JPL PUBLICATION 81-84

Telecommunications in Cometary Environments

Warren L. Flock

(NASA-CR-164956) TELECOMMUNICATIONS IN COMETARY ENVIRONMENTS (Jet Propulsion Lab.) 43 p HC A03/MF A01 CSCL 17B

N82-11340

Unclas

G3/32 08279

July 1, 1981

NASA

National Aeronautics and Space Administration

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The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

ABSTRACT

Propagation effects on telecommunications in a cometary environment include those due to dust, the inhomogeneous plasma of the coma and tail, and ionization generated by impact of neutral molecules and dust on the spacecraft. Attenuation caused by dust particles is estimated to be on the order of 10^{-5} dB for the Halley Intercept Mission (HIM). Ionization generated by impact on the spacecraft is estimated to result in an electron content of 10^{12} to 10^{13} el/m^2 (3 eV electrons) along the telecommunications path.

An estimate of the electron content due to Comet Halley itself is 10^{16} to 10^{17} el/m^2, compared to a content of 10^{16} to 10^{18} el/m^2 for the earth's ionosphere and 10^{17} to 10^{18} el/m^2 for the interplanetary medium. The cometary plasma is probably highly turbulent and inhomogeneous and can cause some degree of amplitude scintillation at frequencies of hundreds of MHz or more. A margin of 2 dB is recommended to allow for propagation effects on the HIM.

The electron content of the plasma near Comet Halley will cause excess range delay, and a doppler shift of the signal from the spacecraft will occur in proportion to the rate of change of the path electron content. It is recommended that S and X down-link frequencies be employed to monitor the path electron content and amplitude scintillation and spectral broadening of the received signals. These measurements will provide a quantitative base of knowledge that will be valuable for radio science and telecommunications system design purposes.

Acknowledgments

I would like to express my appreciation to the staff of the Jet Propulsion Laboratory for their cooperation and support and for the information that they have supplied in the preparation of this report. Included among those who have supplied especially valuable help are J. Barengoltz, T.N. Divine, M. Koerner, T.A. Komarek, G.S. Levy, G.K. Noreen, E.K. Smith, M.K. Tam, and R.T. Woo.

As of July 1, 1981, I will have returned to my position in the Department of Electrical Engineering at the University of Colorado, Boulder, Colorado. I would additionally like to thank my colleagues at JPL for their assistance in the final processing of this report.

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1. INTRODUCTION

1.1 HALLEY INTERCEPT MISSION

The emphasis of this report is directed specifically to the Halley Intercept Mission (HIM), but the intention is that it be applicable to telecommunications in cometary environments in general as well. Factors that may affect propagation on deep-space missions are reviewed in Sections 1.2, 2, and 3. Sections 4 and 5 then deal with possible impairments of propagation during the Halley Intercept Mission.

A brief description of the HIM is included to show the assumptions that were used in considering possible effects on telecommunications when the spacecraft is in the near vicinity of Comet Halley. The orbits of the Earth and Comet Halley and the path of the spacecraft are shown in Figure 1, where the launch date is given as August 13, 1985 and the encounter date is March 23, 1986 (Blume, 1981). The orbit of Comet Halley is retrograde. (The motion of the comet around the sun is opposite to the direction of rotation of the planets around the sun.) At perihelion (closest approach to the sun), the comet is on the opposite side of the sun from the Earth. The pre-perihelion closest approach of the comet to the Earth occurs on November 27, 1985, and the post-perihelion closest approach of the comet occurs on April 11, 1986. The planned encounter of the spacecraft with the comet is a post-perihelion encounter.

The path of the spacecraft with respect to the comet near the time of encounter is shown in Figure 2 (Blume, 1981). The spacecraft flyby velocity is 62 km/s and the sun-Halley/spacecraft trajectory angle at the time of close encounter is shown in the insert as 112.5°. The closest approach of the spacecraft to the comet is planned to be 1000 km. The encounter takes place at a distance of 1.047 AU from the sun at a distance of 0.718 AU from the earth.

A statement of mission objectives is given in Figure 3.

