X-490-71-72

PREPRINT

NASA TM X- 65508

SUMMARY REPORT 1540 TO 1660 MHz PROPAGATION BETWEEN GEOSTATIONARY SATELLITES AND AIRCRAFT

C. E. WERNLEIN

NOVEMBER 1970

GSFC — GODDARD SPACE FLIGHT CENTER — GREENBELT, MARYLAND

SUMMARY REPORT

1540 to 1660 MHz PROPAGATION BETWEEN GEOSTATIONARY SATELLITES AND AIRCRAFT

C. E. WERNLEIN*

NOVEMBER 1970

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

* WESTINGHOUSE ELECTRIC CORP., FIELD ENGINEERING AND SUPPORT,
P.O. BOX 1693, BALTIMORE, MARYLAND 21203

SUMMARY REPORT

1540 to 1660 MHz PROPAGATION BETWEEN

GEOSTATIONARY SATELLITES AND AIRCRAFT

C. E. WERNLEIN*

NOVEMBER 1970

GODDARD SPACE FLIGHT CENTER

GREENBELT, MARYLAND

* WESTINGHOUSE ELECTRIC CORP., FIELD ENGINEERING AND SUPPORT,
P.O. BOX 1693, BALTIMORE, MARYLAND 21203

TABLE OF CONTENTS

ACKNOWLEDGEMENT

This report has been prepared to summarize the present state of knowledge regarding ionospheric characteristics at L-band frequencies (1550 MHz). It has been used to assist the U.S. panel member in the technical preparation for the ASTRA IV Panel Meeting in Montreal, January 1971. A number of corrections, suggestions and changes have been made as a result of review of the material by the U.S. technical preparation group. The U. S. members of this group are:

Mr. C. A. Petry
Aeronautical Radio Inc.

Mr. F. Clese
Aeronautical Radio Inc.

Mr. Roy Anderson
General Electric Co.

Mr. J. L. Lipscomb
DOT/Federal Aviation Administration

Mr. Charles A. Brooks
DOT/Federal Aviation Administration

Mr. Carlton Keys
DOT/Federal Aviation Administration

Mr. Harold Stein
DOT/Transportation Systems Center

Mr. Peter Engles
DOT/Transportation Systems Center

Mr. Daniel Brandel
DOT/Transportation Systems Center

Mr. Leo Keane
DOT/Transportation Systems Center

Mr. Larry McCabe
DOT/Transportation Systems Center

Mr. Herbert E. Whitney
Air Force Cambridge Research Lab.

Dr. Jules Aarons
Air Force Cambridge Research Lab.

Mr. James L. Baker
NASA/Goddard Space Flight Center

Mr. Tom Golden
NASA/Goddard Space Flight Center

Mr. Ed. Martin
COMSAT Corporation

Mr. Tom Calvit
COMSAT Corporation

Mr. Joe Pope
NOAA/Environmental Research Laboratories

While these persons are not directly responsible for the contents herein their comments and criticisms are sincerely appreciated.

SUMMARY REPORT

1540 MHz - 1660 MHz PROPAGATION BETWEEN
GEOSTATIONARY SATELLITES AND AIRCRAFT

1.0 INTRODUCTION

This report has been prepared to summarize the current state of knowledge, or lack thereof, regarding the propagation and system factors which influence the viability of an L-band (1540 - 1660 MHz) communication system between geostationary satellites and aircraft terminals. When possible, this report contains summaries of published works on L-band propagation and system factors. When no such work is available in open literature, an attempt is made to scale results obtained at other frequencies to this frequency band. As an aid to the reader, whenever data scaling is used to present other results, this report also contains a summary of the radio wave propagation theory on which the scaling is based.

To carry out a complete evaluation of L-band for aircraft to spacecraft communication, it is necessary to consider system factors other than propagation characteristics. These other factors such as aircraft antenna design technology, cost-benefits, spectrum utilization, and growth potential are beyond the scope of this summary report.

2.0 PROPAGATION FACTORS

The performance reliability of any satellite to aircraft link, which would normally be the weakest link in an aircraft communications/ position location system because of the limited EIRP from the spacecraft, is affected by the following propagation factors:

A. ABSORPTION

1) Ionospheric Absorption

2) Tropospheric Absorption

B. SCINTILLATION

1) Ionospheric Scintillation

2) Tropospheric Scintillation

C. OTHER FACTORS

1) Range Bias

2) Faraday Rotation

3) Earth Reflected Multipath

4) System Noise

2.1 ABSORPTION

2.1.1 Ionospheric Absorption

2.1.1.1 Theory of Ionospheric Absorption

The theory behind the absorption of radio waves as they traverse the ionosphere is that it is caused by energy losses resulting from the collision of electrons and neutral particles in the ionised medium.

Davies[1] gives the following relation for ionospheric absorption:

$$K = \frac{e^2}{2\epsilon_o m c} \cdot \frac{N_e \cdot \nu}{(\omega_H \pm \omega)^2 + \nu^2} \quad \text{nepers/meter}$$

The total attenuation suffered in propagation between a geostationary satellite and the subsatellite point is, therefore,

$$A \approx \frac{e^2}{2\epsilon_o mc} \int_0^{36,000\ \mathrm{km}} \frac{N_e(h)\,\nu(h)}{(\omega + \omega_H(h))^2 + \nu^2(h)}\, dh \quad \text{nepers}$$

The definitions of the symbols used in the above equations is as follows:

ω = operating frequency (radians/second)

ω_H = angular gyrofrequency

e = charge on an electron

K = absorption coefficient

ϵ_o = permitivity of space

m = mass of the electron

N_e = electron density per $(\text{meter})^3$

ν = collision frequency for electrons with heavy particles

h = height above the surface of the earth

$A(\omega)$ = absorption in nepers

c = speed of light

Since, under most conditions, $\omega_H \ll \omega$ and $\nu \ll \omega$ for frequencies between 1540 and 1660 MHz ionospheric absorption at these frequencies will be frequency dependent in the following manner :

$$A(\omega) \propto \frac{1}{\omega^2}$$

Typically, $\omega_H \approx 2\pi \times 10^6$ and $\nu < 4 \times 10^4$ at 100 km for auroral absorption so the inverse frequency square dependence of auroral absorption should hold for frequencies above about 60 megahertz.

2.1.1.2 Measurements at Other Frequencies

Most absorption data has been obtained with vertical sounding riometers at 27 MHz (2), and then scaled to the frequency of interest and the path length of interest (absorption, in db, is linearly related to path length through the absorbing medium). A summary of pertinent results for auroral absorption and polar cap absorption (PCA) is given in Reference 3. Multifrequency recordings of polar cap absorption and auroral absorption are reported in References 2 and 4. Reference 2 also describes the dependence of the magnitude of absorptive events on the season of the year, geomagnetic limits of the auroral zone, and the relation between magnetospheric activity and auroral absorption.

Hartz, Montbriand, and Vogan (5) have published a study of vertical auroral absorption at 30 MHz near 63° geomagnetic latitude. Vertical auroral absorption should be less than 3 db. The additional transit length through the D layer increases this margin by a factor of approximately 5.5 for an elevation angle of 10°, which is considered as the minimum angle of interest in the operation of a practical satellite-to-aircraft link between aircraft and geostationary satellites.

Polar cap absorptions of nearly 30 db have been observed (6) when the auroral D region was bombarded by high energy protons. PCA has been shown to be correlated with solar flares, and its frequency dependence has been shown to vary between $[1/f]^{1.0}$ and $[1/f]^{2.0}$ for frequencies <u>below</u> 50 MHz[4]. There is no published data on auroral absorption or PCA at frequencies as high as 1550 MHz.

2.1.1.3 Scaled Absorption

Using the $1/f^2$ dependence for auroral absorptive events and the $1/f^{1.5}$ dependence for PCA predicted by the Appleton-Hartree formula and ref. 4, respectively, and the necessary correction for a 10° elevation angle, the following values for auroral absorption and polar cap absorption are obtained at a frequency of 1550 MHz;

$$A_{auroral} = 3 \times \left(\frac{30}{1550}\right)^2 \times 5.5 = 3 \times \frac{1}{2670} \times 5.5 \quad 5 \times 10^{-3}$$

$\therefore A_{auroral}$ is negligible

$$A_{PCA} = 30 \times \left(\frac{30}{1550}\right)^{1.5} \times 5.5 = 30 \times .00265 \quad 10^{-1}$$

$\therefore A_{PCA}$ is negligible

2.1.2 <u>Tropospheric Attenuation</u>

2.1.2.1 Theory of Tropospheric Attenuation[7]

The absorption of radio waves in the troposphere is caused by the presence of free molecules and suspended particles, such as water drops. In a non-condensed atmosphere the absorption is basically caused by the interaction of the dipole moments of these particles with the propagating electric and magnetic field. This interaction causes partial transfer of field energy to kinetic energy of the particles, and a resulting attenuation of the wave. The most important interactions are those with the electric moment of water-vapor molecules and with the magnetic moment of the oxygen molecule.

Figure 1 shows Van Vleck's theoretical calculations of the anticipated absorption of electromagnetic waves by oxygen and uncondensed water vapor. The water-vapor curve was calculated by assuming a water-vapor density of 7.5 gm/m^3 at sea level at 20°C. This would be a typical value for a mid-latitude summer day. It is evident, from this figure, that at the frequency of interest (1550 MHz) oxygen absorption predominates over water vapor attenuation, and is on the order of 7×10^{-3} db/km.

