
LEVATICH,J.L.	(1967)	A2862	SCINTILLATION OF INTELSAT 1 VHF SA
LIETZKE,R.L.	(1969)	A2875	AN ANALYSIS OF TROPOSPHERIC AND IO
LITTLE,C.G.	(1951)	A461	DIFFRACTION THEORY OF THE SCINTILL
LITTLE,C.G.	(1962)	A1358	AN EXPERIMENTAL INVESTIGATION OF T
LITTLE,C.G.	(1964)	A220	A SURVEY OF IONOSPHERIC EFFECTS UP
LLEWELLYN,S.K.	(1971)	A2607	IONOSPHERIC REFRACTION CORRECTIONS
LYON,J.A.	(1961)	A2622	EQUATORIAL SPREAD F AT IBADAN, NIG
MALIK,C.	(1969)	A2819	A PROPOSED INDEX FOR MEASURING ION
MAWDSLEY,J.	(1970)	A2797	MID-LATITUDE RADIO-SATELLITE SCINT
MAYNARD,L.A.	(1971)	A2702	SIMULTANEOUS MEASUREMENTS OF IONOS
MCCLURE,J.P.	(1964)	AERO25	THE HEIGHT OF SCINTILLATION-PRODUC
MCCLURE,J.P.	(1970)	AERO1	IONOSPHERIC ELECTRON CONCENTRATION
MCELROY	(1970)	AERO38	THE F-2 LAYER AT MIDDLE LATITUDES
MEASUREMENTS + DATA	(1969)	MEAS33	MEASUREMENT OF UNCERTAINITY: HOME
MENG,C.I.	(1971)	AERO16	VERTICAL MOTIONS OF THE MIDLATITUD
MERCIER	(1962)	A775	DIFFRACTION BY A SCREEN CAUSING LA
MERRITT,R.P.	(1962)	A1358	AN EXPERIMENTAL INVESTIGATION OF T
MEYER-ARENDT,J.R.	(1965)	A406	OPTICAL SCINTILLATION; A SURVEY OF
MICHELINI,R.D.	(1971)	A2604	VLBI OBSERVATIONS OF RADIO EMISSIO
MIKKELSEN,I.S.	(1971)	A2830	KNEE OF TOTAL ELECTRON CONTENT AND
MILLMAN,G.H.	(1965)	A2848	OBSERVATIONS OF IONOSPHERIC SCINTI
MILLMAN,G.H.	(1966)	A2877	OBSERVATIONS ON IONOSPHERIC SCINTI

