HIGH LATITUDE IONOSPHERIC EFFECTS ON ERROR RATES OVER A GEOSTATIONARY SATELLITE-TO-EARTH TRANSMISSION PATH AT 136 MHZ

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A

THESIS

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ABSTRACT

Error rate data obtained for a high latitude transionospheric earth-space VHF communications channel are presented. Interpretation of these data with respect to certain ionospheric indicators has resulted in qualitative as well as quantitative correlation between the observed error rate data and F-region irregularities.

Amplitude scintillation has been found to be of the most critical importance to data channel efficiency and reliability. Indications of extra-terrestrial (i.e., solar) control have also been documented. Transionospheric propagation phenomena have been shown to give rise to adverse channel carrier/noise ratios, while waveform distortion and timing instability remain essentially unaffected.

Information on channel reliability during extreme geomagnetic storms has shown that fading margins in excess of 20 dB are necessary in order to maintain channel error rates of $10^{-5}$ or better at VHF over a transionospheric channel at high latitudes.
I would like to acknowledge the invaluable advice and recommendations of R. D. Hunsucker.

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1.1 Digital Information

Digital information differs from analog information in many important aspects. A typical example of analog information transfer is a standard broadcast radio receiver. Audio signals directly modulate a radio-frequency (RF) carrier which propagates via the medium from transmitter to the receiver. If digital encoding were utilized on this analog information system, the audio signal would be subdivided many times per second. The signal voltage per segment (assumed constant over the segment period) is then coded into a unique sequence of binary bits. The bits in proper order represent the analog signal to a close approximation though they bear no resemblance to that signal. The bit sequence then modulates the RF carrier and is propagated to the receiver. At the receiver the reverse process takes place. The bits are analyzed and the analog voltage they represent is reconstructed. The resulting analog signal is an approximate replica of the original.

Proper digital encoding of analog signals will result in an improvement in system information transfer when the propagating medium exhibits adverse effects such as additive noise, distortion, etc. The trade-off, however, is a resultant increase in the channel bandwidth necessary to transmit the information. The ever-increasing volume of computer communication which is digital by nature, coupled
with the inherent improvement in channel information transfer when
digital encoding is utilized for analog signals necessitates the
expansion of communication facilities to accommodate the load. This
in turn requires understanding of propagation phenomena, factors
which will critically effect not only system complexity, reliability
and efficiency, but system cost and feasibility as well.

1.2 Satellite Communications

One such method of digital information transfer is the utilization
of a geostationary satellite as an active repeater between terrestrial
ground stations. This mode of communication, utilizing the large
line-of-sight earth coverage at geostationary altitude (≈42,000 km),
makes possible communication paths between earth stations separated
by thousands of kilometers.

Certain drawbacks do exist for this mode of communication.
Limited power availability on the satellite requires that output
RF power for transmitting the received signal to earth station be
relatively low. This often necessitates the use of sensitive and
complex receiver systems to recover the transmitted signal.

While this is well within the present technology, it is often
economically unfeasible for the large volume of potential users.
Certain equipment cost reductions are, however, possible through
the use of the VHF (Very High Frequency) band instead of the UHF
(Ultra High Frequency) or SHF (Super High Frequency) bands. Use
of the HF (High Frequency) band is avoided due to relative
Ionospheric opacity, ray bending, and other propagation phenomena which interfere in the frequency range between 3 and about 20 MHz. Auroral absorption, polar cap absorption events (PCA's), and rapid signal fading represent additional first order effects on high latitude HF propagation [Hunsucker and Bates, 1969].

A table of the frequency allocations represented by the prefixes mentioned above is presented to avoid confusion.

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TABLE 1

Proper selection of the frequencies to be employed in the satellite-earth station system will facilitate cost reduction by making possible the use of less sophisticated equipment for recovery of the transmitted information. It is factors such as these which can serve to make possible the realization of the full potential of the geostationary satellite communications system.
1.3 Satellite Communication to High Latitudes

Geostationary satellite, hereafter referred to as satellite, communications utilizing high latitude earth stations involves a unique set of propagation phenomena, especially at VHF. In order to properly design communication systems of this type, it is important that the effect of the propagation medium (the high latitude ionosphere) on the digital data transmitted through it be studied carefully. In this endeavor, data have been accumulated for an earth-space path involving the ATS-1 satellite which is in a geostationary position near the equator at 149.2° W. Longitude; and an earth station located near College, Alaska, 64.9° N. Latitude and 147.7° W. Longitude. Figure 1 illustrates the geometry of the propagation path with respect to the ionosphere and pertinent sub-ionospheric earth projections.

The data acquired is in the form of Bit Error Rates (BER) as measured for a digital bit stream modulating the transionospheric signal at 135.6 MHz. A complete description of the data and test procedure will be discussed in later chapters.

1.4 Digital Data Parameters

There are two basic parameters involved with digital communication which critically affect the bit error rate. They are: pulse distortion, which (through degradation of the signal waveform) reduces the probability of proper recognition\(^1\), and loss of timing.

\(^1\)Due to the binary nature of the bit, a decision must be made upon its detection as to which level (either 1 or 0) the bit was when it was transmitted. Any degradation which alters the bit will produce ambiguity when the decision must be made and, therefore, increases the probability of receiver maldetection.
Figure 1
Earth/Ionosphere Ray Path Geometry
synchronization due to random variations in propagation time. Synchronization is necessary for the proper decoding of the digital bit stream. Pulse distortion may manifest itself in several ways; such as the result of dispersive effects on the pulse spectrum, and the ever present problem of additive noise. Low levels of pulse distortion and maintenance of time synchronization between transmitter and receiver are important factors in determining the BER for a given digital communication system. Propagation phenomena affecting either of these parameters will therefore be of critical importance in the design and implementation of such systems.

Analysis of the BER performance of mid-latitude earth station to satellite digital systems has been undertaken by Suguri et al. [1971] at SHF. Due to the marked differences in behavior between the mid-latitude ionosphere and the high-latitude ionosphere, the results of this work cannot be realistically applied to the earth-space path under investigation here. Extrapolation of SHF measurements to fit VHF situations is not valid when the complex frequency dependence exhibited by many of the propagation phenomena is considered.

Much work has also been done in determining the error mechanisms involved with digital data transmission. Theoretical error rates for a channel with additive Gaussian noise for different techniques of modulation/demodulation are well documented in works such as Guenther [1967]. The specific modulation/demodulation method employed for this earth-space communication experiment was Pulse Code Modulation (PCM) which employed Frequency Shift Keying (FSK) of the RF carrier
Included in the data analysis. More specific cases are examined by Conda [1965] who extended the work to non-coherent PCM-FSK data in the presence of atmospheric noise. Salaman [1971] includes the effect of earth noise environment on reception of digital data on an earth-space path. The results of this work are also included in the data analysis.

1.5 High Latitude Earth-Space Propagation Effects

Ionospheric effects upon earth-space propagation have been the subject of active research for many years. Many papers have dealt with specific factors involved with propagation through magnetolonic media. Two survey papers, Lawrence et al. [1964], and Millman [1967] provide information on most of the important aspects involved with earth-space communication. Those works dealing with high latitude effects are especially pertinent to this study. Unfortunately, the amount of work done in this area is small compared to the work involved with the mid-latitude ionosphere.