Van Vleck's work has been used [8] to calculate total one-way oxygen absorption in the atmosphere at frequencies ranging from 300 MHz to 10,000 MHz. This data is presented in figure 2, which is also taken from Reference 8. It can be seen that tropospheric attenuation increases with frequency, and is on the order of 0.2 db at a 10° elevation angle and an operating frequency of 1000 MHz.

Scattering and absorption are the two physical mechanisms which cause the attenuation of radio waves propagating through a medium containing water droplets or precipitation. It has been shown[9] that ice cloud attenuation is more than two orders of magnitude less than water cloud attenuation, so this type of absorption may be considered negligible. Figure 3 shows the attenuation in db/km for frequencies above 5000 MHz. At frequencies less than this the attenuation in a water cloud should be completely negligible. Theory indicates that as long as the particle size

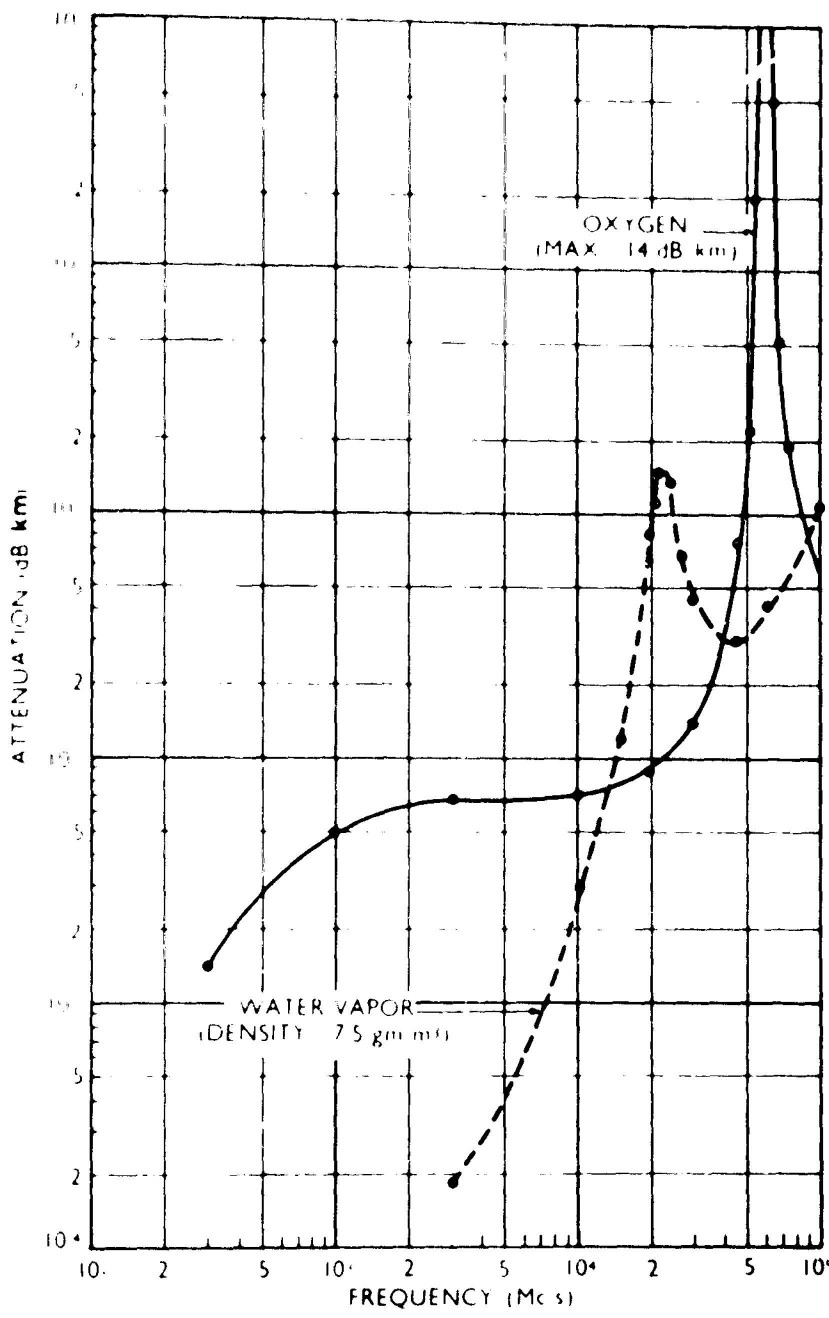

Figure 1. Tropospheric Attenuation of Oxygen and Uncondensed Water Vapor at Sea-Level for a Temperature of 20°C (After Van Vleck) (Ref. 8)

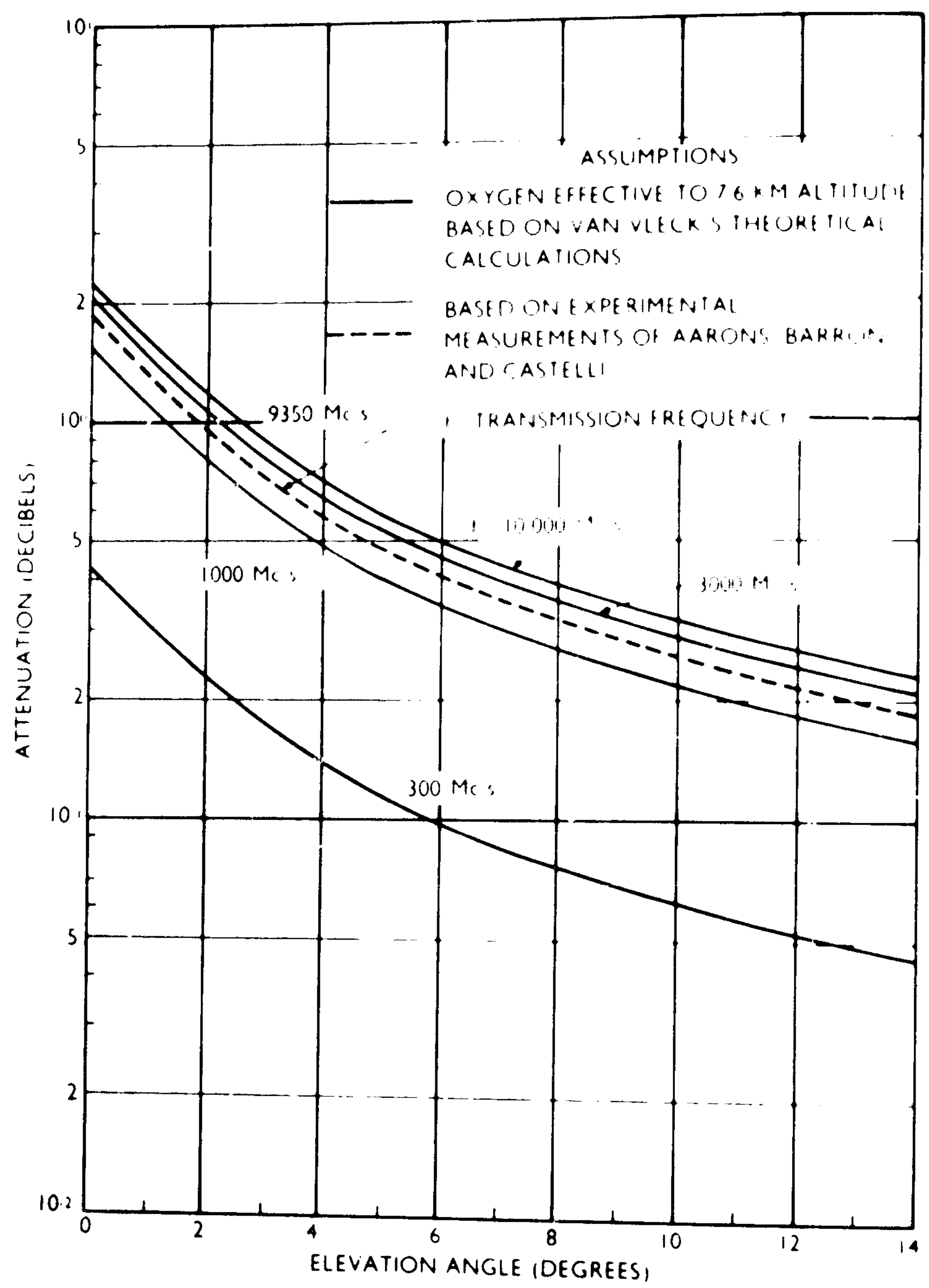

Figure 2. Attenuation in the Troposphere Due to Oxygen, One-Way Transmission Path (Based upon Van Vlecks, Aarons, Barrow and Castelli, Ref. 8)

