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HF AND VHF COMMUNICATIONS CIRCUITS EARTH ORBITING SPACECRAFT AND GROUND CIRCUITS

Manned Spacecraft Center
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MANNED SPACECRAFT CENTER

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HF AND VHF COMMUNICATIONS CIRCUITS

EARTH ORBITING SPACECRAFT AND GROUND STATIONS

PREPARED BY

James M. Towey

James M. Towey
Electromagnetic Systems Branch

AUTHORIZED FOR DISTRIBUTION

Warren Gillespie, Jr.

for Maxime A. Faget
Director of Engineering and Development

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
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ABBREVIATIONS

AGC	automatic gain control
AOS	acquisition of signal
AZ	azimuth
BW	bandwidth
CW	continuous wave
E_R	reflected signal
E_T	transmitted signal
f_o	transmitted frequency
f_R	reflected frequency
G.m.t.	Greenwich mean time
G/S	ground-to-spacecraft
g.e.t.	ground elapsed time
HF	high frequency
Lat	latitude
Long.	longitude
LOS	loss of signal
N	noise
n. mi.	nautical mile
RF	radio frequency
r	propagation path length
S + N	signal plus noise

$\frac{S + N}{N}$	signal plus noise-to-noise ratio
T/R	transmitter and receiver
V	velocity of vehicle relative to the earth
λ	transmitted wave length

HF AND VHF COMMUNICATIONS CIRCUITS

EARTH ORBITING SPACECRAFT AND GROUND STATIONS

By James M. Towey

INTRODUCTION

Ionospheric radio propagation has been studied extensively over the years by many investigators. Ionospheric Radio Propagation Monograph 80 (ref. 3) is one of the most generally used sources of information on the subject. The published literature for the most part has been developed from the interpretation and analysis of experimental data gathered from many parts of the world and is directed toward applications pertaining to surface-to-surface communications.

With a spacecraft in low earth orbit (200 to 250 km altitude), the vehicle will be in different positions in the ionized layers during the daylight portion of each orbit and while in the earth's shadow (see figs. 1 and 2). This feature, together with the rapid motion of the vehicle relative to the ionosphere and to the earth, will present communications problems not encountered in earth-based systems.

A vehicle orbiting in the upper atmosphere will increase the ionization intensity of the earth's plasma sheath which in turn can give rise to certain electromagnetic anomalies. There is considerable literature on this subject. Many of the current experimental data and the conclusions arrived at by many of the investigators remain controversial. One of the best sources of information on the subject is summarized in reference 4.

These effects are common in space communications and must be considered in the design of ground-to-space and space-to-earth communications circuits. The most significant of these are discussed in the following sections.

DOPPLER EFFECT
HF COMMUNICATIONS CIRCUIT
EARTH ORBITING SPACECRAFT AND GROUND STATIONS

A signal propagated over a fixed path will be received on the same frequency as transmitted; however, if there is a relative motion between the source, the reflecting surface and/or the receiving antenna, there will be a shift in frequency. This may be explained with the aid of figure 1. The unmodulated transmitted signal will be of the form

$$e_T = E_T \cos 2\pi f_o t \tag{1}$$

Due to the transmission path, the received signal will contain a phase shift $-\frac{2\pi r}{\lambda}$ and may be expressed

$$e_R = E_R \cos\left(2\pi f_o t - \frac{2\pi r}{\lambda}\right) \tag{2}$$

If there is a relative motion between the transmitter, the reflection region, and receiver (fig. 1), the transmission path length will be varying as a function of time. For small intervals of time (t), the path length for a particular ray may be represented as

$$r(t) = r_o - Vt \cos T \tag{3}$$

where

r_o = an initial distance

V = vector sum of the SC velocity and earth's tangential velocity

T = the angle between the velocity vector and the angle of departure of the ray when transmitting or the direction of arrival of the wave front on reception

f_o = transmitted frequency

Substituting (3) in (2) above, the received signal becomes

$$e_R = E_R \cos\left(2\pi f_o t - \frac{2\pi r_o}{\lambda} + \frac{2\pi Vt}{\lambda} \cos T\right) \tag{4}$$

Substituting $\lambda = \frac{c}{f_o}$ and rearranging terms

$$e_R = E_R \cos\left[2\pi f_o t\left(1 + \frac{V}{c} \cos T\right) - \frac{2\pi f_o r_o}{c}\right] \tag{5}$$