MILLMAN,G.H.	(1967)	A1130	A SURVEY OF TROPOSPHERIC, IONOSPHE
MILLMAN,G.H.	(1968)	A2876	IONOSPHERIC PHASE FLUCTUATIONS OF
MILLMAN,G.H.	(1969)	A2875	AN ANALYSIS OF TROPOSPHERIC AND IO
MILLMAN,G.H.	(1970)	A898	IONOSPHERIC PHASE FLUCTUATIONS OF
MILLMAN,G.H.	(1971)	A865	TROPOSPHERIC EFFECTS ON SPACE COMM
MOCEYUNAS,A.J.	(1965)	A2848	OBSERVATIONS OF IONOSPHERIC SCINTI
MOCEYUNAS,A.J.	(1966)	A2877	OBSERVATIONS ON IONOSPHERIC SCINTI
MOTT,J.M.	(1965)	A410	SATELLITE SCINTILLATIONS OBSERVED
MOZHAEV,A.M.	(1971)	AERO6	SPORADIC FORMATIONS IN THE F REGIO
MUELLER,E.J.	(1970)	SATT121	ABSORPTION EFFECTS ON VHF PROPAGAT
MUELLER,E.J.	(1970B)	A976	SCINTILLATION, POLARIZATION, AND M
MUELLER,E.J.	(1971)	A977	AERONAUTICAL SATELLITE SYSTEM CHAR
MULLEN,J.P.	(1963)	A412	GEOMAGNETIC CONTROL OF SATELLITE S
MULLEN,J.P.	(1964)	A411	THE STATISTICS OF SATELLITE SCINTI
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MULLEN,J.P.	(1965)	A2821	A SYNOPTIC STUDY OF SCINTILLATIONS
MULLEN,J.P.	(1969)	A1088	VHF ATMOSPHERIC STUDIES AND COMMUN
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NASA	(1970)	SATT89	ERC PHASE A ANALYTICAL REPORT NAVI
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NEWMAN,P.	(1966)	A1502	SPREAD-F AND ITS EFFECTS UPON RADI
NUPEN,W.	(1960)	A181	BIBLIOGRAPHY ON IONOSPHERIC PROPAG
NUPEN,W.	(1961)	A180	BIBLIOGRAPHY ON METEORIC RADIO WAV
NUPEN,W.	(1962)	A179	BIBLIOGRAPHY ON AURORAL RADIO WAVE
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ORHAUG,T.AA.	(1965)	A1199	SCINTILLATION OF DISCRETE RADIO SO
PAI,K.H.	(1969)	A2594	MEASUREMENTS OF TOTAL ELECTRON CON
PANDOLFINI,P.	(1971)	SATT158	SYSTEM FOR PHASE MEASUREMENT ON CO
PARK,C.G.	(1971)	AERO16	VERTICAL MOTIONS OF THE MIDLATITUD
PARKIN,I.A.	(1963)	A767	ON THE VARIATION OF RADIO STAR AND
PERELYGIN,V.P.	(1971)	AERO5	SMALL-SCALE INHOMEGENEITY OF THE F
PITTEWAY,M.L.V.	(1971)	AERO12	THE INTERPRETATION OF IONOSPHERIC
PLANTIER,M.	(1971)	SATT153	RESULTS OF EXPERIMENTS IN SIMULATI
POMALAZA,J.	(1970)	A2676	SCINTILLATION OBSERVATIONS AT ANCO
POMALAZA,J.	(1970)	A2841	STATISTICAL STUDY OF EQUATORIAL SC
POPE,J.H.	(1970)	A2679	OBSERVATIONS OF SIMULTANEOUS SCINT
POPE,J.H.	(1970)	A2766	EFFECTS OF POLAR CAP ABSORPTION EV
POPPOFF,I.G.	(1971)	A2700	FUNDAMENTALS OF AERONOMY: ELECTROM
RANGASWAMY,S.	(1971)	A1048	MEASUREMENT OF TOTAL ELECTRON CONT
RATCLIFFE,J.A.	(1950)	A768	DIFFRACTION FROM AN IRREGULAR SCRE
REID,G.C.	(1962)	A1358	AN EXPERIMENTAL INVESTIGATION OF T
RING,W.F.	(1971)	A616	DEPENDENCY OF SCINTILLATION FADING
RISHBETH,H.	(1971)	AERO13	MAPS OF THE VERTICAL F-LAYER DRIFT
RUESKAMP,W.	(1969)	A2731	STUDIES OF THE IONOSPHERE USING TR
RYSS,I.K.	(1971)	AERO6	SPORADIC FORMATIONS IN THE F REGIO
SADOBNIKOVA,R.S.	(1968)	AERO4	HIGH ALTITUDE VELOCITY DISTRIBUTIO
SAMBASIVA RAO,R.	(1969)	AERO21	THE HYSTERESIS VARIATION IN F-2 LA
SANDOVAL,J.	(1970)	A2676	SCINTILLATION OBSERVATIONS AT ANCO
SATOH,T.	(1970)	A2615	ATMOSPHERIC ATTENUATION AND SCINTI
SATOH,T.	(1970A)	A846	ATTENUATION AND SCINTILLATION OF M
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SCHMINDER,R.	(1969)	AERO20	ON SOME RELATIONSHIPS BETWEEN CORR