There are several phenomena associated with the high-latitude ionosphere which affect electromagnetic propagation traversing the ionized medium. Table 2 lists these effects (not necessarily in their order of importance).

For the operating frequency under investigation (135.6 MHz), the related tropospheric contributions to refraction, attenuation, distortion, etc. are negligible when compared to the ionospheric components.
For example, tropospheric refraction is small when compared to ionospheric refraction at radio frequencies, primarily a function of temperature, pressure, and water vapor.

According to graphical data presented in Millman [1971], the resultant ray path bending based on the CRPL Reference Atmosphere (a fair assumption in the case for summer over the path under consideration in this investigation [Bean and Dutton, 1966]) is on the order of 1.5 milliradians or less for an elevation angle of 17°.

The amount of tropospherically induced ray path bending is larger for smaller elevation angles since the two factors are inversely proportional. For this reason, tropospheric refraction becomes important when elevation angles less than a few degrees are used. McCormick and
Maynard [1972] documented fades in excess of 16 dB on an earth-space path at 7.3 GHz for elevation angles of less than 1°. Substantial fading occurred for angles up to about 3-4°. The study utilized geostationary satellites and an earth station located near Ottawa, Canada (geographic latitude 45° N.).

1.51 Ionospheric Refractive Index

In evaluating the effects of the various propagation factors listed in Table 2, it is advantageous to develop an expression for the ionospheric refractive index for the earth-space path under investigation.

The refractive index of a magnetolonic medium is given by the Appleton-Hartree equation. Derivation of the equation from basic principles is presented in Budden [1961]. If the operating frequency is much greater than the collision frequency, the equation has the form

$$\mu^2 = 1 - \frac{2X(1-X)}{2(1-X) - \frac{Y_T^2 \pm [Y_T^4 + 4(1-X)^2 Y_L^2]^{1/2}}{2}}$$

where:

- \(X = \frac{\omega_N^2}{\omega^2}\)
- \(Y_T = \frac{\omega_H}{\omega} \sin \theta\)
- \(Y_L = \frac{\omega_H}{\omega} \cos \theta\)

\(\omega_N = \) plasma frequency

\(\omega = \) operating frequency

\(\omega_H = \) electron gyrofrequency

\(\theta = \) angle between ray path and geomagnetic field
For the portion of the ionosphere above about 50 km the condition of $f >> \gamma$ (collision frequency) is valid since $f = 135.6$ MHz. The relative magnitude of $Y_L$ and $Y_T$ determines which of two propagation modes will predominate.

For, $Y_T^4 >> 4Y_L^2(1-X)^2$ the mode is Quasi-Transverse.

For, $Y_T^4 << 4Y_L^2(1-X)^2$ the mode is Quasi-Longitudinal.

Choosing typical values for the equation parameters, one may determine which mode predominates for the earth-space path under investigation.

$B = 0.5$ Gauss (College)

$N = 2 \times 10^5$ e1/cm$^3$

$\omega_N = 5 \times 10^7$ rad/sec

$\omega_H = 9 \times 10^6$ rad/sec

$\omega = 8.5 \times 10^8$ rad/sec

Thus for $X$,

$$X = \frac{\omega_N^2}{\omega^2} = 0.0007$$

Since $X << Y_L$, Equations 2 and 3 may be expressed as:

$Y_T^4 >> 4Y_L^2$ Quasi-Transverse (QT)

$Y_T^4 << 4Y_L^2$ Quasi-Longitudinal (QL)

The transition between the QT and QL modes will occur when,

$$Y_T^4 = 4Y_L^2$$

$$\frac{\omega_H^4 \sin^4 \Theta}{\omega^4} = \frac{4 \omega_H^2 \cos^2 \Theta}{\omega^2}$$
\[
\sin \theta \tan \theta = \frac{2\omega}{\nu_l} = 190
\]

The value of \( \theta \) for which this equation is valid, is within one degree of 90°, implying that for all ray path/field line angles short of near perpendicularity, the quasi-longitudinal mode of propagation will predominate.

For the earth-space path under investigation,

Geomagnetic dip angle = 77°
Ray path elevation angle = 17°

thus, \( \theta = 60° \), well within the quasi-longitudinal (QL) domain.

Using the QL approximation, the equation for refractive index becomes,

\[
\mu^2 = 1 - \frac{X}{\frac{\nu_l}{\nu_L}}
\]

If the effects of the magnetic field and collision frequency are now ignored, the expression becomes,

\[
\mu^2 = 1 - X = 1 - \frac{\text{Ne}^2}{\text{me}_0 c^2}
\]

Equation 8 includes the electron density and operating frequency which is the basis for the evaluation of several propagation phenomena involved with transionospheric ray paths.

1.52 Ray Path Bending Due to Ionospheric Refraction

Millman [1967] assuming a Chapman-like ionosphere, computed the extent of ray path bending at 100 MHz. Assuming a daytime maximum electron density of 1.25X10^5 e1/cm^3 and maximum nighttime concentration
of $4 \times 10^5$ $e_1/cm^3$, the ray path bending for an elevation angle of $17^\circ$ was found to be about 5 milliradians at 555 km. This maximum value reduces to $\approx 2$ milliradians for astronomical distances (a satellite at geostationary altitude - 43,000 km - would fall near this category). While these errors would be important in areas such as satellite ranging [DaRosa, 1969] where precise angle of arrival and ray trajectory information is important, they have negligible effect on the propagated information due to the relatively wide receiving antenna beamwidths. Ionospheric refraction therefore is not a critical parameter with respect to the transionospheric digital information transmission using this particular system.

1.53 Propagation Delays at VHF

When a modulated RF carrier propagates through the ionosphere, the modulation envelope travels at a velocity slightly less than that of free space propagation. Group delay is a measure of the time retardation caused by this velocity reduction. The delay is a function of both electron content integrated over the ray path, and operating frequency. Were the group delay to fluctuate rapidly with a deviation on the order of a bit period, then timing errors would result at the receiver due to loss of synchronization. A brief calculation will, however, indicate that very large fluctuations in electron content would be necessary to generate such errors.
Group delay is given by,

$$T_g = \frac{4 \times 10^7}{c f^2} \int N_e \, ds$$

(after Millman, 1967)

assuming $\int N_e \, ds = 10^{13} \, \text{cm}^2$

$T_g = 0.72 \, \mu\text{sec}$

$T_g$ represents the one-way transit time delay for the earth-space path. The maximum data rate used in the experiment was 20 kbps (kilo bits per second), therefore, the unit pulse width was 50 µsec. Integrated electron content fluctuations of one order of magnitude would result in a propagation delay of 7.2 µsec, quite small compared to 50 µsec, and of little consequence to the decoder time base. In somewhat similar fashion, ray bending due to refraction effects would cause delays due to increase in the phase path. However, using the same parameters as were used in the group delay calculations, the resultant phase path change is found to be about 215 meters. This value, when compared to the propagation velocity, is negligible for the data rates under consideration here. In essence, therefore, ionospherically induced delays have no measurable effect on error rates for the transionospheric channel.