This reveals that the reflected signal differs from the transmitted in amplitude and contains both a fixed and a time varying phase shift of $\frac{2\pi f_o r_o}{c}$ and $\frac{2\pi f_o t}{c} V \cos T$, respectively. In fact, they differ in frequency $f_R = f_o\left(1 + \frac{V}{c} \cos T\right)$. The doppler frequency is proportional to the time rate of change in phase shift, and may be expressed

$$\Delta f = f_o - f_R = -f_o \frac{V}{c} \cos T$$

In order to simplify the explanation, a single ray was considered in the above discussion. In practice, of course, the antennas have finite beamwidths (omnidirectional on the spacecraft and 30 degrees or more for the ground antennas). Consequently, the signal will be propagated over many paths as illustrated in figure 1. These path differences can give rise to many communications problems as will be discussed later.

In a space-to-ground communications circuit, at least a portion of the transmission path is through the ionosphere where the intensity of ionization, and hence the index of refraction, is changing rapidly with time. This will give rise to additional components of doppler shift due to changes in the length of the path and the rate of change in the refraction index. These effects at HF and VHF frequencies are small as compared to the doppler shift due to the motion of the spacecraft, and, therefore, can be neglected.

Since the received signal is the resultant of a myriad of reflecting angles $\left(T_1, T_2, \ldots T_N\right)$, it will not be a discrete frequency, but rather a spectrum of frequencies about the transmitted carrier.

The Gemini HF transmitting and receiving antenna is a quarter-wave monopole mounted on the adapter section of the spacecraft. In the absence of attitude control, the vehicle will orbit with a low-rate tumbling motion about its center of gravity. The antenna in assuming different orientations will introduce a rotation in the place of polarization and a time varying phase shift. There will also be an amplitude modulation as the antenna pattern nulls and lobes are rotated.

SPACE CHARGE AND WAKE FORMATION

A small plot in the upper right-hand corner of figure 1 gives a graphic presentation of the approximate depth of the various ionosphere layers in contrast with the comparatively thin shell (approximately 50 km in height) of the nonionized atmosphere immediately above the earth. The disappearance of the D, E, and F1 layers while the vehicle is orbiting in the earth's shadow extends the height of the nonionized region to 300 km.

A vehicle orbiting the earth's atmosphere will produce an ion and electron sheath in its wake, the extent depending on vehicle size and velocity. This would suggest the creation of electromagnetic anomalies similar to that resulting from meteor activity as will be discussed later. Experiments were conducted during Gemini X and XI missions (refs. 5 and 6) to determine the ion and electron wake structure relative to the ambient medium. The test data are currently being evaluated. A preliminary analysis indicates that the motion of the vehicle results in a shadow zone extending approximately 100 feet behind the vehicle. Instrumentation was installed in the Gemini X mission (ref. 7) to measure the electrostatic charge acquired by the vehicle while in orbit. Due to instrumentation malfunctions, precise measurements were not obtained. The tests did disclose that the maximum charge did not exceed 5 or 6 volts. It was concluded that this was not sufficient to create an operational problem.

A meteor trail reflection can result in a deflection of as much as 10 degrees right and left of the normal great circle path direction between the sender and receiver. Because of this, together with scatter and tilted ionosphere effects, a high gain antenna for a vehicle to surface communications link may have limited effectiveness unless an accurate means of detecting the angle of signal arrival is used. This may have been in part responsible for the consistently inferior performance of the HF communications link by the Gemini stations using a high-gain antenna (11 dB) as compared to those sites using an omnidirectional antenna system.

From figures 2(a) and 2(b), it will be found that the electron density and depth of the ionosphere is a minimum at midnight and a maximum in both density and depth during the evening. Whereas, figure 2(c) reveals that the observed meteor burst rate has a substantial value at midnight and a reduced value in the evening. This suggests that meteor activity may be responsible for a major portion of the fluctuations in signals received at night (particularly when using the relatively high frequency of 15 Mc employed by Gemini) while during the day, it is predominately due to turbulent scattering in the ionosphere. The signals reflected from intense meteor trails can be recognized by their sudden rise of 20 to 25 dB above the level of normal back scatter from the ionosphere. The short term characteristics of the signal received from a large number of small meteors is difficult to differentitate from the scatter due to turbulent fluctuations in the ionosphere. A shower of small meteors arrive in a random manner, and the total received signal is the vector sum of a large number of signals of random amplitude and phase modulation.