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SHEFTEL,V.M.	(1971)	AERO6	SPORADIC FORMATIONS IN THE F REGIO
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SKINNER,N.J.	(1961)	A2622	EQUATORIAL SPREAD F AT IBADAN, NIG
SKINNER,N.J.	(1971)	A2743	SCINTILLATION FADING OF SIGNALS IN
SKINNER,N.J.	(1971)	A2790	STUDIES OF F REGION IRREGULARITIES
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SMITH,F.L.,III	(1971)	A2742	ELECTRON CONTENT MEASUREMENTS AND
SPAANS,E.A.	(1970)	A983	L-BAND ATS-5/ORION/S.S. MANHATTAN
SPRENGER,K.	(1969)	AERO20	ON SOME RELATIONSHIPS BETWEEN CORR
STEIN,V.	(1970)	A831	THE INFLUENCE OF ATMOSPHERE ON THE
STEINBERG,J.L.	(1957)	A2703	TITLE UNKNOWN AT THIS TIME: SCINTI
STILTNER,E.	(1962)	A1358	AN EXPERIMENTAL INVESTIGATION OF T
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APPENDIX C: INFORMATION ON NASA ATS-5,-F, AND -G SATELLITES

The ATS-5 synchronous satellite, which is spinning, produces a return signal beam which sweeps across the Earth every 783 milliseconds. A signal reception window of approximately 50 milliseconds is available with each rotation.

The visibility of the ATS-5 satellite and the proposed ATS-F satellite can be determined by consulting Figure C-1 which was taken from Clausen, Lerner, Rupp, and Winter (1970). The contours of equal elevation angle are plotted on a geographic grid of the earth. More detailed orbit information can be obtained from the ATS Project Office at NASA Goddard Space Flight Center in Greenbelt, Maryland.

The L-band performance characteristics of the ATS-5 satellite are discussed in great length by Kissel (1970). He considers the parameters affecting propagation measurements such as: orbit geometry, polarization loss, off-beam center allowance, measurement techniques, earth station antenna pointing and earth station noise temperature.

The communications subsystems for the ATS-F and G satellites are considered in detail by Sabelhaus (1971). Various opportunities to use the ATS-F satellites on ionospheric research are considered by Hargreaves (1970) and Schmidt (1970).