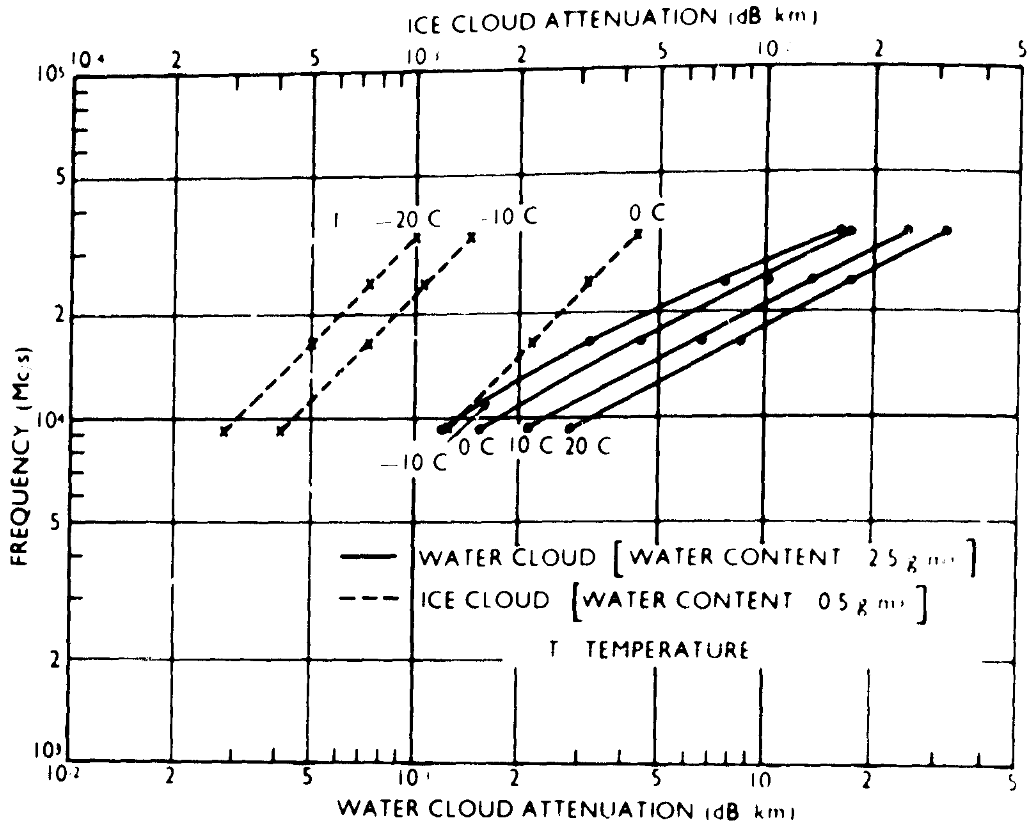

Figure 3. Attenuation by Water and Ice Clouds, One-Way Transmission Path (From Bean, After Gunn and East) (Ref. 9)

is small (< 1 mm), rain and water attenuation is the predominant mechanism causing absorption in the troposphere at all frequencies in the microwave range.

The one-way attenuation as a function of frequency is shown for rainfall rates from 0.25 mm/hr (drizzle) to 50 mm/hr in figure 4. It can be seen that at 1.5 GHz the rain attenuation constant at 18°C is much less than .01 db/km in an extremely heavy rain. Since the thickness of the path in which heavy rain is encountered is significantly less than 10 km, the worst effect of rain absorption will be much less than a tenth of a db signal loss.

2.1.2.2 Predicted Tropospheric Attenuation

Most of the authors who have done experimental studies of tropospheric attenuation have used line-of-sight earth-based measuring systems. The values given in the preceding paragraphs are in close correlation with theoretical values, as can be seen in Reference 9, or in References 10 and 11.

Since tropospheric attenuation is dependent on the moisture content of the air, even at frequencies as low as 1.5 GHz, the estimate of tropospheric attenuation given in this summary paper will assume 10 km thick layer of heavy rain and a worst case look angle (elevation angle) of 10 degrees. The total tropospheric attenuation would then be

10° elevation angle result = 0.25 db oxygen attenuation at sea level

Total Tropospheric Att. $<$ 0.25 db maximum at 1500 MHz at sea level

Total Tropospheric Attenuation Negligible at Normal Altitudes

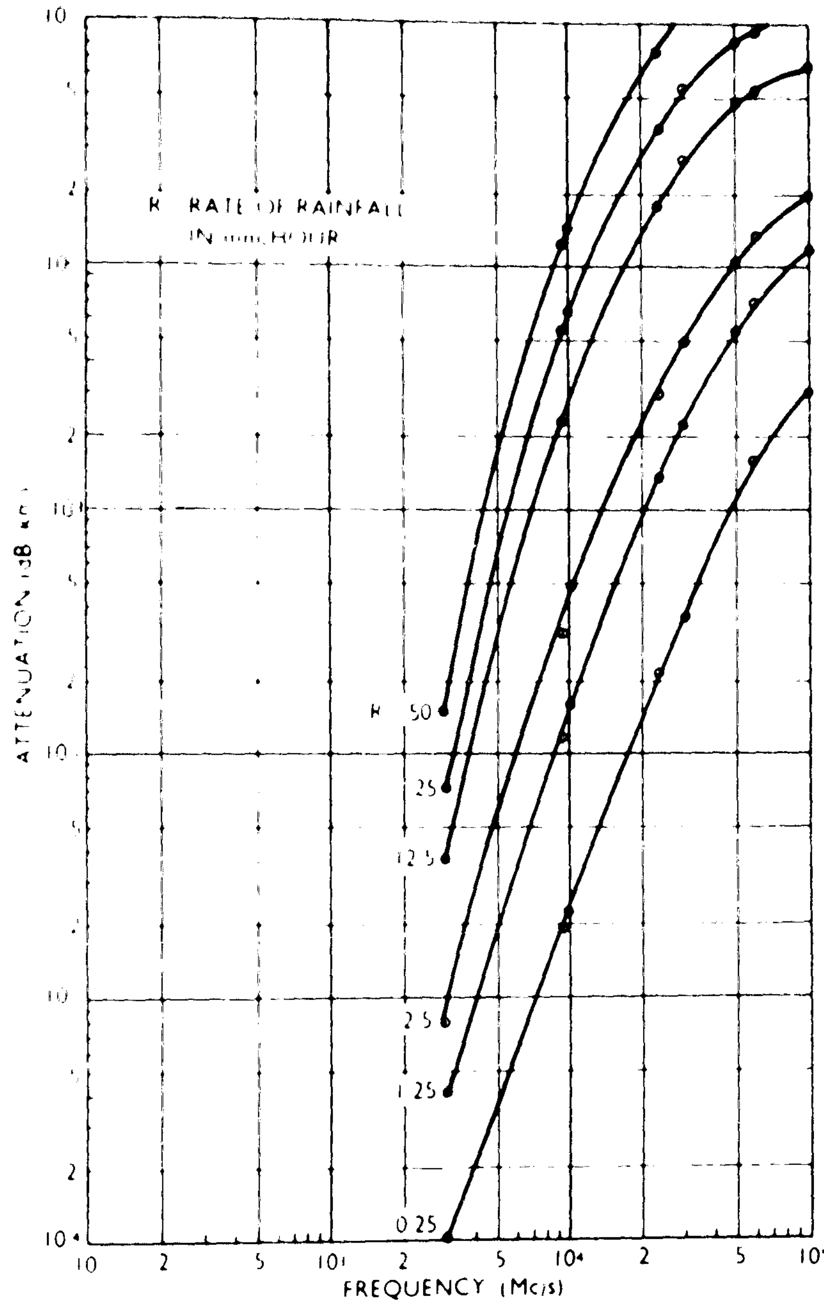

Figure 4. Attenuation as a Function of Frequency for Rainfalls of Various Intensities, Temperature 18°C, One-Way Transmission Path (From Kerr, After Ryde and Ryde) (Ref. 12)

In conclusion, a conservative estimate of tropospheric attenuation at 1.5 GHz on the propagation path between a geostationary satellite and a low altitude user aircraft would be 0.25 db. For commercial aircraft at normal altitudes of 30,000 ft., and above, this attenuation would be negligible. The rather high attenuations that are possible in very low level sea mist are not considered a factor in this system, since such mist usually is only very close to the surface, and aircraft using the system would always fly above it.

2.1.3 Overall Absorption Effects

Based upon the data and scaling of data used in the preceding sections, the expected values of ionospheric absorption are negligible for both auroral absorption (< 0.006 db) and for PCA (< 0.1 db). The expected values for tropospheric absorption are about 0.25 db maximum, exclusive of the nonrealistic case of the aircraft being actually in low level sea mist. Since the tropospheric and ionospheric absorption effects are not correlated with one another, and can both occur over quite long periods, it must be assumed they could occur simultaneously. Based upon the references used here, therefore, the overall allowance required for these effects is approximately 0.36 db. In the most common case of the aircraft being above all or most of the troposphere this number would fall to $<$ 0.1 db.

2.2 SCINTILLATIONS OF AMPLITUDE

2.2.1 Ionospheric Scintillations

2.2.1.1 Theory of Amplitude Scintillation [13]

When a radio wave travels through an irregular ionized medium it is scattered by the irregularities in electron density. The scatter results in a redistribution of the amplitude of the radio wave in a manner similar to the effects of a diffraction grating, and also causes irregular fluctuations in the apparent position of a radio source viewed through the ionosphere. These scattering processes are usually described as amplitude and angular scintillations.

Observations of scintillations have shown that the ionosphere contains irregularities in electron density which are elongated along the earth's magnetic field, and patches of these irregularities extend over wide geographic areas. It has been shown by various authors[14, 15] that such a distribution of irregularities can be treated as a random phase-changing screen. The thickness of the phase screen appears to be a function of invariant geomagnetic latitude.

If one assumes a plane wave to be incident on the ionosphere and that no absorption of the wave takes place, then immediately below the region containing the irregularities the surface of constant phase will be corrugated in an irregular manner.

To investigate the process by which signal level fluctuations at an earth station are generated from the phase modulation on this wavefront one must consider the angular spectrum of the wave. The angular spectrum of a phase-changing screen is analogous to the frequency spectrum of a phase-modulated carrier wave, the deviation in angle of a particular component being equivalent to the shift in frequency of a particular sideband with respect to the carrier. For the case of a phase-modulated carrier it is known that sidebands occur both at all frequencies present in the modulation and at sums, differences, and multiples of these frequencies. The relative magnitudes of these sidebands are dependent on the phase **deviation**. By analogy, Hewish[16] has shown that for the case of diffraction, without specifying the screen in any detail, that the total spread of the angular spectrum depends on the phase deviation as well as on the lateral scale of the phase variations measured across the wavefront.