From the foregoing, it is apparent that the received signal will be the vector sum of many wave forms from each of the countless number of reflectors in the ionosphere which are illuminated at any given time. The reflectors also have an apparent motion due to variations in electron density at the point of reflection, since the variations result in a rapidly varying phase shift. This in turn gives rise to a doppler frequency component proportional to the time rate of phase shift. These waves have a different time varying amplitude, frequency, phase, and polarization relative to the transmitted signal resulting in a received signal that is amplitude and frequency modulated in a random manner (ref. 2). Typical examples of this effect are shown in figures 3 and 4. As may be seen, the resultant signal at the ground receiving antenna is a random fluctuation of approximately 5 dB about the median at 6 to 7 Hz. As the spacecraft moves over the horizon with respect to the ground antenna, the short term characteristics of the signal change from a random to a periodic fluctuations. Figure 5 is an example of this effect as the spacecraft was within line of sight of the ground station. The period and amplitude of these oscillations increase uniformly from approximately 0.15 to 2 seconds and from 4 to 34 dB, respectively, as the spacecraft moves over the horizon to the point of closest approach (PCA), and then both parameters decrease again as the vehicle moves away toward the horizon again when the signal returns to the random fluctuation.

From an inspection of figure 5, it will be found that the signal consists primarily of the combination of two or more sinusoidal waves of approximately equal amplitude and relative phase difference varying with distance so that the two major component wave fronts traveling over different paths arrive at the receiving antennas alternately in-and-out of phase, thus producing the sharp nulls and blunt lobes in the signal. The large amplitude fluctuations are more pronounced at ground receiving sites surrounded by water as a reflection surface than at sites surrounded by large land masses. In listening to the recorded voice and tone reception, the above effect was readily apparent from the recorded flutter components.

In case of an earth to spacecraft circuit operating on 15.016 MHz, the maximum doppler frequency shift due to vehicle relative motion can be found from the relation

$$f = \frac{Vf}{c} \tag{7}$$

where

V = relative velocity component in the direction of the ray

T = angle between vehicle velocity vector and effective angle of departure and/or arrival of spacecraft radiation

c = velocity of light, 984×10^6 feet per second

f = frequency, 15.016 MHz

$\lambda = c/f = 65.0$ feet at 15.016 MHz

$$\Delta f = \frac{3 \times 10^4 \times 15.016 \times 10^6}{984 \times 10^6} = 460 \text{ Hz} \tag{8}$$

Therefore, the frequency received will be spread over the range 14.556 to 15.476 MHz. In the above solution for the doppler frequency shift, it was assumed that the propagation was along a direct path. However, since the dielectric constant of the earth's atmosphere varies with altitude, a radio beam will be subject to refraction or downward bending as it traverses through the atmosphere which will introduce an error in the doppler shift. At 15 MHz this error is of the order of a few cycles per second, and therefore, was not taken into account.

MODULATION TECHNIQUES

In an earth-to-spacecraft communication circuit, the doppler shift will have an effect on system performance, especially in deep-space missions where the velocity will be orders of magnitude greater than in earth-orbital missions, and, therefore, must be taken into account in the system design.

For the sake of simplicity only the unmodulated carrier was considered in the above discussion. The influence of the doppler shift on the modulation techniques and its effect on the choice of modulation system are discussed in the following.

(1) Amplitude modulation double sideband system: In this case the modulated wave consists of three waves, the carrier and the upper and lower sidebands. Each of the component waves has a constant amplitude, frequency and phase angle. Since the upper and lower sidebands differ from the carrier frequency by the modulation frequency, the difference in doppler shift between the three waves will be very small as compared to the carrier shift. Therefore, the resulting distortion will not be very detrimental. A single sideband-suppressed carrier system would not function unless some form of carrier tracking were employed. However, a system transmitting one sideband plus the carrier (compatible AM) would have many advantages over a double sideband system. The system bandwidth would be reduced in half with an accompanying 3 dB reduction in transmitter power requirements and minimize the possibility of adjacent channel interference and the problems arising from selective fading. The requirement for having an exact phase relationship between the sidebands and the carrier is also negated.

(2) Frequency modulation: The frequency-modulated wave is similar to the amplitude-modulated wave discussed above in that it has a carrier and upper and lower sidebands, but differs in the relative phase of the sideband frequencies, as well as in their number. For sinusoidal modulation there will be a very large number. In general FM requires more sideband frequencies than the one upper and lower sidebands associated with AM. Bandwidth increases with modulation and with deviation, which in turn is directly proportional to the amplitude of the modulation signal. For this and other reasons, FM requires a bandwidth approximately three times that required for an AM double sideband system. That is approximately 30 kc for voice in order to accommodate the additional sidebands and for the doppler shift.