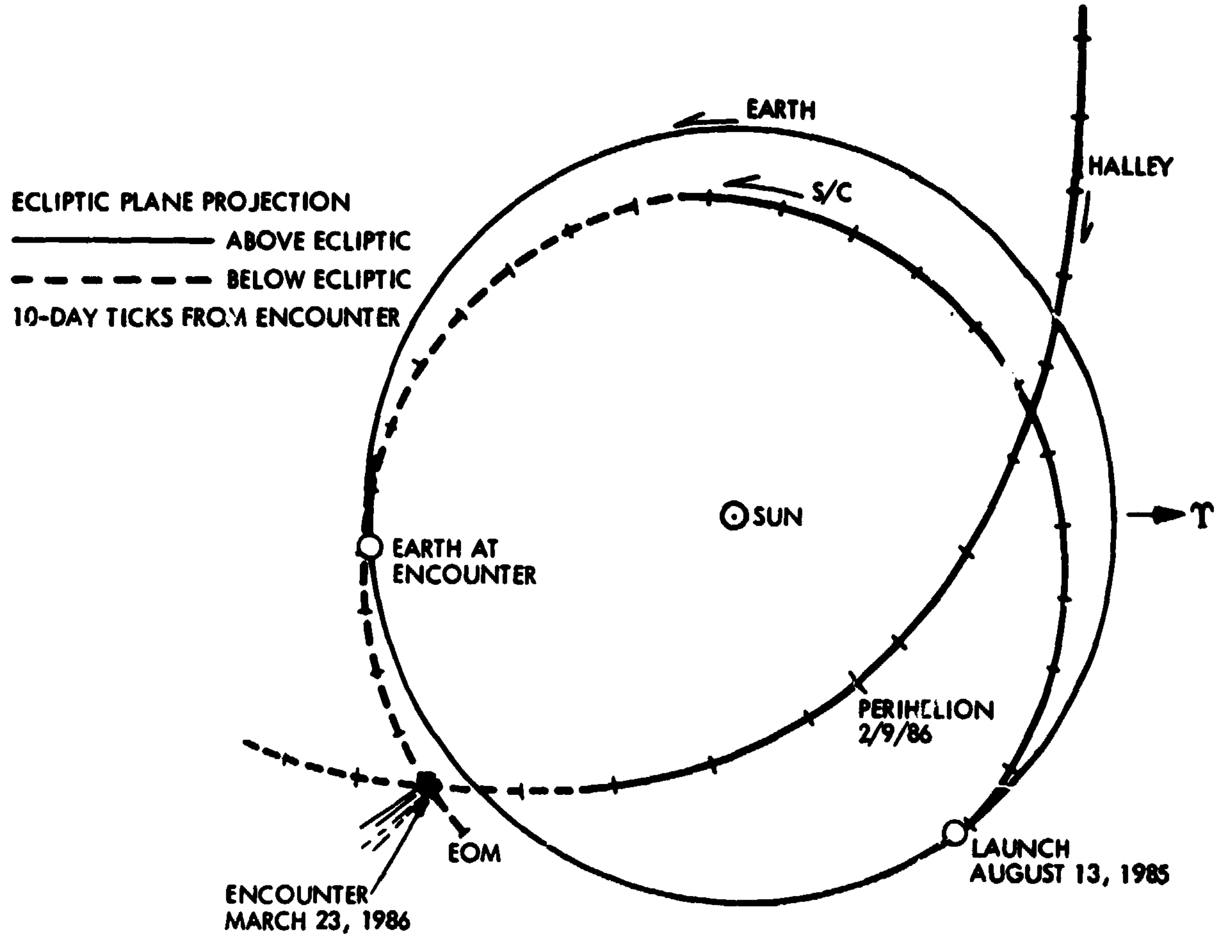

Figure 1. Postperihelion Halley Intercept Trajectory from Launch to End of Mission (EOM)