1.54 Dispersive Distortion

Pulse distortion arising from the dispersive nature of the ionosphere can be described as follows. Ionospheric dispersion causes the frequency components of the modulation spectrum to propagate
at different velocities, the higher frequencies traveling faster than the lower ones. The level of pulse distortion would, of course, be dependent upon the modulation spectrum bandwidth compared to the carrier frequency. The difference in propagation time for the upper and lower frequencies for a given pulse spectrum may be expressed as,

\[
\Delta t = \frac{8 \times 10^7 \Delta f}{c f_c^3} \int N_e \, ds \quad \text{(after Millman, 1967)}
\]

\(\Delta f\) = difference between upper and lower frequencies

\(f_c\) = carrier frequency

If \(\int N_e \, ds = 10^{14}\) el/cm² and the pulse width is 50 \(\mu\)sec,

\[\Delta t = 2 \times 10^{-9}\] sec

This represents the worst case situation for the experiment conducted. A pulse is said to be distorted if \(\Delta t\) is of the same order as the pulse width. As can be seen, the dispersive delay is roughly four orders of magnitude smaller than the pulse width and, therefore, of no consequence to the error rate data.

In cases where wideband channels are utilized, such as those necessary for high speed data or video, the effects of ionospheric dispersion have been modeled using a generalized linear filter to represent the ionosphere [Bedrosian, 1970]. In this manner, data on signal distortion and crosstalk have been obtained for wideband channels using low carrier frequencies over earth-space paths having low elevation angles.
1.55 Ionospheric Attenuation

Ionospheric attenuation at VHF is also of little concern to this research due to the inverse square relationship between operating frequency and the attenuation. The attenuation is given by,

\[ A = \frac{1.17 \times 10^2}{f^2} \int N_e v ds \]  
(after Millman, 1967)  

\[ v = \text{collision frequency} \]

Millman has calculated daytime and nighttime values of ionospheric attenuation for a 100 MHz carrier propagating along an earth-space path having a 17° elevation angle. The daytime attenuation is about 0.65 dB, and the nighttime value is 0.20 dB. Extrapolating these results to 135.6 MHz using the inverse square relationship, the values become 0.35 dB and 0.11 dB respectively. This small amount of signal loss is quite negligible when compared to receiver system losses as well as other propagation phenomena not yet discussed which cause signal losses an order of magnitude greater. It is interesting to note at this point that the losses due to tropospheric attenuation are more than one order of magnitude smaller than the ionospheric attenuation, thus confirming the relatively negligible contribution of the troposphere at VHF.

1.56 Polarization Rotation

Due to the interaction of electrons in motion with the geomagnetic field, a linearly polarized radio wave incident upon the ionosphere emerges with a resultant angular displacement in its polarization.
angle. This effect, referred to as Faraday Rotation, is outlined in Lawrence et al. [1964]. It occurs when the two circular components with opposite rotation which combine to form the linear polarized wave interact while propagating at different phase velocities. The amount of rotation is proportional to the integrated electron content along the ray path,

\[ \Omega = \frac{2.36 \times 10^4}{f^2} \int H \cos \theta \sec \phi N_e \, dh \quad \text{(after Millman, 1967)} \]

\( \Omega = \) angular rotation of plane of polarization  
\( H = \) magnetic field intensity in Gauss  
\( \theta = \) ray path/geomagnetic field angle  
\( \phi = \) ray path/zenith angle  
\( N_e = \) electron density

While this effect is extremely useful in approximating columnar electron content [Evans, 1957 and many others], it is of relatively little importance to the research undertaken here. There are two major methods of eliminating signal loss due to signal/receiver antenna polarization mismatch. The more complex method, but that which results in the least amount of signal loss, is to utilize a linearly polarized receiving antenna which is itself rotatable. By employing polarimeter equipment it is then possible to track the signal polarization angle and adjust the receiving antenna to match. This results in maximum power transfer from signal to antenna. Since the velocity of polarization rotation is slow, mechanical rotation of the receiving antenna adequately serves the purpose.
The second method employs a much simpler receiving system but results in a 3 dB reduction in received signal power. By utilizing a circularly polarized receiving antenna, signal-antenna polarization mismatch is also avoided. Unfortunately, the inclusion of the antenna in quadrature with the original linear antenna results in a 3 dB increase in received noise power with no attendant increase in signal power over that obtainable using the linear antenna; assuming signal-antenna polarization match. The 3 dB loss is, however, much less than that which would result if a single fixed linear antenna were used at the receiver. The use of polarization diversity to alleviate short and long term fading at VHF is described by Takahashi [1969].

The error rate data was obtained utilizing a circularly polarized receiving antenna system whose circularity was adequate (+0.5 dB) for the test durations. As a result, Faraday Rotation is of little consequence.

1.57 Amplitude Scintillation

Amplitude scintillation, in the present context, refers to fluctuations in received signal power of a transionospheric radio wave which result from scattering by irregularities in electron density. The effect of the irregularities, found predominantly at F-region heights [Bates, 1959], may be likened to that of a diffraction grating. The result of the radio wave scattering in the ionosphere is the creation of a complex interference pattern at the earth's surface. The peaks and nulls in the pattern shift with respect to the earth
as the irregularities move. In this case, the radio source (satellite) is stationary with respect to the earth, resulting in zero source velocity relative to the ground station. This produces a temporal variation in received signal power whose rate of fluctuation is dependent upon irregularity velocity and scale size. The amplitude variation is dependent upon the amount of electron density enhancement in the irregularities.

Lawrence et al. [1964] gives a more detailed analysis of the phenomenon; however, they do not treat the case in which a geostationary satellite serves as the radio source. Certain modifications to their development must be made in order to properly adapt it to this specific case, especially when one considers the time constant associated with the scintillations. Since the rate of signal fluctuation would be increased if the radio source had a velocity relative to the ground receiver with a velocity component transverse to the ray path (a longitudinal velocity would manifest itself as a Doppler shift in the signal frequency), a radio wave from an orbiting satellite would produce a far different pattern of scintillation observed on the ground.

While the major extent of research has been conducted in connection with the correlation of scintillation and F-region irregularities, there has been some work done concerning possible E-region effects. Benson [1960] concluded that a direct connection between visible auroral forms and radio scintillation (both amplitude and angle-of-arrival) on a ray path through the aurora exists. Though no direct evidence has been produced to prove that the source of the
scintillation is in fact at the same level as the visual aurora, additional work done by Fremouw [1967] produced similar results for polar orbiting satellites observed at College. Fluctuations exceeding 20 dB were documented. Although the auroral forms analyzed occur at E-region altitudes, the work has been extended through the generation of a model for F-region scintillation adaptable to auroral latitudes as well as the equatorial and mid-latitudes [Fremouw & Rino, 1971].

Study of E-region scintillation at mid-latitudes has been conducted by Aarons & Whitney [1968] wherein there were found to be two distinct daily maxima. The near-midnight maximum was attributed to F-region phenomena being well correlated to spread F and geomagnetic factors while occurring over large latitudinal areas. The near-midday maximum was, however, attributed to patches of sporadic-E characterized by high foE's (critical frequency). The correlation was best during periods of low geomagnetic activity.

It would be advantageous in the type of research project being reported here to be able to make some progress in the study of E-region scintillation. This has not been possible due to the lack of definitive data on the E region at the particular ionospheric/ray path intersection point of interest. Scintillation data obtained on the ATS-1/COLLEGE communication path will, however, be compared to Sitka magnetometer data in attempts to link the observed signal fluctuations to E-region phenomena.

The destructive effects of 20 dB signal fluctuations at VHF cannot be overemphasized when compared to the other propagation phenomena which have been discussed. Amplitude scintillation seems
to be the most critical factor involved with VHF earth-space communications to high latitude ground stations. This is especially true when system design does not allow at least a 20 dB fading margin for transionospheric channels. As will be seen, amplitude scintillation plays a very important part in the error rate data.