As pointed out in the above discussion, the doppler shift introduces a frequency modulation and this, in turn, produces a variable increase and decrease in bandwidth which is given by the relation $\Delta b = \pm\frac{bV}{c}$ where b is the system bandwidth.

The broadening of the bandwidth will impose additional requirements on the radio-frequency spectrum. This has resulted in adjacent channel interference during the Gemini V and VII HF communications tests (refs. 1 and 2), which ranged from being a nuisance harassing reception to complete loss of signal. Doppler shift, such as experienced, requires either frequency shift correction or the use of signal sideband in order to reduce bandwidth.

GUIDANCE PROPAGATION

On several occasions during the Gemini V and VII missions, HF communications tests showed the reception of the 1000 Hz tone and good quality voice was obtained at distances of 8500 and 6000 miles, respectively (refs. 1 and 2). There were two occasions during which tone was recorded as being received to distances of 12 000 miles. In view of the spacecraft transmitter power limitations (5 watts) and the normal multihop path distance and ionospheric absorption losses at the above distances, it would be impossible to receive sufficient signal to override the local atmospheric noise. Circuit calculations (ref. 2) indicate that approximately 20 dB more spacecraft transmitter power would be required. It is expected that some form of ducting and/or focusing through the concentric spherical surfaces of the ionosphere was responsible for this apparent 20 dB of signal enhancement.

An example of this performance occurred during the Gemini VII mission (ref. 2). At this time the spacecraft transmitter was returned to the voice mode as the vehicle was orbiting over South America at an altitude of 250 km. Signals were received in the Western and Eastern Hemisphere at the distances shown in the following summary.

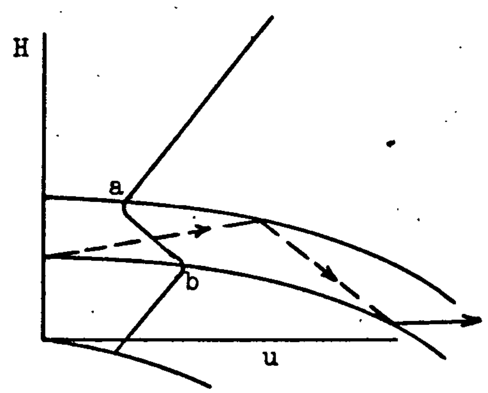
Receiving site	Distance, mi	Signal power received, dBW	$\frac{S+N}{N}$, dB	Local time	Signal augmentation, dB
Hawaii	8 500	-142	5	12:40	18
California	6 500	-118	10	14:40	22
Kano, Africa	4 200	-122	21	22:40	26
Texas	12 000	-138	5	17:07	15

The column captioned "Signal augmentation" is the difference between the required spacecraft transmitter power and its actual power (5 watts) for transmission losses that would occur for a multihop transmission mode. Circuit calculations indicate under the normal multihop mode of transmission, the spacecraft transmitter would require at least 20 to 25 dB increase in power in order to provide the minimum power level required at these distances. Figure 1 is a sketch illustrating a possible ducting mode of propagation as suggested. This shows the vehicle in an equatorial orbit at an altitude of 250 km, which places it between the F_1 and F_2 layers with the maximum ionization intensity just above the vehicle. Therefore, the rays striking the reflecting surfaces of the ionosphere at very small angles of incidence would tend to be focused and/or ducted instead of being reflected away from it.

CONCLUSIONS AND RECOMMENDATIONS

Changes in the refractive index with height above the earth results in the bending of a ray traveling through the atmosphere to be deflected away from regions of low dielectric constant to a higher dielectric constant. It has been proven that this effect has been responsible for propagation beyond the radio horizon in the VHF and UHF bands.

At the lower latitudes (40 degrees North and South latitude) air masses near the surface of the earth form spherically stratified layers, each having a different temperature and/or moisture content resulting in a varying index of refraction with height as indicated in the sketch. Under certain weather conditions, the index increases with height in the normal manner. At some height (b), the index will start to decrease as altitude is increased. At a higher altitude (a), it will start to increase linearly with height as indicated at (a). This tends to form a duct between (a) and (b), thus giving rise to over-the-horizon propagation conditions referred to in the above. An analogous set of propagation conditions exists in the ionosphere and has been experienced at HF and VHF frequency. In this situation the varying index of refraction is due to variations in the electron density in the ionosphere.