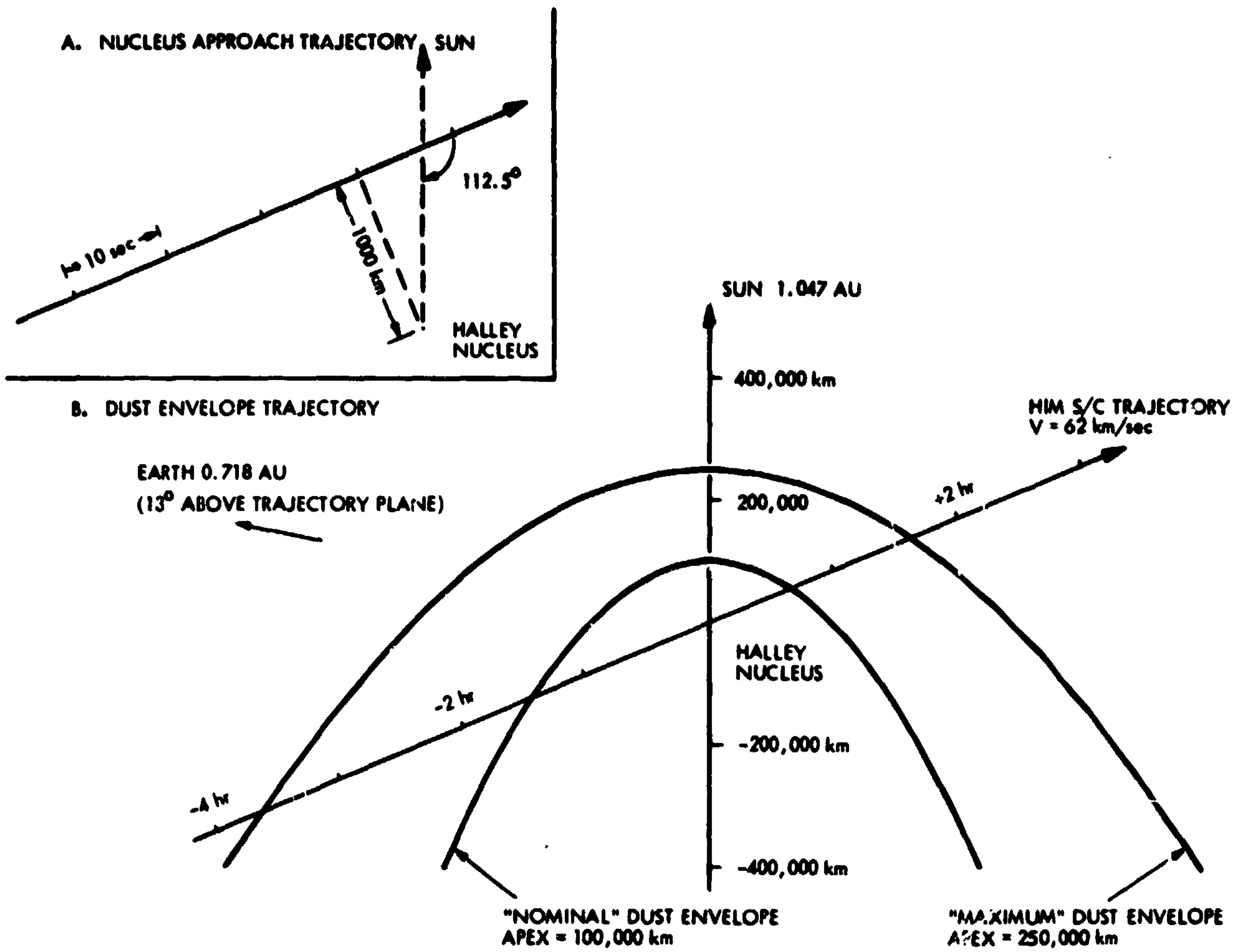

Figure 2. Halley Intercept Mission Near-Encounter Trajectory (Postperihelion--March 23, 1986)

- DETERMINE THE PHYSICAL STRUCTURE OF THE NUCLEUS OF HALLEY'S COMET
- STUDY PROCESSES WHICH OCCUR IN BRIGHT, ACTIVE COMETS (HALLEY AND NEW COMETS)

  A) CHARACTERIZE THE CHEMICAL AND PHYSICAL NATURES OF THE COMET HALLEY ATMOSPHERE AND IONOSPHERE AS WELL AS THE PROCESSES THAT OCCUR IN THEM

  B) DETERMINE THE SIZE AND SPACE DISTRIBUTIONS AND THE COMPOSITION OF DUST GRAINS

  C) DETERMINE THE NATURE OF THE INTERACTION BETWEEN THE SOLAR WIND AND THE COMA

  D) DETERMINE THE NATURE (STRUCTURE AND DYNAMICS) OF THE TAILS

Figure 3. Halley Intercept Mission Objectives

1.2 PROPAGATION EFFECTS IN DEEP-SPACE TELECOMMUNICATIONS

In this section an introduction is given to propagation effects which may be pertinent for telecommunications to and from cometary environments. Effects in interplanetary media and planetary and cometary environments and effects due to the impact of dust and gaseous molecules on the spacecraft are introduced. These effects of most obvious potential importance are discussed further in Sections 2 and 3.

1.2.1 Interplanetary Media

Propagation of electromagnetic waves on deep-space paths is influenced by dust and by the solar wind or extended solar corona. Dust particles of space are believed to be responsible for the zodiacal light, but the loading of dust per volume of space is so low and the particle sizes are so small that the dust of interplanetary space has negligible effect on microwaves.

A model of the electron density in the solar wind out to 1 AU (1.496×10^{11} m) has been formulated by Berman (1979). Based on determinations of electron density by a number of investigators, the model has the form of

$$N(R) \cong \frac{2.21 \times 10^{14}}{R^6} + \frac{1.55 \times 10^{12}}{R^{2.3}} \quad \frac{el}{m^3} \tag{1}$$

where R represents distance from the sun in units of solar radii and N is electron density in electrons/m^3 (el/m^3). At $R = 1.1\ R_\odot$ the density is $1.25 \times 10^{14}/m^3$ according to the model, and at R = 1 AU ($214.94\ R_\odot$) the model predicts a density of $6.70 \times 10^6/m^3$ or $6.7/cm^3$. (The symbol $R_\odot$ stands for the solar radius, 6.96×10^8 m.) The electron content of the solar wind can cause the various effects on propagation that can occur in other plasmas, especially the effects that tend to be prominent in highly turbulent, inhomogeneous plasmas, such as amplitude and phase scintillations, Doppler frequency fluctuations, spectral broadening and angular broadening. The effects are discussed in Sec. 3. All of the effects tend to be proportional to the total electron content (TEC) along the path, $\int N dl$, where N is electron density and dl is an increment of length. The effects are most intense for paths which pass close to the sun but can be noticeable for paths at 1 AU and farther (Woo, 1977).