1.58 Phase Scintillation

Phase scintillations arise from the same phenomenon as amplitude scintillations. The magnitude of their effect on the radio wave is, however, much smaller. Calculations made to determine the extent of phase alteration induced by scintillation have shown the deviation to be about one radian for frequencies in the lower VHF region [Lawrence et al., 1964]. Using the inverse frequency relationship for the ionosphere [Hillman, 1967], this would be reduced by a factor of three or four when applied to 136 MHz. This phase deviation of about 15° - 20° is quite negligible for FSK transmission and would generate no timing error in the digital data (phase jitter) at the receiver.

1.59 Propagation Across the Plasmapause

Quite coincidentally, the 17° ray path from College to ATS-1 traverses the ionosphere at about L=4 geomagnetic latitude. The F-region intersection point is slightly south of L=4 at about L=3.8. This region is thought to be the location of the plasmapause.
The plasmapause is thought to define the boundary between parts of the ionosphere which are affected by corpuscular radiation (the high latitude and polar regions) and those which are normally affected by solar ultra-violet radiation (mid-latitude and equatorial regions).

Information on propagation across the plasmapause at VHF is virtually nonexistent. The prime research tools have been topside sounders and observation of VLF (Very Low Frequency) phenomena [Helliwell, 1965]. In the near future there may be established an incoherent scatter radar at about $L=4$ to be used for the purpose of investigating this boundary [Evans, 1972].

Correlative data thought to be associated with plasmapause motion is included in the data analysis in attempts to determine whether or not this is a factor worthy of consideration. Further study is necessary in order to establish any connection which may exist between propagation across the plasmapause and VHF propagation error rates.
2.1 Evaluating the Error Rate

The following method was utilized to measure error rates for the VHF earth-space path. A predetermined repetitive bit sequence was transmitted to the satellite (uplink) from the College earth station. The bit sequence was pseudo-random, which is to say, no repetitive bit pattern existed whose period was shorter than that of the sequence generator (63 bit). Every 63 bits, the bit pattern repeated itself; therefore, the sequence was not totally random. Six specified bits within the 63 were utilized for synchronization.

The received signal from the satellite (downlink) underwent extensive signal processing to reproduce the binary bit sequence. The bit sequence was then synchronized to a 63 bit sequence generator identical to that which generated the transmitted bit stream. A bit-by-bit comparison of the two bit streams provided the data for computation of the error rates.

The bit error rate (BER) represents the number of bit errors as a function of the total number of bits received during the measurement period. For example,

Given 100 errors occurring in a 10 kbps (kilobit per second) bit stream in one second, the BER is in this case:

\[
\text{BER} = \frac{10^2 \text{ bit errors/unit period}}{10^4 \text{ bits/unit period}} = 10^{-2}
\]
The probability of error is in this case:

\[ P_E = 1.0\% \]

In utilizing the pseudo-random bit sequence, we get a more reliable measure of the channel error characteristic through the elimination of any periodicity in the digital data short of 63 bits.

2.2 Outline of Equipment

The data transmission and recovery systems are presented in block diagram in Figures 2 and 3. A NASA-AMES data generator provided the PCM data in binary levels of +5 volts and ground. The data rate was held within stringent tolerances through the use of a crystal controlled time standard subdivided to obtain the desired data rate. An operational amplifier modulation controller converted the PCM data to \( \pm \) voltage levels, symmetrical to ground, which then modulated a 250 Watt VHF FM transmitter whose exciter had been modified to permit transmission of the wideband information. The RF carrier at 149.22 MHz containing the FSK digital data was then transmitted to the satellite using a single helical antenna.
The data recovery system shown in Figure 3 was somewhat more complex than the transmit system. Two crossed-yagi antennas, each followed by individual low-noise RF preamps (Gain = 35 dB, Noise Figure = 2 dB), comprised the pre-receiver portion of the system. The two preamplified antenna signals were combined in proper phase and fed to a rebuilt NASA MOD 1 telemetry receiver. The receiver, designed specifically for 136 MHz satellite telemetry work, provided two predetection bandwidths, 10 kHz and 30 kHz, switch selectable. Receiver tuning was crystal controlled (switch selectable in increments of 1 kHz) and proper tuning was accomplished through the use of a center tune meter coupled to the receiver discriminator.

The two signals provided by the receiver, the FM detected output and the 3rd IF amplifier AGC (Automatic Gain Control) voltage, were then channelled to the PCM bit synchronizer and Strip Chart Recorder respectively. The synchronizer reduced the noisy, distorted receiver FM output to a binary bit sequence with a synchronous clock for error comparison. The synchronizer employs a matched filter-type detector preset to the data rate followed by a digital DC restorer and level comparator circuitry for optimum bit determination in the presence of noise and signal distortion. A phase-locked-loop clock generator tracks the incoming data and produces the synchronous clock necessary for decoding.

The PCM data and synchronous clock were routed to a NASA-AMES 63 bit error comparator unit which, when manually synchronized to the incoming data (via the six bit sync word), performed the
CROSSED YAGI ANTENNA ARRAY

DATA RECOVERY SYSTEM

LOW NOISE RF PREAMP

DOWNLINK=135.6MHz

LOW NOISE RF PREAMP

MOD 1
TELEMETRY RECIIVER

FM OUTPUT

BIT SYNCHRONIZER

180° CLOCK

PCM DATA

ERROR COMPARATOR

ERROR FLAGS

RC FILTER

AGC

AGC LESS SPIN MOD.

DUAL CHANNEL STRIP CHART RECORDER

ACUMULATOR OUTPUT

EVENT COUNTER

PRINT TIME MARK

MONOSTABLE TIME PULSE GENERATOR

PRINT FLAG

DIGITAL DATA / TIME RECORDER

1 Hz

MASTER FREQ. SUBDIVIDER

1 Hz

1 MHz

1 MHz CRYSTAL OSC

Figure 3
bit-by-bit comparison. Resulting non-correlations were flagged by the unit as errors.

The error flags were accumulated by an event-per-unit-time (EPUT) counter whose measurement period was switch selectable between 1 second and 10 seconds. The accumulated error count was then recorded in decimal format by a digital printer. A companion digital clock, slaved to the 1 MHz crystal standard, provided reference time for each error count record. Print rate, dependent upon the EPUT counter sample rate, was controlled by the clock.

The 3rd IF AGC voltage (proportional to the log of the received signal power) was fed through a single pole RC filter to reduce fluctuations of period shorter than 0.5 second. This was necessary in order to remove the characteristic satellite spin modulation present on the downlink. Due to the spin modulation, small power fluctuations having periods shorter than 0.5 second would have been masked. There was, therefore, no appreciable loss of useful data owing to the incorporation of the filter. The filtered AGC voltage was then recorded on one channel of the dual channel Sanborn chart recorder.

Time marks corresponding to the print flags generated by the digital printer were fed to the other channel of the Sanborn recorder. This provided the link between the error rate data, on paper tape, and received signal power data, on strip chart, necessary to time-correlate the two sets of data.

In addition to the operational equipment, several pieces of test equipment were used to monitor and calibrate the system throughout the experiment. A VHF Generator was used to calibrate the AGC voltage
In terms of received power relative to the receiver (Figure 4). A VHF Test Generator, capable of wideband modulation, and FM Deviation Meter were used to set transmitter deviation and verify proper performance of portions of the data system (Figure 5).