As the wavefront leaves the screen, relative phases will be changed owing to the different directions of propagation within the angular spectrum. In this way, both amplitude and phase variations will be introduced into the interference pattern. The amplitude variations will grow in magnitude as the distance from the screen increases until the initial phase relation is completely destroyed. The width of the angular spectrum increases with the degree of **disturbance** of the screen, and the diffraction pattern becomes finer.

To estimate the smallest magnitude of the irregular component in electron density which is needed to produce scintillations, it is necessary to compute the variations needed to cause one radian phase changes in path length, at the operating frequency, from the "normal" electrical path length for waves emerging at places separated by about the Fresnel-zone radius.

The magnitude of the change in path length is given by

$$|\Delta \ell| = \frac{b}{\omega^2} \int_0^h N_e \, dh$$

Where: N_e is the electron density

$|\Delta \ell|$ is the magnitude of the path length difference from free space path length

h is any height above the phase screen

$b = \dfrac{e^2}{2\epsilon_0 m} \approx 1.6 \times 10^3$ (MKS)

ω is the radio wave angular frequency and where the integral is taken along the ray path

Using a typical integrated electron content of 10^{17} electrons/meter^2, and assuming a radio wave frequency of 1.5×10^9 Hz, one obtains a $|\Delta \ell| \simeq 1.8$ meters. Since $\lambda = 0.2$ meters, if one assumes a range Z to the irregularities of 500 km, the Fresnel-zone radius $\sqrt{Z\lambda}$ is approximately 300 meters.

For strong scintillation, this thin phase-screen theory of scintillation requires changes in phase path of about one radian over the Fresnel-zone distance, as mentioned above. This corresponds to a $d|\Delta \ell|$ of 0.2 meters, or $d\left[\int_0^h N_e \, dh\right]$ of approximately 11% in a radius of 300 meters. It would be expected that appreciable ionospheric amplitude scintillations would not occur at frequencies of 1.5 GHz and above.

2.2.1.2 Theoretical Derivation of Frequency Dependence

To determine how scintillation magnitudes vary with frequency, for a fixed phase screen, Booker's[17] approximation, which assumes an assembly of electron-density irregularities in the ionosphere, will be used.

Booker[17] shows that in passing through the ionosphere the mean square phase fluctuation suffered by the signal $\overline{(\Delta\varphi)^2}$ is given by

$$\overline{(\Delta\varphi)^2} = 2\pi^2 r_e^{\,2} \lambda^2 \sec\chi \, L \, \overline{(\Delta N)^2}$$

Where r_e is the classical radius of an electron (2.8×10^{-15} meters), λ is the wavelength of the radio wave (assumed to be small compared with the plasma wavelength for VHF and UHF) χ is the zenith angle, $\overline{(\Delta N)^2}$ is the mean square departure from mean of the electron density resulting from irregularities of electron density in the ionosphere, and L is the scale size of the irregularities.

The significance of the above, from the standpoint of this report, is the conclusion that $\overline{(\Delta \varphi)^2}$ is proportional to λ^2 and therefore proportional to $\frac{1}{f^2}$. However, this result depends on the assumption that the other quantities in the above expression are frequency independent.

To establish a quantitative measure of the amplitude scintillations caused by these phase scintillations, consider a wave of amplitude A which has small phase fluctuations imposed on it. At a distance from the screen which is large compared with the Fresnel radius for diffraction, these phase fluctuations cause small amplitude fluctuations which have random phase relationships with respect to the specular wave. If one writes the composite wave as $R(\phi) = A \cos \phi + \Delta A \cos(\varphi + \Delta\varphi)$ and averages over all possible $\Delta\varphi$, recognizing that φ and $\Delta\varphi$ are uncorrelated, the following result is obtained

$$\overline{\left(\frac{\Delta A}{A}\right)^2} = \overline{(\Delta \varphi)^2} \propto \frac{1}{f^2}$$

If the phase fluctuations are on the order of one radian or more, then a large fraction of the original wave is scattered. The mean-square fractional deviation predicted on the basis of this diffraction theory then reaches a limiting value.

Briggs and Parkin [18] developed a more general relation for scintillation index which includes the effect of the non-infinite distance from the screen to the point of observation and the effects of zenith angle on scintillation.

Their result was:

$$S \propto \frac{1}{f} \quad (\sec i)^{1/2} \quad \left[1 + \frac{\pi^2 r_o^4}{4 \lambda^2 z^2} \right] \; *$$

where:

S = scintillation index = $\left(\frac{\Delta P}{P} \right)$

P = average power received

ΔP = difference between maximum power and minimum power received

f = operating frequency

i = zenith angle at ionospheric layer intersection point

Z_1 = slant range from ground to irregularity layer

Z_2 = slant range from irregularity layer to satellite

$Z = Z_1 Z_2 / \left(Z_1 + Z_2 \right) \approx Z_1$

r_o = scale size of irregularities

* It should be noted that general agreement does not exist that $S \propto (\sec i)^{1/2}$ Other theories call for the use of other powers of (sec i) or for other functions of the zenith angle (shell theory). This disagreement causes difficulty in scaling for different zenith angles but do not affect the conclusions drawn here regarding frequency dependence.

To determine the effect of the zenith angle, i, two limiting cases can be discussed [19]. If λ/r_0^2 is very small, the observer is situated in the near zone for all zenith angles. S is then proportional to $Z, (\sec i)^{\frac{1}{2}}$. Since Z and sec i both increase with the zenith angle, there is a large increase in scintillation depth as the zenith angle increases. If λ/r_0^2 is larger, observations are made entirely in the far zone, S is independent of Z and only the $(\sec)^{\frac{1}{2}}$ factor remains. In a similar way, when comparing scintillation index at two wavelengths, it can be shown that the wavelength dependence is $S \propto \lambda^2$ in the near zone and $S \propto \lambda$ in the far zone.

These relations indicate that the frequency dependence of scintillation should be $\overline{\left(\frac{\Delta P}{P}\right)} \propto \frac{1}{f^x}$

where x lies between 1 and 2.

In both cases described above it is assumed that scintillation can be described by a thin phase screen. The difference in frequency dependence is probably caused by the assumption of small scintillations that was used in deriving a relationship between $\overline{(\Delta \phi)^2}$ and $\overline{\left(\frac{\Delta A}{A}\right)^2}$ in this detailed development of a mathematical model for scintillation. The measured frequency dependence of scintillation index, as well as its dependence on other ionospheric factors, will be discussed as part of the section on scintillation measurements.

2.2.1.3 **Measured Scintillation at Other Frequencies**

Most of the observations of amplitude scintillation on signals from orbiting and geostationary satellites have been made at frequencies ranging from 30 MHz to 136 MHz. An excellent summary of this work is contained in Reference 20. Using "scintillation index" as a measure of scintillation activity, it has been shown that this index is dependent on a number of geophysical parameters and also varies with frequency and the time at which measurements are made. Table 1 is a summary of the general dependence of scintillation index, as presently understood, for the auroral zone (above the scintillation boundary of about 55° invariant latitude at night, and about 75° invariant latitude near local noon), the mid-latitude zone, and the equatorial zone (within ± 20° of the geomagnetic equator).

TABLE 1. GENERAL DEPENDENCE OF SCINTILLATION INDEX

Parameter	Auroral Zone	Mid-Latitude Zone	Equatorial Zone
K-Index *	Increases with K	Increases for K ≥ 4	Decreases as K Inc.
Sun-Spot Number	?	Slight Increase With Sun Spot Numbers	Increase with SS Number
Latitude	Depends on Inv. Latitude	Depends on Inv. Lat.	Depends on Geomagnetic Lat.
Elevation Angle (i)		$(\sec. i)^{1/2}$	?
Season	?	Slight Equinox Peak	Equinox Peak
Diurnal	Night Peak Anytime at High K	Equinox Nighttime Peak Summer Night and Noon	Nocturnal
Frequency	Deep Fades $1/f$, Shallow Fades $1/f^2$	$1/f^2$	?

* Geomagnetic Activity

Unfortunately, the relations shown in Table 1 are qualitative, rather than quantitative. For instance, it is known that the peak scintillation magnitude increases as one moves from mid-latitudes toward either the scintillation boundary or the nighttime equaterial region, but there is no established numerical relation between peak scintillation index and the invariant latitude of the observing station.

A semi-empirical model for the world-wide distribution of $\overline{\left(\frac{\Delta N}{N}\right)^2}$ has been offered by Fremouw and Bates[21], who also suggest that the first order statistics of the received signal amplitude are Ricean. To date the assumption of Ricean statistics is not supported by evidence, but if it is proven to be correct under most scintillation fading conditions it would give the systems designer a method of predicting the margins needed for 99% and 99.9% availability from the margin needed at a lower service availability. The Air Force Cambridge Research Laboratory in a recent memorandum, suggested another way of characterizing the first order statistics of a scintillated wave from a geostationary satellite. Using their data on scintillation indices, plus recorded signal levels during selected intervals, Herbert Whitney[22] developed conditional distributions for received signal level given certain classes of scintillation indices. Then, assuming that the signal level distribution could be characterized by the scintillation index, Whitney developed signal level distributions for three sites and for two elevation angles at one site. Use of S.I., alone, to characterize the 15-minute statistics of signals received from geostationary satellites has yet to be shown to be valid or yield valid long term scintillation statistics, particularly at very high time availabilities. Reference 22 is a first attempt at using that propagation data now available in terms of percentage of the time a given S.I. was exceeded in generating the necessary distribution of the received signal. The AFCRL data used in this channel characterization was all recorded at a receiving frequency of 136 MHz.