1.2.2 Planetary and Cometary Atmospheres

Several of the planets have atmospheres which affect the propagation of electromagnetic waves to a significant degree. The Earth provides examples of the various effects, but some are more pronounced in the dense atmosphere of Venus and elsewhere. The effects can be separated into those involving nonionized gases and particulate matter, commonly discussed under the heading of tropospheric propagation in the case of the Earth, and effects involving ionized gases, treated under the heading of ionospheric propagation.

The nonionized gases of the Earth's atmosphere have an index of refraction n which is only slightly greater than unity and is a function of pressure, temperature, and water vapor pressure as indicated by

$$N = (n - 1) \times 10^6 = \frac{77.6p}{T} + \frac{3.73 \times 10^5 e}{T^2} \qquad (2)$$

where p is total pressure in mb, e is water vapor pressure in mb, and T is temperature in kelvins. Because n is only slightly different from unity, N, defined in Eq. (2) and not to be confused with the electron density of Eq. (1), is commonly used in its place. Surface values of N, referred to as refractivity, range from near 200 in high, dry locations to about 400 in humid, tropical areas of the Earth. In spite of the small departure of n from 1, this deviation is responsible for significant range or group delay, bending and elevation angle errors, amplitude and phase scintillation, beam spreading, and sometimes intense fading on near-horizontal paths (Hall 1979).

On Venus much higher values of N, between about 15,000 and 18,000, can be calculated for the surface on the basis of the various published values of pressure, temperature, and composition, while on Mars the N value is only about 3.

Absorption due to the gases of the Earth's troposphere is low at frequencies below 10 GHz but becomes about 0.5 dB for a one-way vertical path from sea level at the water-vapor absorption peak at 22 GHz and over 100 dB for the same path at the oxygen absorption peak at 60 GHZ. Amplitude scintillations due to the Earth's troposphere have been reported as about 0.1 dB or less at elevation angles of about 10° at a frequency of about 7 GHz at a temperate northern latitude (Crane and Blood, 1979). More intense amplitude scintillations have been observed during radio occultation of spacecraft by Venus (Woo, Armstrong, and Ishimaru, 1980). Two associated effects have also been encountered in such occultations. One is the occurrence of a critical level where "super refraction" occurs Below this level no information can be obtained about the atmosphere by occultation techniques. At the critical level the radius of curvature of the refracted ray is equal to the distance from the center of the planet. The ray from the spacecraft therefore circles the planet and does not reach the Earth (Eshleman, 1973). The same phenomenon of super refraction can occur in the Earth's atmosphere, where it is sometimes responsible for abnormally long ranges of terrestrial radar systems. Before the critical level is encountered during occultation, the second of the two effects referred to above, signal attenuation due to beam spreading (also referred to as defocusing) occurs (Kliore, 1972; Young, 1976). This effect is one of differential refraction that takes place because the index of refraction varies with height above the surface of the planet. The result is that a family of rays within the spacecraft antenna beam become more widely separated than in empty space, which indicates that signal intensity is reduced. The effect is usually of minor importance in the Earth's atmosphere. In analyzing scintillation in radio occultation of Venus, Woo, Armstrong, and Ishimuru (1980) found a defocusing attenuation of about 10 dB on S and X bands (larger on X-band than S-band).

Attenuation and noise due to rain in the Earth's atmosphere becomes increasingly serious above 10 GHz but causes problems in the DSN at X-band as well. Dust and sand storms have received little attention but may present a problem for satellite communications at X-band, especially if both terminals of a domestic satellite system experience storms at the same time, as might occur in desert areas of North Africa and the Mideast.

The possible effects of the electrons of planetary atmospheres or ionospheres can be separated into two categories - those that are inherent in any plasma or ionized gas and those that occur only in inhomogeneous plasmas. Possible effects in homogeneous plasmas include absorption, Faraday rotation, phase advance, group delay, dispersion, and doppler shift in frequency. Additional effects that may be observed in inhomogeneous planetary plasmas include amplitude scintillation, phase scintillation, doppler frequency fluctuation, and spectral broadening. The effects tend to be proportional to total electron content (TEC) along the path but are a function of the degree of turbulence as well.