**Figure 4**

**Verification Transmission System**

**Figure 5**
2.3 Test Environment

In order to ascertain propagation effects on the digital data, it was necessary to hold all other critical variables constant (as closely as possible). In this endeavor the following parameters were controlled,

A) Data Transmission Rate - frequency stability of the 1 MHz standard was measured using the EPUT counter, accurate to one part in $10^8$, indicating a maximum variation of ± 1 Hz in the standard. This would represent a maximum of $10^{-4}$% error in the data rate stability.

B) Transmitter Carrier Frequency - The fundamental frequency of the transmitter was set with the counter. Received signal frequency measurements (made at the receiver, capable of resolving drift with a resolution of about 500 Hz), showed no discernible drift in the carrier frequency over the test periods.

C) Transmitter Deviation - The deviation (modulation level) was set and monitored continuously with the deviation meter. All tests were run at ± 5 kHz deviation.

D) Receiver System Gain - Held as constant as possible utilizing the same equipment and configuration throughout the experiment.

E) Transmitter Output Power - Transmitter final RF voltage and current set in accordance with power calibration using a metered dummy load (power fluctuations in the uplink are less critical due to the saturation characteristic of the satellite transponder. Tests have shown that under normal operating
conditions, the uplink signal was on the order of 3 db above the necessary transponder saturation level assuring a constant downlink power for even moderate fluctuations in transmitter power.)

F) Receiver Bandwidth - Switch set to either 10 kHz or 30 kHz dependent upon the data rate.

Factors external to the ground station such as sky noise temperature, noise environment, etc., although difficult to control, were observed and found to be negligible, in general (with the exception of some rare burst interference). All data acquisition was accomplished during roughly the same period of the day (± 1 hr) in order to minimize effects due to earth rotation which could result in significant variations in the sky noise temperature. The period (7 pm - 9 pm local standard time) was situated such that throughout the experiment the sun remained outside of the antenna main lobe. The noise level was quite low at the ground station since its location was well away from places of habitation, roads, and industrial areas. Certain anomalies in the BER data did, however, occur which remain unexplained other than the possibility of external interference. This subject is treated in more detail in the following chapter.

Maintenance of all these parameters, as constant as possible, allows correlation of data taken throughout the experiment without involved adjustment of the data.

2.4 System Contribution to BER

In order to determine the propagation medium contribution to
the error rate, it is necessary to subtract the system error rate from the measured results. The contribution of the transmit system to the measured error rates was determined in the following manner (Figure 6). The FM transmitter was placed in operation precisely as though a measurement was to be made using the satellite link. The PCM-FM information was detected using the deviation meter loosely coupled to the transmitter antenna cable. The output of the deviation meter was fed to the bit synchronizer and from there to the error comparator. The resultant system error rate was undetectable (at 10 kbps no errors were recorded in 5 minutes, implying better than $10^{-7}$ error rate). The system error rate is therefore entirely negligible when compared to the error rates measured on the earth-space VHF link.

TRANSMISSION SYSTEM BER

![Diagram](image)

FIGURE 6
2.5 Closed System BER

The BER system measurement outlined in the previous section did not include the antenna/receiver system whose error rate is a function of the signal level present at the antenna. In order to provide information about the entire receiving system, an additional experiment was performed to obtain BER data as a function of receiver carrier/noise ratio (CNR). The data represent a baseline, below which the received data becomes susceptible to equipment limitations such as receiver noise temperature.

The method utilized to provide the baseline data is as follows (reference Figure 5). The 63 bit PN data modulated a VHF Test Generator whose RF frequency was set to the receiver system frequency, 135.6 MHz. The PCM-FSK carrier was then transmitted from a test yagi antenna located several hundred yards down range from the receive antenna array about 10 - 15° off axis. The test was performed during periods when the satellite was shut down to eliminate possible propagated interference.

BER data on the detected carrier was recorded as a function of receiver CNR by varying the output power of the VHF test generator. The resulting data are presented in the following chapter and interpreted with respect to the BER data obtained using the earth-space link. Even though the baseline data were obtained during a period roughly six hours later than the normal data acquisition period, the change in sky noise temperature has been assumed to be a negligible factor in comparing the two sets of data.
CHAPTER III

ANALYSIS OF THE DATA

3.1 BER Data

BER data for the satellite-earth communication channel were obtained during the summer of 1972 at College, Alaska.

Bit errors were tabulated by the equipment at ten or one second intervals. The ten second interval was the measurement period used for the majority of the tests. The one second interval was used only during tests in which relatively large scintillation fading was present on the downlink. The one second interval was used to facilitate analysis of the error rate response to the fading channel.

Data transmission periods were held to approximately 15 minutes for each of two specified data rates in order to adequately assess the effects of the propagation medium on the bit stream. During many of the "quiet" test periods, the 20 kbps test was dispensed with in favor of a single 10 kbps test.

The original data, reduced to figures representing the number of errors per second, were then averaged over specific periods corresponding to the measurement period of comparison data. Averaging periods varied from 5 minutes to as long as 20 minutes. The averaged data, referred to as the mean bit error rate, \( \overline{BER} \), represents the main body of the research data.
In addition to the BER data, the maximum variation in BER was scaled for each period. This information served as a measure of the error rate temporal variability.

\[
<\text{BER}> = \frac{\text{BER}_{\text{max}}}{\text{BER}_{\text{min}}}
\]

\(\text{BER}_{\text{max}}\) = maximum BER observed in a ten second period
\(\text{BER}_{\text{min}}\) = minimum BER observed in a ten second period

The BER data is limited, to a certain extent, due to inherent inadequacies in the measurement techniques utilized. The scope of the research did not permit the equipment necessary to undertake a full study of the error rates with respect to burst characteristic and type of error occurrence. These essentially "microscopic" aspects of error analysis require computer processing in order to handle the large volume of raw data as well as to perform the statistical manipulations necessary. This analysis of the error characteristics of the transionospheric path, therefore, makes no inferences as to behavior involving time frames of less than one second (the minimum observable time frame of the equipment).

Due to the fact that different equipment settings were used for the 10 kbps and 20 kbps (kilobits per second) phases of the experiment, the reduced BER data for each were compiled independently and are discussed individually in the analysis.

3.2 Scintillation Data

Simultaneous received signal power data, recorded on the two
channel strip chart, made possible the measurement of the level of scintillation present on the downlink during each test.

A standard technique for quantitatively evaluating the magnitude of scintillation (the scintillation index) was utilized to obtain representative numerical data. The scintillation index is explicitly defined by Aarons [1970].

\[
\text{Scintillation Index (SI)} = \frac{P_{\text{max}} - P_{\text{min}}}{P_{\text{max}} + P_{\text{min}}}
\]

\( P_{\text{max}} \) and \( P_{\text{min}} \) represent the 3rd-highest and 3rd-lowest excursions scaled from the AGC chart recording. \( P_{\text{max}} - P_{\text{min}} \) can be reduced from chart data using precise knowledge of the recorder amplitude calibration. \( P_{\text{max}} + P_{\text{min}} \), however, requires measurement of the absolute signal at the antenna. In order to simplify the reduction of the scintillation data in the absence of a measure of the absolute power at the antenna, a graphical method proposed by Whitney & Malik [1968] was employed. This made possible the evaluation of the index from information contained on the AGC charts.