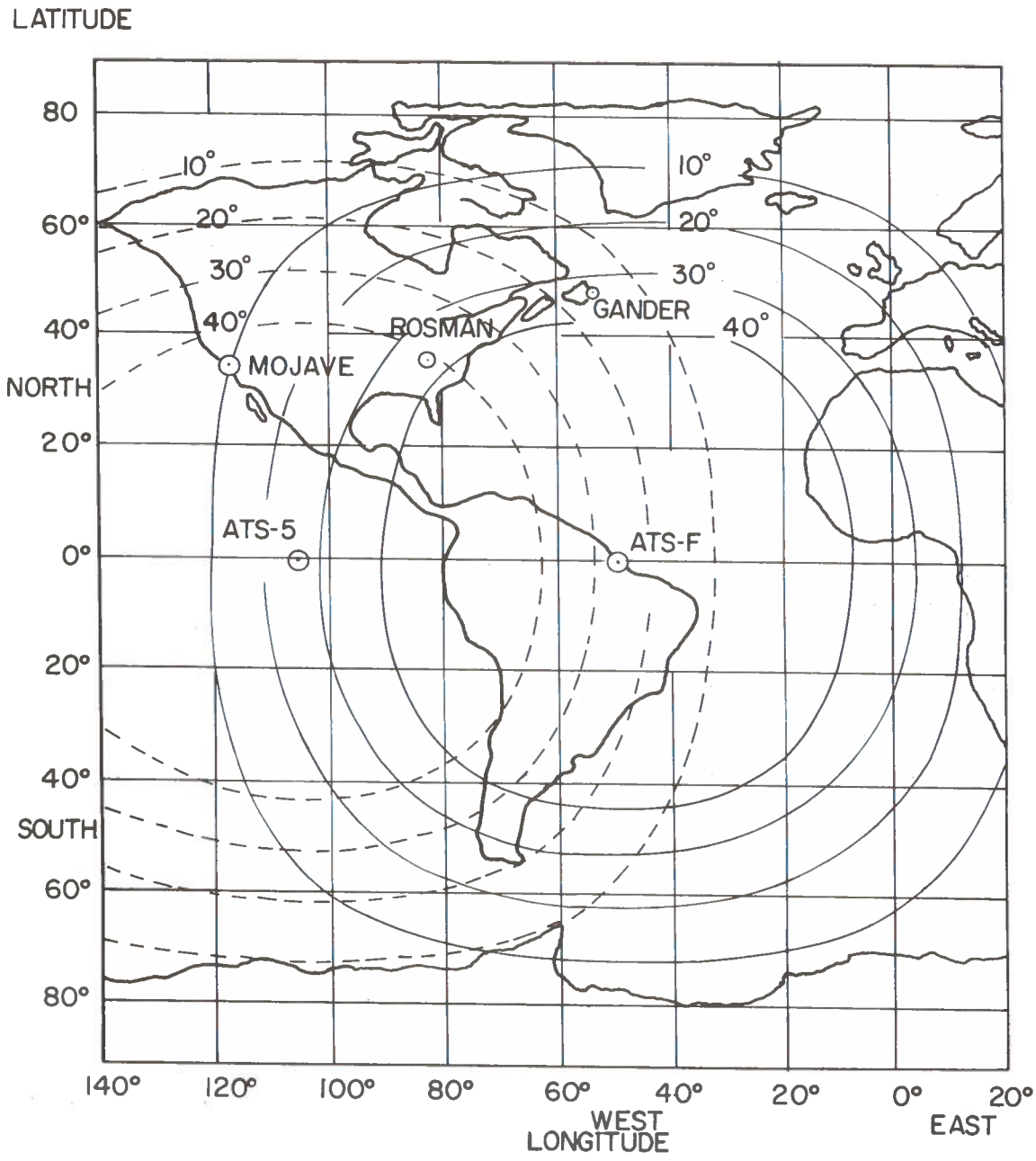

Figure C-1. Visibility Plot of ATS-5 and Proposed ATS-F Satellites. Contours are Lines of Equal Elevation Angle. After Clausen, Lerner, Rupp, and Winter, (1970, SATT-91)

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APPENDIX D: DISCUSSION OF RELEVANT STATISTICAL INFORMATION

D.1 PROBABILITY DENSITY FUNCTION

The probability density function for random data describes the probability that the data will assume a value within some defined range at any instant of time. Consider the sample time history record x(t) illustrated in Figure D-1. The probability that x(t) assumes a value within the range x and (x +Δx) may be

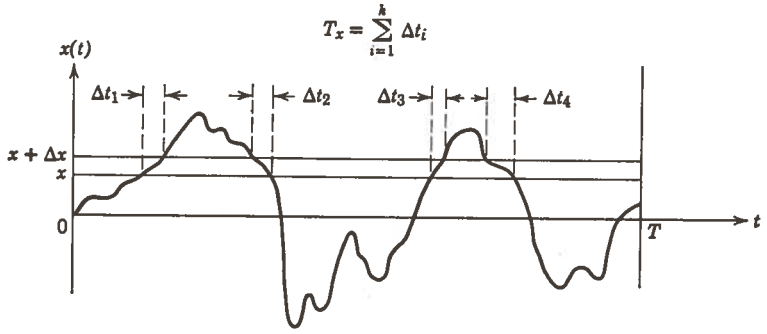

Figure D-1. Probability Measurement

obtained by taking the ratio of T_x/T, where T_x is the total amount of time that x(t) falls inside the range (x, x + Δx) during an observation time T. This ratio will approach an exact probability description as T approaches infinity. In equation form,

$$\text{Prob}\left[x < x(t) \leq x \pm \Delta x\right] = \lim_{T\to\infty} \frac{T_x}{T} \qquad \text{(D-1)}$$