Dust, neutral molecules, and ionized gases are present in the comas and tails of comets. Separate dust and ion tails are commonly observed. The amount of information on the effects of cometary atmospheres on the propagation of radio waves is small, but observations were made on January 5, 1974 of the occultation of a radio star by Comet Kohoutek (Ananthakrishnan, Bhandari, and Rao, 1975). Radio source PKS2025-15 was occulted by the comet's tail. Observations at a frequency of 327 MHz showed a scintillation index S_4 of 0.2 to 0.3 (ratio of standard deviation to mean value of signal power). The fluctuations in intensity were interpreted by Lee (1976) as indicating rms fluctuations in electron density of 8×10^7 el/m^3, an inner scale of fluctuation of 8×10^5 m and a largest scale of 4×10^8 m. The turbulence in the comet's tail was attributed to a Kelvin-Helmholtz instability, due to velocity shear, by Lee and Wu (1979). Fluctuations were observed when the radiowave path passed through the tail but not when the path was near the nucleus.

This observation of occultation by a comet is useful. In addition, experience with propagation in planetary atmospheres and interplanetary media is utilized here to consider possible effects in cometary atmospheres. Information on propagation in terrestrial dust and sand storms is helpful in considering the effects of dust in cometary atmospheres.

The subjects of atmospheric effects on telecommunications and radio science are closely related. Radio science provides information that is useful for telecommunication purposes, and telecommunications systems are important tools for radio science. Radio occultation observations have provided information about planetary atmospheres (Eshleman, 1973). Radio science opportunities for the Halley Intercept Mission have been considered by Levy (1981) and are discussed in Sec. 5.

1.2.3 Effects Associated with Spacecraft

Spacecraft may cause effects on telecommunications which would not otherwise occur. Dust particles and gaseous molecules striking the spacecraft, primarily the dust shield in the case of the Halley mission, will cause some ionization. In the case of spacecraft using ion thrusters, such as the proposed Solar Electric Propulsion stage, ionization is introduced into the vicinity of the spacecraft.

An analysis of ionization due to the impact of dust and gaseous molecules has been made by Barengoltz (1981) and is discussed in Sec. 4. Possible effects of ion thrusters on S-band telecommunications have been considered by Ackerknecht and Stanton (1977) and Stanton (1980). Initially there was concern that the ion thrusters might cause beam spreading resulting in serious attenuation, but it was later concluded on the basis of experimental evidence that effects would be minor.

2. PROPAGATION IN DUST ENVIRONMENTS

Interplanetary space is not empty but is permeated by the solar wind and also has a content of dust. The dust particles of space are believed to be responsible for the zodiacal light, and the origin, distribution, and characteristics of interplanetary dust have received considerable attention (Halliday and McIntosh, 1980). Quoted values of the density of interplanetary dust that have been noted are about 10^{-17} or 10^{-18} g/m^3 (10^{-23} or 10^{-24} g/cm^3). These values represent the loading of dust per volume of space. The loading of dust is so low and the sizes of the particles are so small that the dust of interplanetary space has negligible effect on microwaves.

A very limited amount of information is available on propagation in terrestrial sand and dust storms. Sand and dust storms may reduce visibility to 10 m or less, reach a height of 1 km or more, and extend for hundreds of km over the earth's surface. Based on extrapolation of laboratory measurements at 10 GHz by Ahmed and Auchterlonie (1975), it has been estimated that the attenuation constant at 10 GHz for a particulate density of 10 g/m^3 is less then 0.1 dB/km for sand and 0.4 dB/km for clay (CCIR, 1978). It was concluded that total attenuation on earth-space paths should be less than 1 dB.

An analysis by Bashir, Dissanayake, and McEwan (1980) for 9.4 GHz has included the case of moist sandstorms and, assuming oblate spheroidal particles, has provided different values of attenuation for horizontal and vertical polarizations. Values for attenuation for moist sandstorms were as high as 1.83 dB/km for horizontal polarization. For dry sand the values were about 0.27 dB/km. Particulate densities or loading of air (g/m^3 of air) were not given, but values of particle volumes were included. If the particles themselves have densities of 1 g/cm^3, the loading of air would be about 1 g/m^3. Thus particulate densities in the order of 1 to 10 g/m^3 have been assumed for obtaining estimates of attenuation in the cases cited above. Bashir et al. (1980) concluded that attenuation in sandstorms could be a problem for domestic-satellite services in desert areas if sandstorms were encountered at both of two earth stations that were communicating via satellite.