Under AF Contract AF 33(615)-1230, Raytheon Company has been investigating guided propagation in the HF and VHF bands in the lower regions of the ionosphere.

Tests have been conducted between two spacecraft orbiting on the opposite sides of the earth at an altitude of approximately 160 kilometers. Three frequencies were used in the tests in 21, 35, and 47 MHz. Final evaluation and analysis of the data has not been completed; however, preliminary results suggest that a wave transmitted over an omnidirectional antenna will be propagated through the ionosphere layers in all directions across the earth's surface and meet again at a receiving vehicle orbiting on the diametrically opposite side of the earth, regardless of the azimuth angle at which they are radiated.

It has been proven that the above mode of propagation has promise in the frequency band between 15 and 100 MHz for global communications between two orbiting spacecraft and between spacecraft and earth-based stations. An area requiring further investigation is the method of coupling the ionospheric ducts and earth stations for more effective techniques for injection and extraction of the signal from the ionospheric ducts to earth stations.

Figure 1 is a graphic representation of a typical beyond the horizon space to surface communications circuit. It will be noted that the signal received is the summation of many component waves which travel from transmitter to receiver over paths of different lengths. These components may add or subtract depending on their relative phase at the receiving antenna which results in fading and distortion of the signal. From figure 5 it will be found that the fading periods varies from approximately 0.5 to 2 seconds as the amplitude varies from 5 to 35 dB. The different path lengths (different delays) result in the reception of some portions of the transmitted energy several microseconds later than others resulting in extension of the pulse length (pulse expansion) if pulse modulation is used and in contraction of useful bandwidth for CW modulation. In either event, there is deterioration of quality and reliability of reception. Increasing transmitted power is not the solution because fading and distortion occurs regardless of signal level. For this, as well as other reasons, it is recommended that an investigation be undertaken in the application of improved and more sophisticated modulation and multiplexing techniques for CW communications and for the transmission of digital data.

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6. Gemini XI Program Mission Report, MSC-9-12-66-8.