For small Δx, a first-order probability density function p(x) can be defined as follows,

$$\text{Prob}\left[x < x(t) \leq x + \Delta x\right] \approx p(x)\Delta x \qquad \text{(D-2)}$$

More precisely,

$$p(x) = \lim_{\Delta x \to 0} \frac{\text{Prob}[x<x(t)<x+\Delta x]}{x} \lim_{\Delta x \to 0} \lim_{T \to \infty} \frac{1}{T}\left(\frac{T_x}{\Delta x}\right) \qquad \text{(D-3)}$$

The probability density function p(x) is always a real-valued, non-negative function. The above came from Bendat and Piersol (1966).

D.2 PROBABILITY DISTRIBUTION FUNCTION

The probability that the instanteous value x(t) is less than or equal to some value x is defined by P(x), which is equal to the integral of the probability density function from minus infinity to x. This function P(x) is known as the probability distribution function, and should not be confused with the probability density function p(x). Specifically

$$P(x) = \text{Prob}\ [x(t) \leq x] = \int_{-\infty}^{x} p(\xi)d\xi \qquad \text{(D-4)}$$

The distribution function P(x) is bounded by zero and one, since the probability of x(t) being less than $-\infty$ is clearly zero while the probability of x(t) being $+\infty$ is unity (a certainty). The probability that x(t) falls inside any range (x_1,x_2) is given by

$$P(x_2) - P(x_1) = \text{Prob}\left[x_1<x(t)\leq x_2\right] = \int_{x_1}^{x_2} p(x)\ dx \qquad \text{(D-5)}$$

D.3 SCINTILLATION INDEXES

Many workers have used signals from radio stars and satellites to record on strip charts the changes in amplitude known as scintillations. A scintillation index (S.I.) can indicate the depth of scintillation. Various indexes are described by Briggs and Parkin (1963) and by Bischoff and Chytil (1969). These indexes

vary as to whether the mean or rms value of the amplitude or power of the signal is used to indicate the fluctuations.

The Air Force Cambridge Research Laboratories (AFCRL) and the Joint Satellite Studies Group (JSSG) have adopted a standard method of measurement for ionospheric studies (Whitney, Malik, and Aarons, 1969). The aim of the studies was to describe the morphology of the irregularity structure. Therefore, a simple method had to be utilized to reduce the strip charts. The index adopted is defined as:

$$S.I.\ (\%) = \frac{P_{max} - P_{min}}{P_{max} + P_{min}} \times 100 \qquad \text{(D-6)}$$

where P_{max} is the third peak down from the maximum and P_{min} is the thrid minimum up from the lowest excursion in the given sample period. Various methods for estimating cumulative probability distributions of ionospheric scintillations are discussed in Aarons, Whitney and Allen (1971) and Whitney, Aarons and Seemann (1971) and Fremouw and Bates (1971). Basically, the AFCRL method utilizes both analog and digital recordings of the same phenomena. From this data standard curves are derived from which to estimate other scintillation data.

D.4 CHANNEL-DELAY SPREAD FUNCTION, $S(\tau)$

Two second order statistics of the received signal amplitude that are of particular importance in characterizing the effects of ionospheric scintillation on the received signal are the channel delay spread functions, $S(\tau)$, also known as the autocorrelation of the signal, and the channel Doppler spread function, $S(f)$, also known as a spectrum plot.

The quantity $S(\tau)$, the channel delay spread function, is a plot of received signal power as a function of the propagation time regardless of its spectral distribution. The multipath spread L which is a measure of the width of $S(\tau)$ and defined as

$$L = \left[\int S^2(\tau)\, d\tau\right]^{-1} , \qquad \text{(D-7)}$$

provides a rough measure of the spread in propagation times of the channel. This function is further described in Green (1968) and CSC (1971).