For dust particles that are small compared to microwave wavelength, as for the water droplets of clouds, the theory of Rayleigh scattering applies. When this is the case the power attenuation constant α_p is proportional to mass loading (mass per unit volume of space, e.g., g/m^3) as indicated by

$$\alpha_p = K\rho \quad \text{dB/km} \tag{3}$$

where α_p is in dB/km or dB/m and ρ is in g/m^3. K varies with frequency but has a fixed value for a given frequency. The total attenuation in A, in dB, is given by

$$A = \int \alpha_p \, dl = K \int \rho \, dl \quad \text{dB} \tag{4}$$

If the mass loading were constant along the path length this expression would take the form of $A = K\rho L$ where L is the path length. Whether ρ is constant or not, the total attenuation is given by

$$A = KM \quad \text{dB} \tag{5}$$

where M is the total mass along the path.

If an attenuation of 0.3 dB/km = 3×10^{-4} dB/m is assumed [compared to 0.27 dB/km quoted by Bashir et al. (1980) for dry sand], if a density of 1 g/cm^3 is assumed for the sand, and if L = 1 m, ρ = 1 g/m^3, and M = 1 g/m^2, the above relation becomes

$$3 \times 10^{-4} = K\,1$$

so that

$$K = 3 \times 10^{-4} \ (\text{dB/g/m}^2)$$

with A in dB and M in g/m2. This value will be used later in considering attenuation due to dust in the Halley mission. It may be more realistic to assume a density of 10 g/cm^3 for the density of sand. This value will result in $M = 10$ g/m^2 and $K = 3 \times 10^{-5}$. Use of $\rho = 1$ g/cm^3 for sand (treating it as a porous material) gives a larger K value which results in a higher predicted value of attenuation. Thus $K = 3 \times 10^{-4}$ is a more conservative value than $K = 3 \times 10^{-5}$ as far as predicting effects in advance is concerned.

3. PROPAGATION IN IONIZED MEDIA

3.1 EFFECTS IN HOMOGENEOUS PLASMAS

The effects which occur in a homogeneous plasma are absorption, Faraday rotation, range or group delay, phase advance, doppler frequency shift, and breakdown of bandwidth coherence. Expressions for these effects for high frequencies are shown in Table 1.

Table 1. Effects in Homogeneous Plasmas

Effect	Units	Expression
Absorption	dB	$A = \dfrac{1.17 \times 10^{-6}\ \nu(TEC)}{n_{re}\ f^2}$
Faraday rotation	radians	$\phi = \dfrac{2.36 \times 10^4}{f^2}\ \overline{B}_L(TEC)$
Range or group delay	m	$\Delta R = \dfrac{40.3}{f^2}\ (TEC)$
	s	$\Delta t = \dfrac{\Delta R}{c} = \dfrac{1.34 \times 10^{-7}(TEC)}{f^2}$
Phase advance	radians	$\Delta\phi = \dfrac{\Delta R\ 2\pi f}{c} = \dfrac{8.44 \times 10^{-7}\ (TEC)}{f}$
Doppler frequency	Hz	$f_D = \dfrac{\Delta\phi}{2\pi\ T_c} = \dfrac{8.44 \times 10^{-7}}{2\pi f}\ \dfrac{\Delta(TEC)}{T_c}$
Bandwidth coherence	$\dfrac{\text{radians}}{\text{Hz}}$	$\dfrac{\Delta\phi}{\Delta f} = -\ \dfrac{2.68 \times 10^{-7}\ (TEC)}{f^2}$
	$\dfrac{\text{s}}{\text{Hz}}$	$\dfrac{\Delta t}{\Delta f} = -\ \dfrac{2.68 \times 10^{-7}\ (TEC)}{f^3}$

$TEC = \int N\,dl$, where TEC is total columnar electron content in el/m^2, N is electron density in el/m^3, and the integral is evaluated along the path. Frequency, f, is measured in Hz. In the expression for absorption, ν is the collision frequency in Hz, and n_{re} is the real part of the index of refraction. In the expression for Faraday rotation, $B_L = B_o \cos\theta$ is the longitudinal component of magnetic flux density in Wb/m^2, with B_o the total magnetic flux density and θ the angle between the field lines and the path. The overbar indicates the effective value of B_L. Instantaneous doppler frequency f_D equals $(1/2\pi)$ $d\phi/dt$. In the table f_d is the average doppler frequency during the count time or interval T_c in which the phase change $\Delta\phi$ takes place. The expressions are applicable for high frequencies including 100 MHz and higher. Normally at such frequencies and for propagation in planetary atmospheres, n_{re} is very close to unity.

At microwave frequencies in solar and planetary atmospheres and interplanetary media, absorption is very low and can normally be neglected. Faraday rotation may be significant [3 to 7^o in the earth's ionosphere and 20 to 200^o in a path passing within 4 $R_\odot$ of the sun at 2.3 GHz (Smith and Edelson, 1980)]. The phenomenon of Faraday rotation, however, refers to the rotation of linearly polarized waves. Telecommunication signals from spacecraft are normally circularly polarized, and circularly polarized waves are characteristic waves which propagate without any change in polarization.