7. Gemini V Program Mission Report MSC-G-R-65-4.

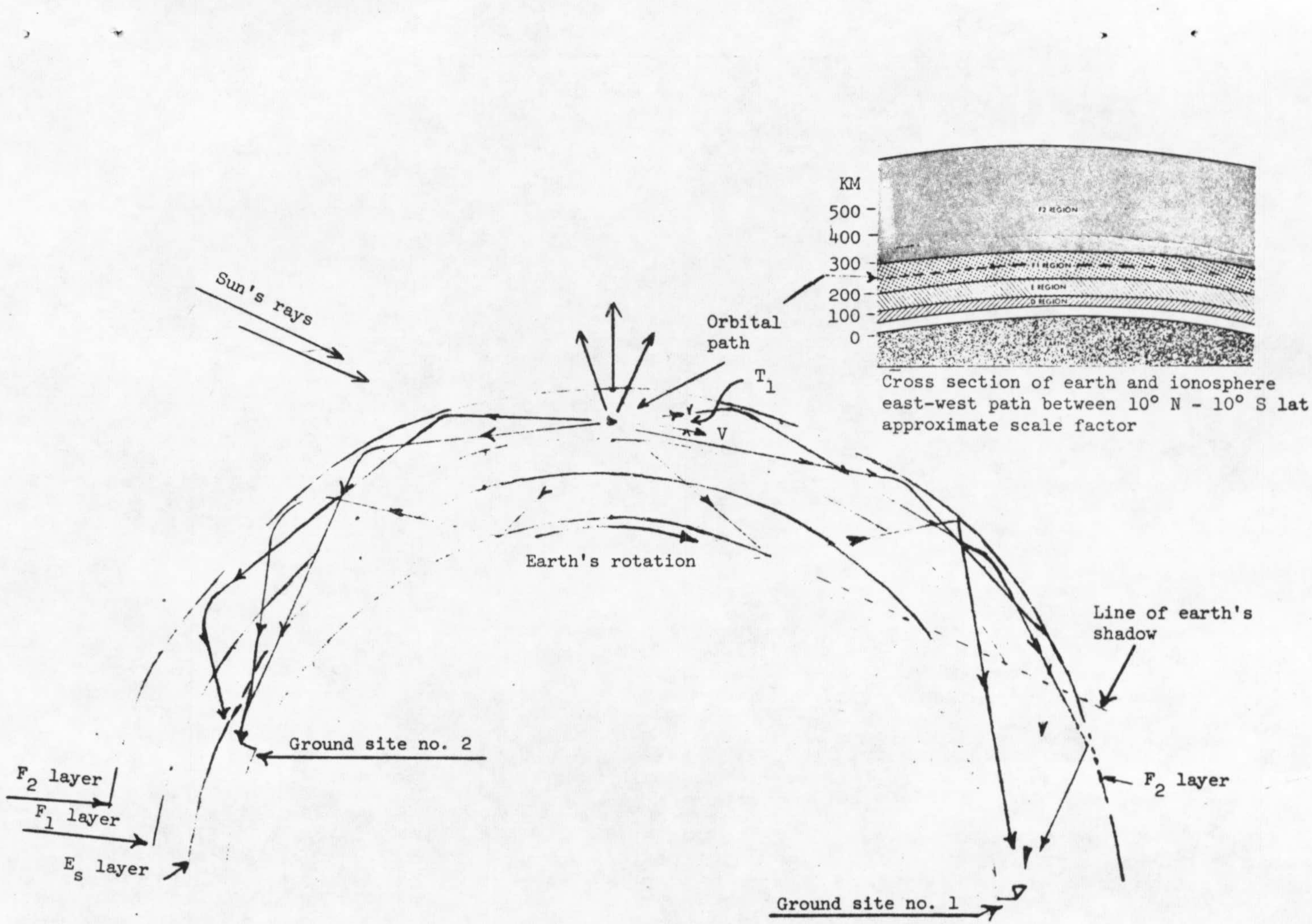
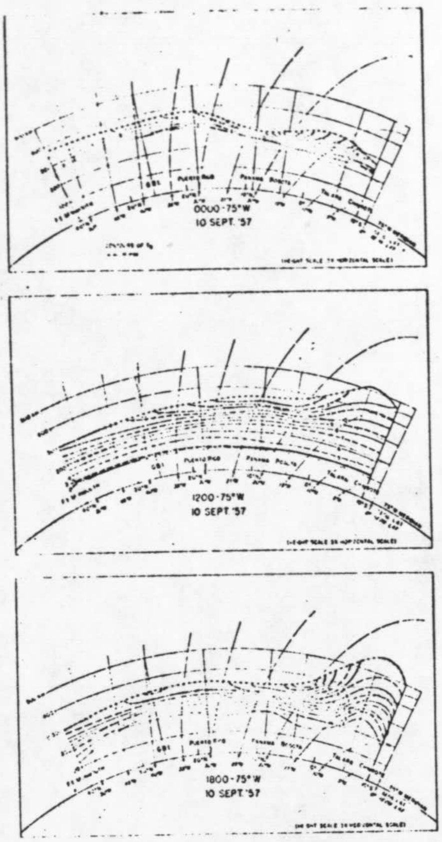
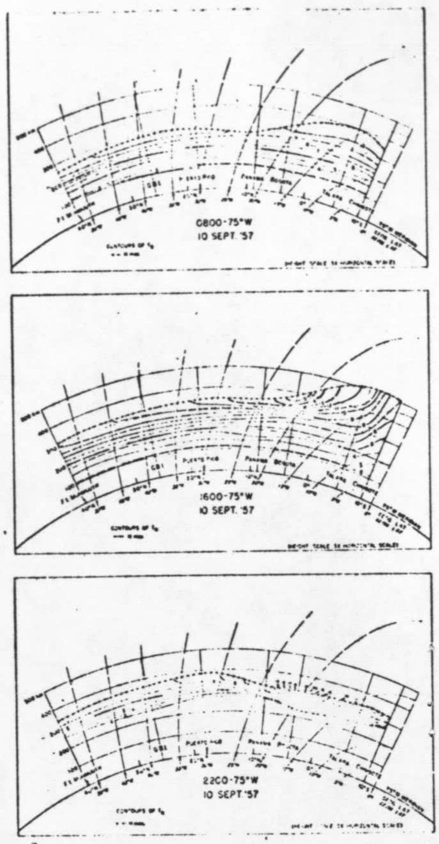


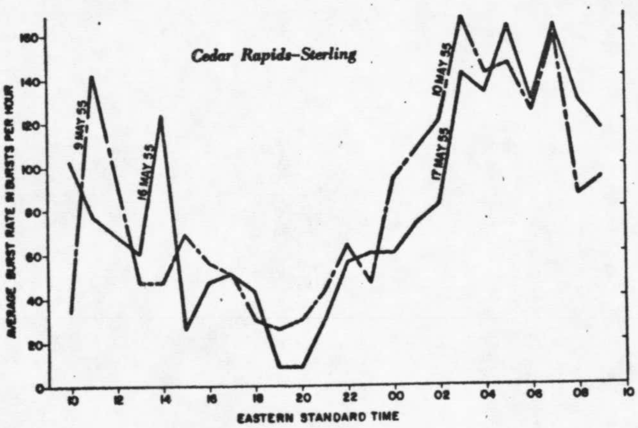
Figure 1.- Possible HF mode of propagation through the ionosphere orbiting spacecraft to earth sites.