Next, specific measurements of time availability or peak-to-peak scintillation made at various sites will be reviewed. The largest body of statistically significant data on signal level distributions was developed by the COMSAT Corporation from data acquired at Hamilton, Massachusetts. Data recording was done on the 136-MHz telemetry beacon signals from Intelsat satellites, and then merged into distributions for various periods of time. References 23 and 24 show that the excess signal power needed to overcome scintillation fading at Hamilton, Massachusetts, varied from 0.8 db to 4.8 db for 99% time availability at this sub-auroral site. The corresponding margin needed for 99.9% time availability ranged from 3 db to 10 db.

Aside from the COMSAT work, there is very little published data on signal level distributions caused by scintillation. Most of the other workers in the field of ionospheric radio wave propagation have used scintillation index to characterize fluctuations in received signal power, although there is some limited data on peak-to-peak variations in the auroral zone and at least one sample distribution for an equatorial site. Coates and Golden have reported that during a 3-year period (1965 through 67) on the average, 25 percent of the satellite data acquisition passes, recorded at College, Alaska[25] using a 136-MHz signal, had signal scintillations of 12 db or greater, peak-to-peak.* Some of these earlier data (references (25)and(47)) have limited usefulness in time analysis because peak scintillation did not persist throughout the entire pass.

*Mullen, et al[19] shows that 17% of the time peak-to-peak fades equal to or greater than 9.5 db occur in high latitude regions.

A limited sample of 136 MHz equatorial data, recorded at the University of Ghana on 11/11/69 and 11/12/69, as part of the NASA/GSFC World Wide Propagation Experiment[26] showed that for one percent of the time the signal level was 16-db below the median value. For 0.1 percent of the time the level was more than 26 db below the median.

The geomagnetic dependence of scintillation fading has been clearly demonstrated during the World Wide Propagation Experiment[26]. In auroral zones, scintillation may go on all day but its depth generally does not exceed 12 db[25]. In mid-latitude zones, scintillation has both a low probability of occurence and is rarely more than a few db, peak, at VHF. In contrast, equatorial scintillations are usually confined to a six hour period near local midnight, but the depth of scintillation frequently exceeds the dynamic range of the measuring equipment. These are, of course, generalizations. As pointed out on Table 1, S.I. is dependent on a number of geophysical parameters other than the geomagnetic latitude. Reference 27 contains a discussion of these dependencies, as well as the dependence of $\overline{(\Delta P/P)}$ on frequency.

Table 2 summarizes all available measured data on scintillation fading needed at 136 MHz,[22] except for the Ghana data discussed above. In some cases only scintillated data was processed, so that there are only four cases in which all the data was processed in arriving at 99% or 99.9% system availability.

TABLE 2. OBSERVED SCINTILLATION FADING

STATION	U.S. AF CAMBRIDGE RESEARCH LAB HAMILTON, MASS.										
GEOG. LAT	42°47'N										
GEOG. LONG	70°51'W										
GEOM. LAT	53°N										
SATELLITE	INTELSAT-I EARLY BIRD				INTELSAT-II CANARY BIRD						
SAT. LONG											
FREQ.	136 MHz				136 MHz						
ELEVATION°	25°				3[illegible]°						
DATE OF DATA	5-5-65 TO 6-10-65	6-10-65 TO 7-17-65	[illegible]-9-65 TO 8-8-65	5-5-65 TO 8-9-65	5-[illegible]-67 TO 6-10-67	6-10-67 TO 7-[illegible]-67	7-[illegible]-67 TO 8-10-67	8-[illegible]-67 TO 9-10-67	9-10-67 TO 10-10-67	[illegible] TO [illegible]-67	[illegible]-67 TO [illegible]-68
PROCESSED DATA-HOURS	21.2	50.7	9.5	2280	156	235	205	208	44[illegible]	[illegible]7	4050
DAILY SCIN DATA REDUCED	✓	✓	✓		✓	✓	✓	✓			
ALL DATA REDUCED				✓					✓	✓	✓
SUNSPOT #	*A 15	*A 15	*A 16	*B 15	*A 87	*A 67	*A 92	*A 107	*A 77	*A 86	*B 83
MAGNETIC AP.	*C 6	*C 10	*C 8	*D 8	*C 25	*C 12	*C 8	*C 3	*C 16	*D [illegible]	
95%	-1.8dB	-1.5dB	-1.5dB	-0.2dB	-3.[illegible]dB	-1.8dB	-[illegible]dB	-3.6dB	-1.8dB	-1.9dB	-[illegible]dB
99%	-3.2dB	-3.2dB	-3.6dB	-0.8dB	-6.6dB	-3.5dB	-[illegible]dB	-6.[illegible]dB	-3.9dB	-2.[illegible]dB	-[illegible].8dB
99.9%	-5.2dB	-7.8dB	-7.5dB	-3.0dB	*F	*F	-6.8dB	-6.8dB	-6.[illegible]dB	-3.6dB	*F
NOTES	1. AZIMUTH 126.7° 2. SUB-IONOSPHERIC COORDINATES 38°N LAT, 64°W LONG. 3. COLUMN 4 COMPOSIT OF COLUMNS 1,2 & 3 PLUS NON SCINTILLATION DATA 4. SCINTILLATION DATA LESS THAN 2% OF ALL DATA RECORDED 5. DATA REDUCED BY COMSAT				1. SCINTILLATION DATA 17% OF TOTAL RECORDED DATA 2. DATA REDUCED BY COMSAT						
REFERENCES	23				24						

*A - SUNSPOT NUMBER USED FROM MONTH WITH MOST NUMBER OF DATA [illegible] YEARLY [illegible] NUMBER PER [illegible] REPORT [illegible] 46 [illegible])
*B - SUNSPOT NUMBER IS AVERAGE NUMBER [illegible] PERIOD OF DATA [illegible] YEARLY RUNNING [illegible] NUMBER PER [illegible] REPORT [illegible] 46 [illegible])
*C - A_p NUMBER, MEAN VALUE OF DAILY READING FOR MONTH WITH MOST NUMBER OF DATA [illegible]
*D - A_p NUMBER, MEAN AVERAGE VALUE OF MONTHLY READING OVER PERIOD OF DATA [illegible]

2.2.1.4 Measurements Made at UHF

There is very little published data on the signal level distributions or S.I.'s at Earth stations, of satellite signals at frequencies above 136 MHz. Notable among the reported data is that contained in reports by Golden(28), Kissel(29), Maynard(30), and Pope(47). Pope concludes that the frequency dependence of scintillation fading is such that a scaling of the margins needed for 90% time availability, or more, is approximately 1/f, in db. This data is representative of high latitude (Alaska) frequency dependence.

Caution should be used in applying the 1/f scaling law. As Pope(43) and other authors(20), (27) have noted, the exponent in the frequency dependence law decreases as the depth of scintillation increases. It may be the weak scattering theory (diffraction) does not apply in the case of severe scintillations caused by a thick or multiple layer of irregularities in the F layer.

Golden's report(28) shows simultaneous 1700-MHz and 136-MHz recordings of AGC level made at College, Alaska. It is concluded that there is not enough scintillation on the 1700-MHz records to determine fade depths, while 136-MHz records show fade depths of up to 14 db. Golden concludes that there is visible evidence of the serious effect of the auroral ionosphere on VHF signals, and that the fading depth, in db, decreases at least inversely as the first power of frequency at maximum fade depths.

Kissel's [29] work contains a short section on measured propagation characteristics at 1550 MHz from the ATS-5 spacecraft. His data, which was not compared with VHF data, showed a maximum standard deviation (for any hour) of 0.37 db. This would indicate that scintillation depths exceeded for 1% of the time would be less than 0.87 db and those exceeded for 0.1% of the time would be less than 1.17 db if the logarithm of the received signal power were normally distributed. In summary, Maynard's data, Golden's report, and Kissel's report all indicate that mid-latitude scintillations at 1.5 GHz should be on the order of, or less than, 1.5 db for 99.9% availability.

Of particular interest are the measurements made between ATS-5 and the SS Manhattan reported in reference 31. Measurements were made between April 3rd and 24th, 1970 for a total of 62.3 hours with the vessel between 37°N 76.5°W and 73.5°N and 60°W with satellite elevation angles between 38° and 1.83° respectively. Apart from an fect attributed to multipath at high latitudes and very low elevation angles, it is stated that there were "small variations of signal strength (±2 db)". These variations would include tropospheric, and ionospheric scintillations and absorption, and include data down to lower elevation angles than are contemplated in the aircraft system. The directive antenna (normally a 3 ft. dish) used during these tests would eliminate multipath effects, except at very low elevations.

The problem with all these data sources is the limited sample size for the case of synchronous spacecraft. Kissel's data was taken over a 24-hour interval; Golden's shows "representative" AGC records totalling less than 5 minutes of pass time; and Maynard's was taken at 235 MHz instead of 1550 MHz. The data studied by Pope[43] was for 40 days of satellite observations (about 500 passes), but this was recorded from non-synchronous spacecraft. The largest number of L-band readings from synchronous spacecraft were those on the SS Manhattan cited above (62.3 hours). In the report, however, no correlation is shown between position and fading.