The range or group delay may be expressed either in terms of distance or time. The range delay shown is an excess range delay above the delay corresponding to true range. In the case of positioning and navigation systems it represents a range error, and should be estimated or determined as accurately as possible and subtracted from the indicated range to obtain true range. The excess range delay can be determined by using two frequencies, such as X- and S-band frequencies. The range delay in itself presents no problem for telecommunications and is a potentially valuable tool for radio science. Rapid phase variations and accompanying high doppler frequencies may present a problem for telecommunications but are most apt to occur in inhomogeneous plasmas.

3.2 AMPLITUDE AND PHASE SCINTILLATION

Additional effects that occur in inhomogeneous plasmas are amplitude scintillation, phase scintillation, doppler frequency fluctuations, spectral broadening, and angular broadening.

Irregular variations or scintillations of the amplitude of radiowaves received from radio stars were first recorded by Hay, Parsons, and Phillips (1946) who reported variations in the amplitude of signals from Cygnus and Cassiopeia at 36 MHz. With the advent of satellites, scintillations of signals from such spacecraft were also observed (Yeh and Swenson, 1964). The signals from radio stars are incoherent and broadband and allow the recording of amplitude scintillations but not phase scintillations. Coherent, monochromatic signals from spacecraft allow the recording of phase scintillations and spectral broadening as well as amplitude scintillations (Crane, 1977; Woo, 1977; Smith and Edelson, 1980). The early observations of scintillation were at rather low frequencies and on the basis of the assumed form of decrease of scintillation intensity with frequency, it was expected that frequencies as high as those of the 4 and 6 GHz bands planned for the INTELSAT system would be free from scintillation effects. It developed, however, that scintillation occurs at frequencies at least as high as 6 GHz. In particular, significant scintillation occurs at 4 and 6 GHz in equatorial latitudes (Craft and Westerlund, 1972; Taur, 1973).

The occurrences of scintillation mentioned above have been attributed to diffraction patterns formed at the ground by a steadily drifting pattern of irregularities in the ionosphere (Hewish, 1952). Most analyses have assumed that the irregularities occur in a thin layer or that they could be produced by an equivalent thin layer or screen. Immediately below the diffracting screen only phase fluctuations occur but farther below the screen at distances in the order of the Fresnel distance and greater, amplitude fluctuations develop. The Fresnel distance z is given by $z = L^2/\lambda$ where L is the scale length of the irregularities and λ is wavelength.

Stars twinkle in visible light but, because of their larger angular size, planets do not. The same effect of size occurs for radio waves. The reduction in scintillation, when the source has an angular width greater than a certain value, is due to the fact that the diffraction pattern on the ground is the convolution of the point-source pattern and the brightness distribution of the source. For weak scattering the angular width of the source, $\Delta\theta$, must be less than the angular width of the irregularities as seen from the ground if scintillation is to develop. The relation used by Lawrence, Little, and Chivers (1964) is that

$$\Delta\theta < \frac{L}{2\pi d} \tag{6}$$

for scintillation to occur, where L is the scale size of the irregularities and d is the distance to the modularities. Typically radio sources must be smaller than about 6 to 10 minutes of arc if ionospheric scintillation is to develop.

In recording signals from radio sources of very small size on paths passing close to the sun, Hewish, Scott, and Wills (1964) observed scintillations having short periods, typically about 1 s, which is small compared with the periods, typically around 30 s, that are associated with ionospheric scintillations. For such short-period scintillations to be recorded, the sources must have angular widths of about 0.5 second of arc or less. On the basis of the relation of Eq. (6) and taking into account that the signal paths passed close through the solar wind close to the sun, it was concluded that the scintillations were of interplanetary origin. An account of the early observations of interplanetary scintillation (IPS) has been provided by Cohen (1969). The use of IPS of spacecraft signals has become an important means for obtaining information about the solar wind (Woo, 1977).

In terms of their utility for radio science, phase scintillations have advantages over amplitude scintillations. The intensity of amplitude scintillations have been measured by various indices, such as S_4, defined as the standard deviation of received power to mean value, or m, defined as the ratio of the rms fluctuation to the mean value. Amplitude scintillation can build up to a value of S_4 or m of unity but saturates or limits at this value. Phase scintillation does not saturate but can increase indefinitely. Amplitude scintillation can provide information about irregularities having a scale size in the order of the first Fresnel zone diameter and smaller, whereas phase scintillation can provide information about larger irregularities as well. The factor limiting the capability of amplitude scintillations is that elements of radiation from the even Fresnel zones interfere destructively with elements of radiation from the odd Fresnel zones. Thus the identity of irregularities that are large compared to the first Fresnel zone is lost. Sometimes the small scale structure of turbulence is of much interest, however, and amplitude scintillation can provide information about this structure.