(a) Electron density profile.



(b) Electron density profile.



(c) Hourly rate of meteor bursts.

Figure 2.- Hourly variation of observed meteor bursts, and density of the ionosphere versus latitude (reproduced from National Bureau of Standards Monograph 80).

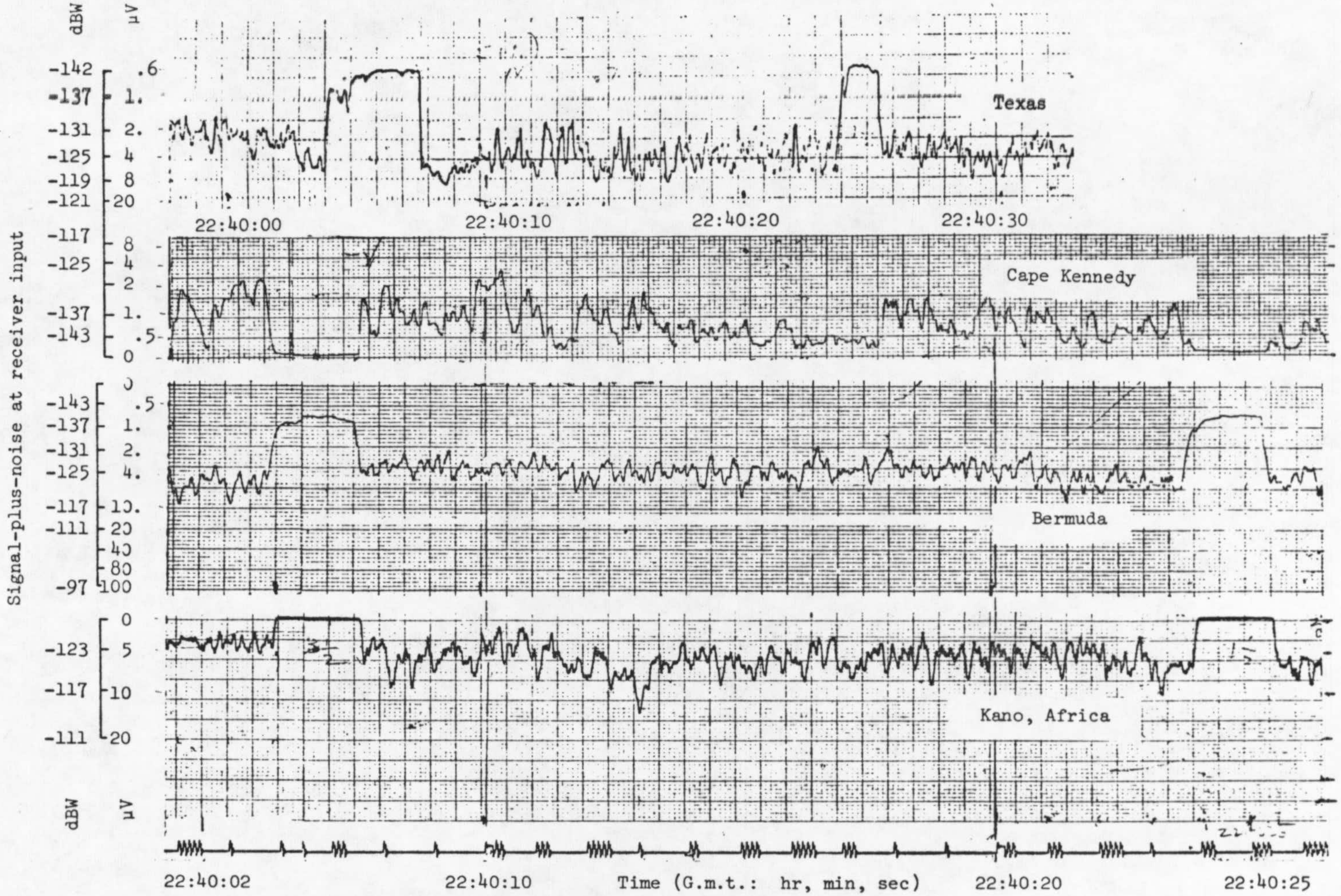


Figure 3.- Short term signal characteristics HF communications test no. 1, Gemini VII mission.