Each AGC recording was subdivided into 5 minute intervals which were scaled to obtain the scintillation index. The scaling period was chosen so as to best fit the BER test lengths while maintaining the minimum time necessary to observe all other scintillation phenomena.

The 10 kbps BER data is compared to scintillation data in Figures 7 and 8. The 10 kbps <BER> data is compared to scintillation data in Figure 9. Comparisons of the 20 kbps BER data and SI data may be found in Figures 10 and 11 with comparisons of the 20 kbps BER variation data and SI data presented in Figure 12.
Figure 7
Figure 8

MEAN ERROR RATE
VS.
SCINTILLATION INDEX

DATA RATE = 10 KBPS
Figure 9

BER MAX. / BER MIN. VS. SCINTILLATION INDEX

DATA RATE = 10 KBPS
Figure 11

MEAN ERROR RATE VS. SCINTILLATION INDEX
DATA RATE = 20 KBPS
Figure 12
3.3 Carrier/Noise Ratio Data

The strip chart recording of the receiver AGC voltage also provided information on the system received carrier/noise ratio (CNR), an important parameter relating the received carrier power to the predetection noise power. Expressed as the ratio of the two powers, CNR is a sensitive indicator of channel reliability in the presence of noise. CNR measurements are most useful when the noise is characterized by a given spectrum whose power density remains temporarily stable. Short period fluctuations in both carrier power (scintillation, for example) and noise power (noise bursts) complicate CNR measurement reliability when the measurement cannot be reduced to a range over which both factors may be assumed to be constant. It is for this reason that the CNR data presented here must be interpreted with respect to other data, primarily the scintillation data, in order to account for inconsistencies.

Due to the aforementioned equipment limitations, noise bursts were to a large extent undetectable, resulting in some ambiguity in the data. Fortunately, the general noise environment was favorable. The small bandwidth (=30 kHz) about the carrier frequency, 135.6 MHz, may be assumed to have a constant noise spectral density with no loss of precision. Temporal variations in noise power, as observed with the receiver system, were well correlated with observed scintillation. Man-made interference, a primary source of burst noise, was kept to a minimum due to the relative isolation of the earth station.
Certain error bursts did, however, occur throughout the test period as can be seen in Figure 13; though the associated loss of data constituted a very small fraction of the total data transmitted. None of the measurable propagation parameters indicated the nature of the source of these bursts. As Figure 13 demonstrates, the error anomalies were uncorrelated with simultaneous $K$ indices, scintillation index, and CNR. For this reason, it is doubtful that the source of the anomalies was the propagation medium. Further study would be necessary to confirm this.

The error rate anomalies, characterized by an increase of at least an order of magnitude in BER, were attributed to interference, not necessarily associated with the propagation environment, whose period was short of that requisite for detection ($<1$ second). The anomaly of June 28, 1972, was attributed to lightning noise which was observed in the receiver output at the time of the burst error occurrence. Further analysis of these burst errors has been deleted due to their statistical rarity when compared to more prevalent propagation problems.

Composite BER/CNR data for the 10 kbps tests are presented in Figure 7. Similar data for the 20 kbps tests are displayed in Figure 10. CNR was scaled from the charts for each 5 minute period, therefore, no adjustments in the BER data are necessary for comparison. In cases of extreme scintillation ($S > 50\%$), CNR values were inestimable due to instability in the AGC recording.
Baseline receiver system CNR data were obtained using the equipment configuration and method outlined in Section 2.5. These data are plotted along with the transionospheric channel CNR data as an indication of deviation attributable to the ionosphere (reference Figures 14 and 15).

In order to check the system performance against theoretical predictions, a third curve is incorporated on the CNR plots. In Guenther [1967] theoretical BER performance data is given for the specific mode of transmission employed in the research. BER vs. CNR information was derived from this data in the following manner.

The theoretical data is in terms of \( (E/n_o) \) relative to a bandwidth equal to twice the data rate where,

\[
E = \text{carrier energy per signal element}
\]
\[
B = \text{bandwidth}
\]
\[
n_o = \text{noise spectral density}
\]
\[
R = \text{data rate}
\]

To convert \( (E/n_o) \) to corresponding CNR values for the system utilized,

\[
\frac{E}{n_o} = \frac{C}{Bn_o}
\]

\( C = \text{measured carrier power} \)

\( N = \text{measured noise power} \)

\( b = \text{receiver bandwidth} \)

\[
n_o = \frac{N}{b}
\]

\[
B = 2R
\]

thus,

\[
\frac{E}{n_o} = \frac{Cb}{BN}
\]
Figure 14
Figure 15
\[ \frac{C}{N} = \frac{E}{n_0} \frac{B}{b} = \frac{E}{n_0} \left[ \frac{2R}{b} \right] = \text{CNR} \]

The theoretical data are therefore modified by a factor of \( \frac{2R}{b} \).

The receiver 3 dB bandwidths for both modes are,

- 10 kHz setting, \( b = 5 \text{ kHz} \)
- 30 kHz setting, \( b = 10 \text{ kHz} \)

for \( R = 10 \text{ kbps} \), \( b = 5 \text{ kHz} \)

\[ \text{CNR} = \frac{E}{n_0} \left[ \frac{2 \times 10^4}{5 \times 10^3} \right] = \frac{E}{n_0} + 6 \text{ dB} \]

for \( R = 20 \text{ kbps} \), \( b = 10 \text{ kHz} \)

\[ \text{CNR} = \frac{E}{n_0} \left[ \frac{4 \times 10^4}{10^4} \right] = \frac{E}{n_0} + 6 \text{ dB} \]

The adjusted information is included on Figures 14 and 15.

Agreement with the system response data is good (within 1-3 dB). Experimental work at higher data rates involving similar noise environments, reported in Suguri et al. [1971], resulted in disparities of up to 4.5 dB when theoretical and measured data were compared.

### 3.4 Geomagnetic Field Data

Three indicators of geomagnetic field perturbation were chosen as comparative data. They are,

- \( Kp \) - planetary geomagnetic index computed from world-wide magnetometer data
- \( Kc \) - geomagnetic index computed from magnetometer measurements made at College, Alaska
- \( Ks \) - geomagnetic index computed from magnetometer measurements made at Sitka, Alaska
These Indices, recorded at National Oceanic and Atmospheric Administration (NOAA) observatories located throughout the world, are computed for each 3 hour interval throughout the day. Due to the relatively short test periods (30 - 40 minutes), one set of indices served to describe the entire test in most cases.

The K indices are derived from magnetometer data which, in general, reflects phenomena taking place within the high conductivity region of the ionosphere (E region) in which large current systems exist. Kp was chosen in order to assess possible correlation between BER and large scale geomagnetic field perturbation. Kc was chosen as a measure of local field perturbation north of the ray path/ionosphere intersection region (reference Figure 1). Ks was chosen specifically to correlate field disturbance at roughly the same geomagnetic latitude as the ray path/ionosphere intersection region (=L = 4). One assumption implicit in the comparison between Ks and the penetration region is that the longitudinal separation (=14°) is of negligible consequence.

Composite BER/K index data are presented in Figure 16 for the 10 kbps tests, and Figure 20 for the 20 kbps tests. More detailed comparisons of the individual indices and BER data are found in Figures 17, 18, and 19 for the 10 kbps tests, and in Figures 21, 22, and 23 for the 20 kbps tests.