In summary, because there are not statistically significant measurements at these frequencies in open literature, emphasis is placed, therefore, in this summary report on data scaling from VHF.

Equatorial ionospheric scintillations on signals from geostationary satellites, based on a preliminary evaluation of 2.3 GHz data taken at Ascension Island and the Canary Islands, deserve a separate discussion. There appears to be some scintillation fading at this frequency in the equatorial regions, but its magnitude, diurnal and wavelength dependence, and frequency of occurrence are still under investigation. It may be possible that the screen model is not applicable to the equatorial ionosphere or that the fade depths, when fading does occur, is so deep at VHF that it exceeds the dynamic range of the measuring equipment. This topic is still under active investigation at NASA/GSFC.

2.2.2 Tropospheric Scintillation

When satellites are viewed at very low elevation angles, the ray path traverses the stratifications of the earth's refraction index profiles in much the same manner as the line-of-sight terrestrial paths used in point-to-point communications systems. Deep fading may result on such paths due to the synoptic meteorological patterns by defocusing the lobe pattern of the antenna and/or by multipath reflections. Such fading, having fade depths of 5 to 30 db or more, have been experienced on many line-of-sight microwave paths and is known to be essentially frequency independent. Using the sun as a source, scintillations at four microwave frequencies were observed for one year at the Manila Observatory, Philippine Islands[32]. Scintillation was a daily occurrence at sunrise at elevation angles from 1.5° to 7.0° (the observatory site cannot observe the sunrise below 1.5° because of a north-south mountain range due east of their antenna site). Scintillations were observed and time correlated between the four observed frequencies: 8800, 4995, 2695, and 1415 MHz.

It is possible for such fading to contaminate the ionospheric fading experienced on VHF satellite links when the elevation angle is in the order of 5 degrees or less. The exact break point has not been fully determined since it is difficult to identify and separate fading from the two sources.

VHF tests employing the ATS-1 satellite at an elevation angle of 5° experienced higher and more frequent fade depths than might have been expected from purely ionospheric irregularities at a mid-latitude station in Maryland.(33) There appeared to be minimal correlation of scintillation with spread-F and little or no correlation with the local magnetic activity index. It is suggested that this data might have contained a combination of tropospheric and ionospheric scintillation.

Since it is generally agreed that an aeronautical satellite system would not attempt to use angles below 10° elevation, and that the aircraft will generally be above the troposphere, it is not likely that this sort of signal fluctuation will be a problem. It is therefore not considered necessary to add tropospheric scintillation effects on propagation.

2.2.3 Overall Scintillation

From the above data it can be seen that at the frequencies of interest and operational elevation angles tropospheric scintillation is negligible, but that ionospheric scintillation might be a major cause of fading. The opinion is expressed above that, based upon the VHF measurements, and the scaling employed, a 1 to 2 db margin for this effect should be sufficient at L-band frequencies for 99% availability at most geomagnetic locations (assuming the 1/f relationship holds near the geomagnetic equator). Greater confidence is held with the 1/f scaling law in the high- and mid-latitude regions. This will be discussed further in a later section.

2.3 FARADAY ROTATION AND ANTENNA POSITIONING

2.3.1 Theory of Faraday Rotation

A linearly polarized electromagnetic wave may be thought of as the sum of two circularly polarized waves of equal magnitude but opposite sense.

The velocity of propagation of these two waves depends on the sense of rotation. Upon summation of the two waves, an elliptically polarized wave is produced whose principle axis has been rotated by an amount depending on the differences in phase of the two circularly polarized waves.

Davies[1] gives the following expression for the total Faraday rotation suffered by a linearly polarized wave propagating through the ionosphere:

$$\Omega = \frac{Q}{f^2} \int_{h_1}^{36,000\ \mathrm{km}} N_e B_e \cos\theta \sec i \, dh$$

where

Ω = Faraday rotation in radians

B_o = Magnetic field strength (in MKS units)

θ = Angle between propagation path and magnetic field

i = Zenith angle

Q = 2.97×10^{-2}

f = operating frequency in Hertz

N_e = electron density per$(\mathrm{meter})^3$

This expression is only valid at frequencies well above the plasma frequency and at angles, θ, which are significantly greater than 5° (quasi-longitudinal propagation).

Reference 7 shows calculated Faraday rotation for a magnetic field intensity of 0.62 gauss and electron density profiles typical of the daytime and nighttime ionosphere, at a frequency of 100 MHz as a function of elevation angle. The worst case calculation shows a daytime Faraday rotation of 7000° at an elevation angle of 10°. Scaling this to 1.5 GHz, one obtains

$$\left(\frac{100}{1500}\right)^2 (7000) = 31°$$

A 31° polarisation error on a linearly polarised receiving antenna reduces the received power to

$$\cos^2 31° = .735 = 73.5\%$$

of nominal, or by about 1.3 db if the transmit and receive antennas radiate in the same plane. In a mobile situation the two antennas will not have co-planar patterns, so losses will sometimes be greater than those calculated above. The best solution to Faraday rotation and antenna motion, in terms of system margin is to transmit and receive on circularly polarized antennas with the same sense of polarization, and avoid suffering any polarization losses. The circularly polarized antennas will suffer some polarization mismatch because they are only circular on boresight.

2.3.2 Measurements

Measurements have been limited to correlating changes in the plane of polarisation with the known diurnal variation in the integrated electron content of the ionosphere.[34, 35] It has been shown that Faraday rotation reaches a minimum near local midnight and a maximum near local noon.

An indication of the validity of assuming Faraday rotation varies as $1/f^2$ is the fact that polarization angle has been used to determine the attitude of synchronous satellites prior to the firing of the apogee motor. "Polang" uses two frequencies, 4 GHz and 136 MHz, to measure the planes of polarization of received signals from the spacecraft. The 4-GHz measurement is used to remove the ambiguity on the 136-MHz measurement by using $1/f^2$ scaling. The technique was used successfully, in real-time on ATS-4 and ATS-5, and in non-real time on Syncom and ATS-1 and ATS-3. The absolute accuracy of the

Faraday rotation predicted by theory is not known, but its frequency dependence and its relation to the integrated electron content have been established by these various measurements.

2.4 EARTH REFLECTED MULTIPATH

2.4.1 Theory of Earth Reflected Multipath

In an aircraft to spacecraft communication link for a service designed to operate on overwater paths, the most important multipath problem is that of earth (sea water) reflected signals. Its effect on a communication and position location system is two-fold. First, the earth reflected signal combines at the user antenna or at the spacecraft antenna with the direct path signal to cause amplitude fading. Secondly, any specular component of the multipath signals combines with the direct path signal to change the phase of the demodulated signal. This, in turn, causes an error in a range and range rate system which uses phase and rate of change of phase to determine range and range rate.

An excellent review of the theory of multipath on aircraft-spacecraft links is given in Reference 36. As is pointed out in the reference, the magnitude of multipath signals is a function of user antenna directivity, the polarization of the wave, and the geometry of the problem. The ratio of specular multipath to diffuse multipath is further complicated by its dependence on the surface roughness of the sea and the motion of the aircraft relative to that of the sea.

Based on radar backscatter measurements, it would appear that for smooth seas the specular and diffuse multipath signals are approximately the same at 136 MHz and 1500 MHz. This is in agreement with the theory that the refractive index of sea water is essentially independent of frequency at these frequencies. There is a limited amount of data for low elevation angles at frequencies between 225 MHz and 400 MHz,[37] but no measured results on multipath amplitudes or spectra at 1500 MHz have been published.

Reference 38 predicts fade lengths of a few seconds at 1600 MHz and elevation angles above 5°, and a spectral width for the multipath of less than 1 Hz at VHF or 1500 MHz. The most significant difference between 1500 MHz and 136 MHz is the ratio of specular multipath to non-coherent energy. Reflection theory[38] says that the ratio of specular power to scattered power should decrease much more rapidly with increasing sea state at 1550 MHz than it does at VHF, since this ratio is dependent on the ratio of terrain roughness to the wavelength of the electromagnetic wave.

Reference 37 also predicts that the incoherent spectra at VHF and 1500 MHz are essentially the same for the same geometry and antenna characteristics. This prediction is based on the assumption that the non-coherent spectral shape is determined by sea motion, or the rate of motion of scatterers, and the velocity of the aircraft relative to these scatterers. Again, there are no measurements to support this theory. As a result, the allocation of fade depth due to multipath cannot be made at this time without further knowledge. This further knowledge which is required involves the specific radiation patterns of the aircraft antenna system, since rejection of the undesired reflected energy depends critically upon this. In addition, further information from measurements is desirable to determine the relative amplitude distributions of the direct and reflected signals as a function of elevation angle and sea state.

It is also to be noted that techniques exist by which the communications (and ranging) channels can be made immune to the effects of multipath propagation. Certain well known spread spectrum techniques can be made to

reject the undesired reflected signal by as much as 30 db, thereby producing a system which is immune to these effects. Such systems in general require much wider than normal RF bandwidths; but the bandwidths required are quite possible within the available spectrum at the frequencies between 1540 and 1660 MHz. These systems have other advantages, such as per-mitting sharing of spectrum space by many users, and should, therefore, be considered serious candidate modulation methods for an aircraft communications/position location system.

2.5 RANGE BIAS

2.5.1 General

Range bias is a term used to describe the difference in time delay between a wave propagating through the ionosphere and troposphere from satellite to user and the theoretical propagation time, using the vacuum speed of light and straight line propagation. As a result of this difference in time delay, there is an error in the apparent range determined by time delay, or relative phase, measurements on radio signals and the true geometric range.