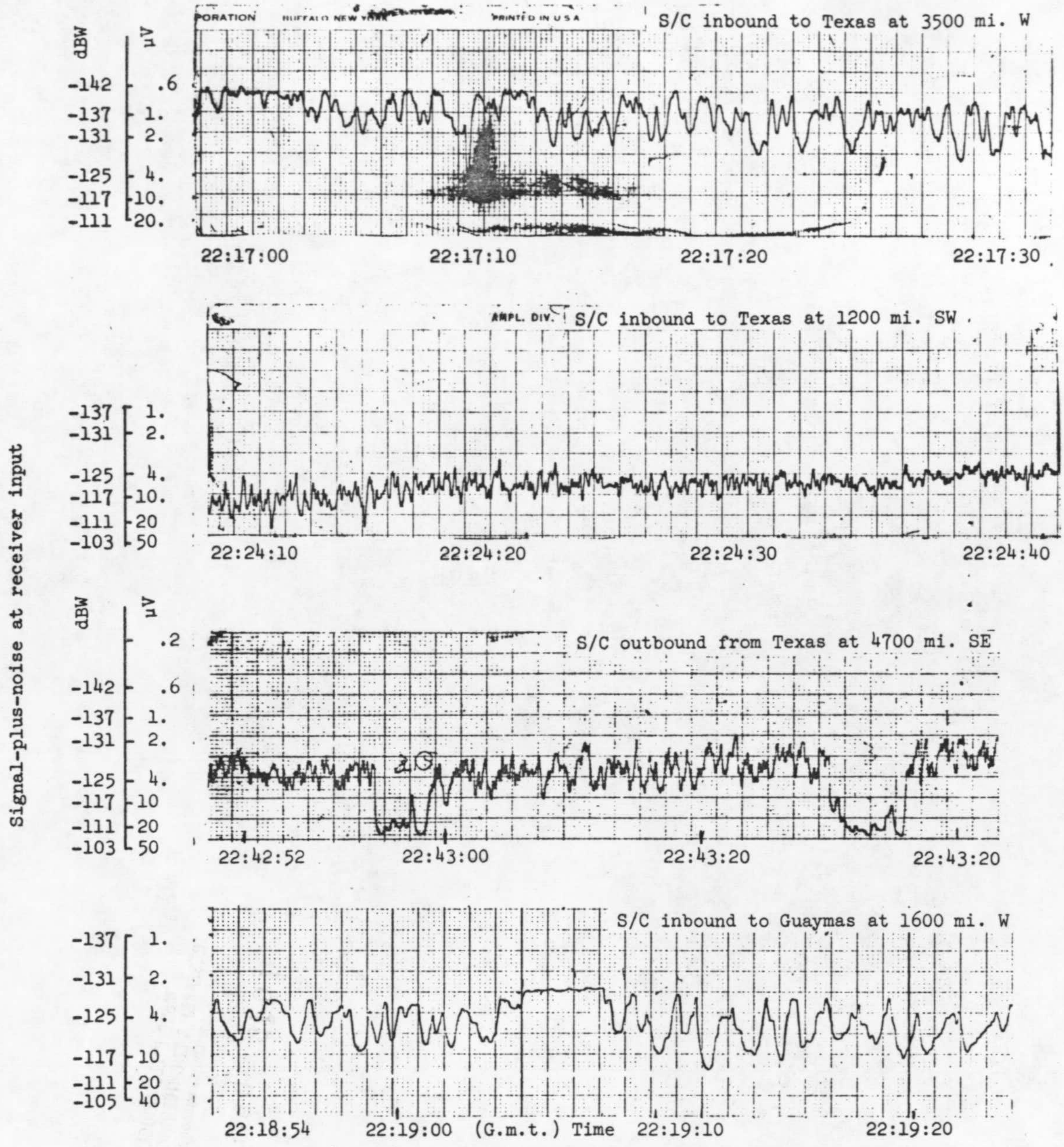


Figure 4.- Signal characteristics at beyond LOS distances, HF communications test no. 1, Gemini VII mission.