The averaging interval of the BER data presented has been adjusted to conform to the larger measurement period of the indices.
Figure 16

10 KBPS DATA

COMPOSITE BER/Ks/Kc/Kp DATA
FOR ALL 10 KBPS TESTS
Figure 17

MEAN ERROR RATE

VS.

K INDEX MEASURED AT SITKA, ALASKA

DATA RATE = 10 KBPS

K INDEX MEASURED AT SITKA, ALASKA
Mean error rate vs. magnetic index measured at College, AK.

Data rate = 10 KBPS.

Figure 18
Figure 19

Mean error rate vs. planetary magnetic index Kp

Data rate = 10 KBPS
Figure 20
Figure 21

MEAN ERROR RATE VS.
MAGNETIC INDEX MEASURED AT SITKA, AK.

DATA RATE = 20 KBPS
Figure 22

MEAN ERROR RATE

VS.

K-INDEX MEASURED AT COLLEGE, ALASKA

DATA RATE = 20 KBPS
Figure 23

Mean Error Rate vs. Planetary Magnetic Index (Kp)

Data Rate = 20 KBPS
3.5 Dst Data

Dst data was chosen as an additional indicator of BER sensitivity to externally generated geomagnetic field perturbation. Dst (storm-time variation) yields the average longitudinal depression in the B-field horizontal component. This depression is proportional to the total kinetic energy of injected particles trapped in the Van Allen belt [Akasofu and Chapman, 1972]. As the incoming particle flux increases, the associated ring current expands, distorting the magnetospheric field. The plasmapause (discussed to some extent in Section 1.69) position is intrinsically a function of the field and, therefore, its motion is related to perturbations of the field such as those produced by increased particle flux into the trapping region. A more detailed analysis of this and other Dst factors, with specific reference to substorm phenomena, is presented in Akasofu and Chapman [1972].

Dst values are available for each hour period throughout the day. BER data, adjusted to the Dst measurement period, are compared to the Dst data in Figure 24 for both experimental data rates.

3.6 BER Analysis

At 10 kbps BER is qualitatively well correlated with SI (reference Figure 7 and 8). The rough linear fit to the data in Figure 8 suggests a possible logarithmic variation between BER and SI. Since SI is defined as a ratio of signal and noise powers expressed logarithmically in dB, it seems reasonable that BER and SI should vary this way, in light of the theoretical dependence of BER on CNR observed in Figure 14.
Results of a computer correlation analysis involving the BER (reduced to logs), SI, CNR, <BER>, Dst and the K indices are presented in Table 3. The correlation coefficient for 10 kbps SI, \( C = +0.712 \), strongly supports the inferred logarithmic proportionality between BER and SI.

While BER varies inversely with the theoretical CNR data and the system CNR data, it shows much less correlation to CNR measured on the transitionospheric path (reference Figure 7 and 14). In this case, the computer correlation analysis resulted in a coefficient, \( C = -0.006 \), implying essentially zero correlation between 10 kbps BER and CNR.

The majority of data points in Figure 14 are within \( \pm 2 \) dB of the system response curve. It is apparent when BER, SI, and CNR curves are compared closely in Figure 7 that certain trade-offs occur between SI and CNR. Deficiencies in the CNR measurement technique, in regard to periods of high SI, have already been explained. Erratic data points on both Figure 8 and Figure 14 may be traced, in some cases, to adverse conditions involving the other of the two parameters. This does not, however, explain all cases of inconsistency in the data or the exceedingly low correlation coefficient.

CNR measurements made on a short-term basis (every 10 seconds) have been analyzed along with simultaneous error rate data. The resulting correlation coefficient, \( C = -0.744 \), indicates that BER is inversely proportional to CNR when the measurement period is short enough to reflect fluctuations on the order of tens of seconds.
This implies that the 5 minute averaging period used in reducing the CNR data was too long, in general.

It is interesting to note that the correlation coefficients for \( \text{BER}/\text{SI} \) and \( \text{BER}/\text{CNR} \) (short period), 0.712 and 0.744 respectively, are quite comparable. The primary error rate mechanism attributed to amplitude scintillation is that of "RF level degradation" which is essentially CNR reduction. It is therefore not surprising that the two effects should be comparable.

At 10 kbps, \( <\text{BER}> \) was also well correlated to SI, \( C = 0.673 \). This emphasizes the fact that SI is the propagation parameter most susceptible to wide variation. It is precisely this fact that makes reliable VHF earth-space propagation at high latitudes difficult to achieve.

At 20 kbps the correlation between \( \text{BER}, \text{SI}, \text{and CNR} \) were quite different. As is demonstrated on Figure 10, there is less visible correlation. This is verified by the coefficient calculations in the case of \( \text{BER}/\text{SI} \) (\( C = 0.405 \)). Interestingly enough, the correlation coefficient for \( \text{BER}/\text{CNR} \), \( C = 0.134 \), exceeded that of the 10 kbps case. This is still, however, quite low -- indicating little correlation between the two parameters. There is less range to the \( <\text{BER}> \), as can be seen in Figure 12, when compared to the 10 kbps case which may be a clue to the improved \( \text{BER}/\text{CNR} \) correlation. \( <\text{BER}> \) was less correlated to SI, \( C = 0.402 \), indicating the presence of other variables affecting error rate fluctuations. An apparent reason for this will be pointed out later.
<table>
<thead>
<tr>
<th>CORRELATION DATA</th>
<th>10 kbps</th>
<th>20 kbps</th>
</tr>
</thead>
<tbody>
<tr>
<td>BER / SI</td>
<td>+0.712</td>
<td>+0.405</td>
</tr>
<tr>
<td>BER / CNR</td>
<td>-0.006</td>
<td>+0.134</td>
</tr>
<tr>
<td>BER / Dst</td>
<td>-0.297</td>
<td>-0.433</td>
</tr>
<tr>
<td>BER / Kp</td>
<td>-0.114</td>
<td>+0.220</td>
</tr>
<tr>
<td>BER / Kc</td>
<td>-0.329</td>
<td>+0.054</td>
</tr>
<tr>
<td>BER / Ks</td>
<td>-0.175</td>
<td>+0.146</td>
</tr>
<tr>
<td>&lt;BER&gt;/ SI</td>
<td>+0.673</td>
<td>+0.402</td>
</tr>
<tr>
<td>SI / Dst</td>
<td></td>
<td>-0.442</td>
</tr>
<tr>
<td>BER / CNR(s)</td>
<td></td>
<td>-0.744</td>
</tr>
</tbody>
</table>

**TABLE 3**

Periods of increased scintillation are reflected in the BER data; although scrutiny of Figure 11 reveals that data point scatter is more widespread than in the 10 kbps case. A shift of roughly an order of magnitude in BER at low levels of SI is also visible when Figures 8 and 11 are compared. This shift is further reflected in the BER/CNR data in Figure 15. The majority of data points indicate a predominantly higher BER for given CNR when compared with Figure 14 (10 kbps BER/CNR). This shift may be due, in part, to the decrease in bit energy density associated with the 20 kbps data. The reduction in energy by a factor of 1/2 could result in a shift on the order of a magnitude in BER. This does not adequately account for the shift in BER/SI. This is thought to be primarily due to the choice
of test periods during which 20 kbps tests were made. The tests were primarily ones involving 'disturbed' propagation conditions thus accounting, in part, for the generally higher statistics.