Although range bias does not affect required system margins per se, consideration of this important factor is given in this paper for the sake of completeness.

2.5.2 Theory of Range Bias

It can be shown[7] that the total range error is caused by three factors; ionospheric refraction, tropospheric refraction, and the difference in the velocity of a wave propagating through the troposphere and ionosphere from the free space velocity of propagation. The first two effects cause the ray path between the geostationary satellite and the user to be somewhat longer than a straight line, hence causing some propagation delay. The last effect is purely a delay which results from the fact that the propagation constants in these media are less than c.

2.5.2.1 Tropospheric Effects

The index of refraction in the troposphere is given by[9]

$$n = \frac{c}{V_p} = \sqrt{\epsilon_r \mu_r}$$

where:

c = speed of light

V_p = velocity of propagation in medium of index n

ϵ_r = relative dielectric constant of medium

μ_r = relative permeability of the medium

Since μ_r is essentially one in the troposphere and ϵ_r is close to one, a common index for the medium is the "refractivity" N, which is given by $N = 10^6 (n-1)$

The refractivity, which is independent of frequency, is related to the temperature, pressure, and water content of the troposphere by the expression[40]

$$N = \frac{77.6}{T} \left[P + \frac{4810\, e}{T} \right]$$

where T is temperature in degrees Kelvin, P is the atmospheric pressure in millibars, and e is the partial pressure of water vapor in millibars. Since it is a function of elevation, some model of the troposphere must be used in calculating N(h). Reference 42 shows there is good agreement between an assumed exponential model, using

$$N(h) = 370 \exp(-0.161h)$$

where h is in kilometers, and measurements taken using a radiosonde. As the surface refractivity varies, the constants in this exponential model of the troposphere will also vary.

The range bias introduced by the troposphere is given by

$$\Delta R_T = \int_0^{h_1} (n-1)\, ds$$

where h_1 is the top of the troposphere and ds is an element of path length. Next, for an elevation angle of ϕ

$$\Delta R_T = \frac{10^{-6}}{\sin \phi} \int_0^{h_1} N dh$$

Using the exponential model troposphere this becomes

$$R_T = \frac{370 \times 10^{-6}}{.161 \sin} \left[1 - \exp(-0.161\, h_1) \right]$$

For the model atmosphere $N \approx 0$ for $h > 30$ km. Using this value for h_1, the tropospheric range delay becomes

$$R_T = \frac{370 \times 10^{-6}}{0.161 \sin \phi}$$

or approximately 13 meters, independent of frequency, at a 10° elevation angle.

It has been shown[7] that at elevation angles above a few degrees the tropospheric range bias caused by refraction is negligible compared with the range bias introduced by propagation delay.

2.5.2.2 Ionospheric Effects

The index of refraction of the ionosphere is frequency dependent, hence the range bias introduced by it depends on the operating frequency. In the absence of an imposed magnetic field and of collision between particles, the refractive index, as given by the Appleton-Hartree formula[4], is

$$n^2 = 1 - \frac{80.5\, N_e(h)}{f^2} \qquad \text{hence} \qquad n = \sqrt{\frac{1 - 80.5\, N_e(h)}{f^2}}$$

where N_e is the electron density.

The range error due to a group velocity less than the speed of light is

$$\Delta R_I = \int_{h_1}^{36{,}000\ \text{km}} \left[\frac{1}{n(h)} - 1\right] ds$$

Using the approximations

$$n = \left[1 - \frac{80.5\, N_e(h)}{f^2}\right]^{1/2} \cong 1 - \frac{40.25\, N_e(h)}{f^2}$$

and

$$\frac{1}{n} = 1 + \frac{40.25\, N_e(h)}{f^2}$$

one obtains

$$\Delta R_I = \frac{40.25}{f^2} \int_{h_1}^{36{,}000\ \text{km}} N(h) \quad ds$$

The integral is the "integrated electron content" of the ionosphere, which also controls Faraday rotation.

It has been shown in reference 4D that if Θ is the elevation angle from the user to the spacecraft, then

$$\int_{h_1}^{36{,}000\ \text{km}} N_e ds = (1 - 0.928 \cos^2 \Theta)^{-1/2} \int_{h_1}^{36{,}000\ \text{km}} N_e \, dh$$

Using this relation, a frequency of 1.5×10^9 Hz, an integrated electron content of 10^{18} electrons/m^2, and a Θ of 10°, one obtains a range error, R_I of

$$\Delta R_I = \frac{40.25}{\sqrt{1 - .928 \times \cos^2 10°}} \times \frac{10^{18}}{2.25 \times 10^{18}} \approx 57 \text{ meters}$$

The highest value of integrated electron content normally observed in the ionosphere is on the order of 8×10^{17} electrons/meter^2[42]. On some days values as high as 4×10^{18} may be obtained. Maximum content is observed near local noon or in the early afternoon. The average value is approximately 2.4×10^{17} electrons/meter^2, although values as low as 1×10^{17} electrons/meter^2 have been measured.[42] In any case, the number given above should represent a worst case ionospheric range bias at L-band.

Reference 7 shows that the effects of ray bendings on ionospheric bias are negligible compared with the error caused by propagation at a velocity less than the speed-of-light.

2.5.2.3 Summary

In summary, the total range bias should not exceed 70 meters with the aircraft at low altitude. Therefore, it should not be necessary to do real time prediction and correction of range bias at 1500 MHz, since the total propagation error is small. For aircraft sensibly above the troposphere the range bias on the average would be about 57 meters near the peak of the sunspot cycle.

2.5.3 Measurements

The orbits for Syncom satellites were determined using a 7-GHz uplink frequency and a 1.7-GHz downlink frequency. Measurements were not made of the absolute accuracy of these range measurements, but at near synchronous altitudes the maximum range errors recorded were less than 60 meters[41]. It should be recognized that this is not a measure of absolute accuracy, but combines instrumentation noise errors with variations in propagation velocity at 1.7 GHz. On the basis of this information the above numbers are conservative.

As far as is known, there is no published data on direct measurement of range bias at L-band frequencies between geostationary satellites and earth stations.

Reference 31 contains data obtained at L-band between ATS-5 and the SS Manhatten. This data indicates that an accurate navigation system is feasible at L-band between a synchronous satellite and a ship. While it indicates quite good agreement between lines of position obtained by ranging from ATS-5 and the ship's position determined by other means, the report recommends additional experimental work under controlled conditions to assess the absolute accuracy of the L-band ranging system.

3.0 ESTIMATION OF REQUIRED SYSTEM PARAMETERS

Based upon the preceding numbers for time availability due to different causes, we may attempt to indicate the required overall margins needed to obtain specified system availability. It is to be clearly understood that all the limitations and reservations regarding scaling which have been stated earlier in this report apply to this overall excess power determination.

In addition, it is necessary to define what reliability is needed, and what is meant by reliability:

A) We will first define that for the purposes of this section, reliability means propagation reliability only. Overall system reliability includes such things as possible inability to operate in a satellite eclipse, and the effects of equipment reliability, but these are not considered here.

B) For our purposes, we will first consider the case of 99% propagation reliability.

C) We will define this reliability as the reliability of a single link between a satellite and an aircraft. In a system using two satellites, path diversity is possible for the communications links, but for these purposes only a single link is considered. Likewise in a ranging system useful data is obtained only when both of the two links operate, but here only a single link is considered.

D) We will assume that a system outage lasts for the time that the signal drops below the arbitrarily defined minimum, which is equal to the unfaded signal level reduced by the margin. In other words no account will be taken of the fact that in a data system loss of synchronization can sometimes last longer than the fade, whereas in a voice system one can often understand messages through short fades.

E) Although it is true that some phenomena (such as polar cap absorption) occur for a relatively small fraction of the year, when they do occur they can last for a quite long time. **Appropriate means of combining factors to establish a proper system margin depend on the correlation between the various propagation variables.**

Considering now the numbers developed above, we find the following:

A) Absorption (ionospheric and tropospheric) .... 0.3 db. (this may be reduced to $<$ 0.1 db if one considers only aircraft flying at about 30,000 ft. and above).

B) Scintillation. For most locations a total margin of 1 db appears adequate, assuming elevations of 10° and above. Since some of the data used to derive this number is based upon long recording periods, it is possible that during some flights, or even periods of a few days, a 1 db margin would give less than **99.9% reliability.** Attention is drawn to the possible limitaions of the 1/f scaling used to arrive at this 1 db. Since there will not be in general correlation between the instant of a scintillation fade and one due to multipath the use of this 1 db plus a suitable number for multipath gives some safety factor. Depending upon the actual multipath fading expected the proper (convolution) combination of scintillation with it __may__ result in little or no overall increase in margin requirements; since they both reach maximum depth for a small part of the time and are not correlated with one another. They will therefore rarely be at their greatest depth at the same instants in time.

C) Faraday rotation. If circularly polarized antennas are used, the importance of this phenomenon is negligible in effect total path loss.

D) Multipath propagation. This is dependent on antenna design and more knowledge of the characteristics of reflected signals from the sea at different sea states. It could range from a very small amount to as much as 10 db for small fractions of the time, depending on antenna design. No reliable estimate can be made here for the magnitude of this effect. It is to be noted that the choice of a suitable modulation technique (spread spectrum) can reduce its __effects__ to insignificance.

4.0 CONCLUSIONS AND RECOMMENDATIONS

Much of the derivation of numbers made here is based upon scaling which is speculative, and upon rather limited sources of data; consequently more quantitative data is desirable.