D.5 CHANNEL-DOPPLER SPREAD FUNCTION, S(f)

The analogous quantity S(f), the channel Doppler spread function, is a plot of received signal power as a function of frequency, regardless of the propagation time of arrival. The Doppler spread B, which is a measure of the width of S(f) and defined as

$$B = \left[\int S^2(f)\, df\right]^{-1} , \qquad \text{(D-8)}$$

provides a rough measure of the frequency interval over which the Doppler shifts of the ionospheric irregularities are spread. This index is further described along with measurement techniques in Green, (1968) and in CSC (1971).

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APPENDIX E: CHARACTERIZATION OF IONOSPHERIC SCINTILLATION

Ionospheric scintillation is produced by the presence of small-scale irregularities within the ionosphere which introduce random phase changes in the wave front of a traversing electromagnetic wave. As a result, the phase of a radio wave emitted by a geostationary satellite transmitter will not be constant over the ground but will form an irregular pattern. This pattern will, in general, appear to move as a consequence of ionospheric winds moving the irregularities and also because of the motion of a mobile receiving platform. The result is that the phase and amplitude of the received signal will appear to fluctuate or scintillate.

The global morphology and the worldwide behavior of average VHF-UHF scintillation has been reviewed by Aarons, Whitney and Allen (1971) and by Fremouw and Bates (1971). According to Aarons, Whitney and Allen two areas of the globe are particularly troubled by scintillation: subauroral to polar latitudes and a belt surrounding the geomagnetic equator. Experience with NASA tracking stations has borne this out.

The radio-frequency dependence of the amplitude variations is helpful in determining the cause of the scintillations. For instance, if turbulence in the troposphere is responsible, then the scintillation magnitude should be nearly independent of frequency (Yokoi, Yamada and Satoh, 1970). On the other hand, if turbulence in the ionospheric plasma is the cause, then the magnitudes should scale in the range between frequency independence and variations proportional to the wavelength squared. The latter relationship should hold for weak scattering in a "nearby" thin plasma layer (Salpeter, 1967; Lovelace, 1970). As the scintillation becomes stronger, the magnitude should approach frequency independence.

The frequency dependence of scintillation may be conveniently expressed in terms of a parameter η defined as follows: if the depth of scintillation is a smoothly varying function of frequency

over the range spanned by two receivers at frequencies f_1 and f_2, the relationship between a scintillation index, S, and the operating frequency may be represented by the relation

$$S = kf^{-\eta} \qquad \text{(E-1)}$$

where k is a constant, and η may be termed the 'spectral index' of the scintillations. If observations are made at two frequencies, this spectral index may be written

$$\eta = -\frac{\log(S_1/S_2)}{\log(f_1/f_2)} \qquad \text{(E-2)}$$

The negative sign in equation (E-2) simply implies that scintillation index increases with decreasing frequency. The same type of equation would of course hold for signal levels that are not expressed in a scintillation index (Aarons, Allen and Elkins, 1967).

The theoretical frequency dependence of the root-mean-square scintillations in the troposphere and ionosphere are given in Table E-1.

TABLE E-1 THEORETICAL FREQUENCY DEPENDENCE OF IONOSPHERIC AND TROPOSPHERIC SCINTILLATION, AFTER MILLMAN (1967)

Scintillation Effect	Troposphere	Ionosphere
Angle-of-Arrival	Independent of f	f^{-2}
Phase	Proportional to f	f^{-1}
Range	Independent of f	f^{-2}
Amplitude	Independent of f	f^{-2}

The theory of amplitude scintillation that has been most extensively developed is restricted to the "weak scattering" approximation, where the random phase deviations in the medium are required to be smaller than one radian. Briggs and Parkin (1963) have developed this aspect of scintillation theory and their results are summarized both by Evans (1968) and Aarons, Whitney and Allen (1971).

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