There is an apparent 2-3 dB reduction in BER/CNR performance over the 20 kbps system response (reference Figure 15) and an even greater (3-5 dB) reduction over theoretical BER. The change in noise bandwidth is compensated for in the CNR data, eliminating it as a possible reason for the shift. The relatively high values of SI throughout the 20 kbps tests (reference Figure 10) suggest the possibility of SI/CNR interaction producing a reduced BER for given CNR. The BER values for CNR = 5 dB are of particular interest. These data points, the only ones falling left of the system response curve (Figure 15), correspond to periods in which SI was at near minimum values. The correlation of the overall BER reduction to CNR/SI interaction is by no means fully established on the basis of such limited information. It does, however, provide a satisfactory explanation for the reduction in BER/CNR performance.

In general, at 10 kbps SI tends to be very important, with CNR (long term) showing poor correlation to the observed BER. At 20 kbps SI is of less importance, while CNR (long term) improves in correlation. In both cases CNR (short term) correlates best with the observed BER.

Correlation of BER and the three chosen K indices was poor, in general, for both 10 kbps and 20 kbps data. Figures 16 and 20
reveal little which would suggest connection between BER and the three parameters. Computed correlation coefficients substantiate this,

<table>
<thead>
<tr>
<th>Data Rate</th>
<th>Kp</th>
<th>Kc</th>
<th>Ks</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 k</td>
<td>-0.114</td>
<td>-0.329</td>
<td>-0.175</td>
</tr>
<tr>
<td>20 k</td>
<td>0.220</td>
<td>0.054</td>
<td>0.146</td>
</tr>
</tbody>
</table>

Table 4

It is interesting to note that at 10 kbps BER/K correlation was inverse, while 20 kbps BER/K was not. There is no apparent reason for the inverse relationship at 10 kbps. Data to be presented will show that the 20 kbps correlation is more in line with that to be expected.

Figures 17, 18, 19, 21, 22, and 23 indicate the general random nature of BER with respect to the K indices. The best correlations, BER/Kp for 20 kbps and BER/Kc for 10 kbps, are only marginally apparent.

BER correlation with Dst was fair at 10 kbps (C = -0.297) and significant at 20 kbps (C = -0.433). These correlations are not strong, but their inverse nature follows logically. High particle precipitation results in large negative values of Dst. Quality of propagation tends to vary directly with SI which is linked to the equatorward motion of the F-region irregularities. This motion is strongly influenced by the energy input due to high energy particle precipitation; resulting in a direct variation between storm intensity and propagation quality. The negative correlation coefficients substantiate this. An additional coefficient between the SI and Dst
data, $C = -0.442$, has shown that substantial covariation occurs between the two parameters. The connections between ring current energy and observed SI is an interesting one.

The implication that Dst control of BER is simply via Dst correlated SI variation is not wholly acceptable since the Dst/SI coefficient is not close to unity. The possibility of unique error mechanisms, described by Dst, is very real although ray path/ionosphere intersection region data would be necessary to make more definitive statements.

3.7 BER Analysis

To point out some of the details involved with the error rate and its response to a fading channel, a graphical reconstruction of BER and downlink RF level is presented in Figure 25. The data were taken from the test of June 8, 1972. Error rate values represent accumulated error occurrences summed over each ten second period. Since this is in essence averaging, the error rate data lag the RF level by 1/2 the averaging period (5 seconds).

The error rate response to large RF fluctuations is quite visible. The error rate data were reduced to logs and compared to the CNR values reduced from the RF level data. The correlation, $C = -0.744$, strongly supports an inverse logarithmic proportionality; precisely that exhibited by the system response curves and theoretical BER/CNR curves seen on Figures 14 and 15.
ERROR ACCUMULATION / RF SIGNAL LEVEL

JUNE 8, 1972  2030:09 - 2036:09 ADT

ACCUMULATION PERIOD = 10 SEC

Figure 25
The scintillation index in this case was 69, the relatively short period fluctuations (20-30 seconds) causing BER variation in excess of three orders of magnitude.

3.8 Extreme Storm Effects

BER data were taken on August 2, 1972, during one of the largest magnetospheric storms of the decade. The results are indicative of the reliability of VHF earth-space communications at high latitudes under extremely adverse propagation conditions.

On August 2, 1972, three solar flares (a 1B, 0B, and 2B) occurred at 0316 Z, 1843 Z, and 1957 Z, respectively. They were followed by a great burst of electromagnetic energy on August 3, 1972. Sagamore Hill reported peak fluxes of 14,800 units at 245 MHz for the 2B flare (peak recorded about 2142 Z) [reference Carrigan, 1972]. At 0500 Z August 3, BER data were taken on the "disturbed" earth-space channel. A portion of the record of downlink received power is reproduced in Figure 26.

The AGC record shows fast scintillation fading on the order of seconds. $I_s$ values were as large as 95%, $K$ indices were at recorded highs for the observational period. The BER was 50% as high as statistically possible for random noise. Periodic loss of receiver synchronization during the fades resulted in additional data losses even during enhancement periods.

It is obvious that support of digital communications over the VHF earth-space channel is marginal during periods of extreme storm
Figure 26

AGC CHART RECORDING
Aug. 3, 1972
2016 - 2026 ADT

BER = 50%
SI = 95%
Kp = 7
Ks = 9
Kc = 8
activity. An important point is the relative infrequency of storms of this magnitude.

Occurrence statistics, accumulated over a 52-year period, have shown that during this time 60 great magnetic storms occurred [Chapman and Bartels, 1940]. The annual distribution of these storms indicated maximum frequency of occurrence for the month of August, with corresponding minimum for the month of December. Similar occurrence statistics for storms of lesser intensity show a total of 342 storms for the period. The annual distribution peaks in October, with a minimum for the month of July.

On the basis of this information, one can expect to see an average of 1.17 great storms per year (severe such as to cause total or near total loss of the digital data) and 6.58 smaller storms per year (critical enough to alter the VHF channel error rate noticeably). Whether or not system design will necessitate compliance with storm-induced propagation phenomena will be, to a great extent, determined by the importance of 100% reliability for all propagation conditions.
CHAPTER IV
CONCLUSION

The error rates, in general, were well correlated with scintillation Index. Since scintillation is thought to be primarily an F-region phenomenon, this places great importance on factors which tend to perturb this region. Equatorward motions of the irregularity zone will cause fluctuation in error rates for data channels utilizing transionospheric paths at VHF.

The strong correlation between bit error rate and short-term carrier/noise ratio coupled with the absence of detectable pulse distortion and timing jitter indicates that the primary error mechanism for the path was carrier/noise ratio degradation.

Poor correlation with the K indices, especially Ks, tends to discount E region contribution to the channel error rate. The best of these correlations, mean bit error rate versus Kp, indicates some connection with worldwide geomagnetic disturbance though the magnitude of the correlation is quite small.

Good correlation with Dst implies some solar influence via high energy particle precipitation. This would tend to agree with the mean bit error rate versus Kp correlation. The link between Dst and scintillation index, although not firmly established, is still present, therefore, making all the noted correlations self-consistent.

It is important to note that no direct geophysical data were available for the exact ray path/ionosphere intersection region.
throughout the duration of the research. This fact prohibits precise definition of the source of the observed propagation phenomena, based on the observed correlations.