In considering system performance and availability, there are many factors involved. These include the definition of the threshold of operation (or the point below which the system becomes inoperative) and the statistical distribution of fading and the correlation of fading. The probability of error of the data channel will be determined by the coding techniques used and the higher order signal level statistics. More work is needed on the method of combining signal level effects such as multipath and scintillation.

5.0 LIST OF SYMBOLS

A = absorption, in nepers

c = free-space velocity of light, meters/second

H = geomagnetic field intensity

m = mass of an electron

B_o = geomagnetic flux density

h = distance along ray path from user, meters

$N_e(h)$ = electron density/meter^3 at height h

$N_+(h)$ = positive ion density/meter^3 at height h

ν = collision frequency of free electrons with heavy particles

ω = angular operating frequency ($2\pi f$)

ω_H = $\mu_o He/m$ = angular gyrofrequency of an electron

ω_N = $(Ne^2/\epsilon_o m)^{1/2}$ = angular plasma frequency

λ = wavelength at the operating frequency

$N(h)$ = refractivity at height h

ϵ_o = permitivity of free space

f = operating radio frequency

μ_o = permeability of free space

μ = real part of the refractive index

e_o = charge of an electron

$X = \omega_N^2/\omega^2$

$\propto$ = varies as

T = noise temperature

n = refractive index of ionosphere

θ = elevation angle of ray path, user to S/C

$i = 90° - \theta$ = zenith angle

a = transmission coefficient of the line preceeding the preamplifier.

6.0 REFERENCES

(1) Davies, K. L., Ionospheric Radio Wave Propagation, NBS Monograph 80, 1965.

(2) Hargreaves, J. K., "Auroral Absorption of HF Radio Waves in the Ionosphere: A Review of Results from the First Decade Riometry", Proceedings of IEEE, Vol. 57, No. 8, pp. 1348-1373, August 1969.

(3) Mueller, E. J., "Summary Report, Absorption Effects on VHF Propagation Between Geostationary Satellites and Aircraft", 1970.

(4) Bennett, S. M. and Rourke, S. M., "Effects on Non-Inverse-Frequency-Squared Absorption Events" in Propagation Factors in Space Communications, AGARD Conference Proceedings No. 3, pp. 261-272, 1967.

(5) Hartz, T. R., Montbriand, L. E. and Vogan, E. L., "A Study of Auroral Absorption at 30 MHz" Canadian Journal of Physics, Vol. 41, 1963.

(6) Ionospheric Radio Wave Absorption Events and Their Relationship to Solar Phenomena, Report UAG-R152, University of Alaska, Basler, R. P. and Owren, L., July 1964.

(7) Millman, G. H., "A Survey of Tropospheric, Ionospheric, and Extra-Terrestrial Effects on Radio Propagation Between the Earth and Space Vehicles", in Propagation Factors in Space Communications, AGARD Conference Proceedings No. 3, pp. 3-55, Technivision, 1967.

(8) Van Vleck, J. H., Propagation of Short Radio Waves, Radiation Laboratories Series 13, McGraw-Hill, 1951.

(9) Bean, B. R. and Dutton, E. J., RADIO METEOROLOGY, NBS Monograph 92, 1966.

(10) Artman, J. O. and Gordon, J. P., "Absorption of Microwaves by Oxygen in the Millimeter Wavelength Region", Physical Review, Vol. 96, No. 5, pp. 1237-1245, 1954.

(11) Birnbaum, G. and Maryott, A. A., "Microwave Absorption in the Compressed Oxygen", Physical Review, Vol. 99, 1955.

(12) Kerr, D. E., PROPAGATION OF SHORT RADIO WAVES, Radiation Laboratory Series 13, McGraw-Hill, 1951.

(13) Lawrence, R. S., Little, C. G., and Chivers, H.J.A., "A Study of Ionospheric Effects Upon Earth-Space Radio Propagation," Proceedings of the IEEE, Vol. 52, pp. 4-27, 1964.

(14) Booker, H. G., Ratcliffe, J. A., and Shinn, D. H., "Diffraction from an Irregular Screen with Applications to Ionospheric Problems", Phil. Trans. Royal Soc. (London) A, Vol. 225, pp. 579-609, 1954.

(15) Bowhill, S. A., "The Scattering of Radio Waves by an Extended Randomly Refractive Screen", J. Atmos. Terr. Physics, Vol. 20, pp. 9-18, 1961.

(16) Hewish, A., "The Diffraction of Galactic Radio Waves as a Method of Investigating the Irregular Structure of the Ionosphere", Proc. Royal Soc. (London) A, pp. 494-514, Vol. 214, 1952.

(17) Booker, H. G., "The Use of Radio Stars to Study Irregular Refraction of Radio Waves in the Ionosphere", Proc. IRE, Vol. 46, pp. 298-314, 1958.

(18) Briggs, B. H. and Parkins, I. A., "On the Variation of Radio Star and Satellite Scintillations with Zenith Angle", J. Atmospheric Terrest. Phys., 25, pp. 339-365, 1963.

(19) Aarons, J., Whitney, H. E., and Allen, R.S., "Global Morphology of Ionospheric Scintillations", Air Force Cambridge Research Laboratories, Bedford, Mass., Sept. 1970.

(20) Mullen, J. P., Whitney, H. E., Elkins, T. J. Allen, R. S., Aarons, J., Klobuchar, J. A., A Survey of Scintillation Data and its Relationship to Satellite Communications, Radio Astronomy Branch, Air Force Cambridge Research Laboratory, August 1969.

(21) Fremouw, E. J. and Bates, H. F., "A Proposed Empirical Model for Worldwide VHF-UHF Scintillations", Radio Physics Laboratory, Stanford Research Institute, 1970, To be published.

(22) Technical Memo, "Conversion of Statistics on Occurrence of Scintillation Indices to Cumulative Distribution of Signal Amplitudes", H. Whitney, AFCRL, 21 July 1970.

(23) Levatich, J. L. and Geli, T. J., "Scintillation of INTELSAT 1 VHF Satellite Signals", Tech. Memo. SDA-10-67, COMSAT Corporation, 1967.

(24) CCIR Document IV/1067 "Technical Characteristics of Communication-Satellite Service to Aircraft and Ships", 1970.

(25) Coates, R. J. and Golden, T. S., "Ionospheric Effects on Telemetry and Tracking Signals From Orbiting Spacecraft" GSFC Document X-520-68-76, March 1969.

(26) WORLDWIDE PROPAGATION EXPERIMENT, ATS PROJECT, NASA/GSFC, 1969-1970. Data reduced by Westinghouse Electric Corporation. Unpublished.

(27) Allen, R. S., "Morphology of Fading of Radio Waves Traversing the Auroral Ionosphere", IONOSPHERIC RADIO COMMUNICATIONS, pp. 294-315, Plenum Press, 1968.

(28) Golden, T. S., "Amplitude Effects of the Auroral Ionosphere on Satellite Telemetry at 136 and 170 MHz", NASA/GSFC Document X-520-70-109, 1970.

(29) Kissel, F. J., "L-Band Performance Characteristics of the ATS-5 Spacecraft", NASA Document X-731-70-51, 1970.

(30) Maynard, L., "High Latitude Performance of Military Satellite Communication Systems," NATO Defense Research Group Seminar on Space Communications.

(31) Hanas, Illikainen, Kratzer, and Spaans, Final Report L-Band ATS-5 —Orin— S. S. Manhattan Marine Navigation and Communication Experiment, June 1970, Contract NAS 12-2260.

(32) Badillo, Victor L., "Solar Microwave Scintillation" Radio Science, Volume 5, Number 6, pages 979-982, June 1970.

(33) Goodman, J. M. and Blundy, J. E., "Amplitude Scintillation at Randle Cliff Derived from ATS-1 Transmissions", Naval Research Laboratory, Washington, D.C. NRL Report 6829, March 17, 1969.

(34) Garriott, O. K., Smith, F. L. III, Yuen, P. C., "Observations of Ionospheric Electron Content Using a Geostationary Satellite", Planetary Space Science, Vol. 13, pp. 829-828, 1965.

(35) Barton, Thomas H., "Measurements of the Strength and Polarization of VHF Signals from a Synchronous Satellite", Proceedings of IEEE Conference on Aerospace and Navigational Electronics, 1965.

(36) Durrani, S. H. and Staras, H., "Multipath Problems in Communications Between Low-Altitude Spacecraft and Stationary Spacecraft", RCA Review, pp. 77-105, March 1968.

(37) Jordan, K. L., "Measurement of Multipath Effects in a Satellite-Aircraft UHF Link", Proceedings of IEEE, June 1967, pp. 1117-1118.

(38) CCIR Document IV/1073 "Multipath Effects in an Aircraft to Satellite Communication Link", 1969.

(39) Horner, Advances in Radio Research, p.121, Academic Press, 1964.

(40) Hirshman , E., "Tropospheric and Ionospheric Effects Upon Radio Frequency (VHF-SHF) Communication", NASA/GSFC Document X-731-67-89, January 1967.

(41) Syncom Projects Office, Goddard Space Flight Center, "Syncom Engineering Report, Volume I", NASA TR R-233, pp. 58-60, March 1966.

(42) Salah & Bowhill, "Collision Frequencies & Electron Temperatures in the Lower Ionosphere", Aeronomy Report No. 14, University of Illinois.

(43) "High Latitude Scintillation Effects on VHF and S-band Satellite Transmissions"; J. H. Pope and R. B. Fritz; National Oceanic and Atmospheric Administration, November, 1970.