Some analyses of IPS have been carried out by use of the diffracting screen model that has been used for ionospheric scintillation, but it has been asserted that this approach has limitations whereas the Rytov approximation or method of smooth perturbations is applicable generally (Jokipii, 1973; Woo and Ishimaru, 1973, 1974; Crane, 1977; Ishimaru, 1978).

In addition to scintillations due to the earth's ionosphere and the solar wind, scintillations due to a planetary ionosphere other than the earth were recorded by Pioneer 10 radio-occultation measurements of the ionosphere of Jupiter (Woo and Yang, 1978). The scintillations are believed to be caused by electron density irregularities similar to those found in the earth's ionosphere. As mentioned in Section 1.2.2 there is also one observation of scintillation during occultation by Comet Kohoutek (Aranthakrishnan, Bhandari, and Rao, 1975).

3.3 ANGULAR AND SPECTRAL BROADENING

Before IPS was recognized, it was noted that radio-star signals that passed near the sun experienced angular broadening (Hewish, 1955). What was actually observed was a decrease in signal amplitude. This decrease could not be explained on the basis of absorption or refraction but only on the basis of angular broadening due to scattering by electron density irregularities. The attenuation observed disagreed with the absolute value expected on the basis of the theory of absorption and varied differently with frequency. The variation of the mean value of electron density could not produce the refraction necessary to explain the attenuation on that basis either. Note that the angular broadening referred to here is a different phenomenon than the beam spreading or defocusing mentioned in Section 1.2.2 which is due to refraction.

Angular broadening has been vividly illustrated as such by two-dimensional displays produced by a radioheliograph operating at 80 MHz in Australia (Blesing and Dennison, 1972). The radioheliograph utilized has a beamwidth at the zenith of 3.9' and produces a 2° square-area picture of the sky every second. Other observations of angular broadening have been made by Slee (1959) and Erickson (1964).

The first angular broadening measurement of a spacecraft signal utilized 2.3 GHz transmissions from Helios spacecraft in a joint program of the United States and West Germany. Radio scattering measurements were made over the range from 1.7 to 180 $R_\odot$. At 1.7 $R_\odot$ a decrease in signal-to-noise ratio of 4.52 dB was encountered. Of this amount about 0.30 dB was attributed to defocusing or beam spreading (refraction) and the remainder of 4.22 dB was attributed to angular broadening (multiple scattering) (Woo, 1978). Spectral broadening measurements were made at the same time as angular broadening observations and the combination of the two allowed determination of the solar wind velocity (Woo, 1977).

The observation of spectral broadening requires a stable monochromatic signal. The first observation of spectral broadening was made when Pioneer 6 was occulted by the sun (Goldstein, 1969). To record spectral broadening the sidebands of the spacecraft signal are eliminated by filtering and only the pure carrier signal is recorded. Spectral broadening causes the carrier signal which originally has a very narrow width (less than 0.5 Hz) to become broadened in frequency. The phenomenon is due to the doppler shift of elements of radiation that are scattered from electron-density irregularities or to amplitude scintillation or to a combination of both mechanisms. Goldstein recorded variable widths of spectral broadening, ranging from about 4 to 22 Hz, apparently corresponding to variations in the intensity of solar activity, at an angular distance of about 2.4° or a linear distance of about 9 $R_\odot$ (9 solar radii) from the sun.

Measurements of spectral broadening made by use of Helios satellites showed broadening to a bandwidth of 58.6 Hz at $R = 2.18\ R_\odot$, 90.8 Hz at $R = 2.02\ R_\odot$, and 119.1 Hz at $R = 1.7\ R_\odot$ (Woo, 1978). At $R = 10\ R_\odot$, the bandwidth was about 1 Hz. These Helios measurements were made at a time of solar minimum, whereas the results reported by Goldstein occurred at a time of solar maximum.

The above observations of spectral broadening were for paths close to the sun, but spectral broadening due to the ionosphere of Jupiter was also recorded on Pioneer 10 and 11 2.3-GHz transmissions (Woo and Armstrong, 1980). The recorded bandwidth in this case was 2.5 Hz. The accompanying amplitude scintillations were weak. It was concluded that the spectral broadening was due to the high fly-by velocity of 3.5×10^4 m/s.

4. EFFECTS OF COMET HALLEY ENVIRONMENT

4.1 INTRODUCTION

Having considered a number of effects on telecommunications that have been observed in interplanetary media and planetary atmospheres, we now turn to the Halley Intercept Mission (HIM) itself. Which, if any, of the effects are likely to be important to the HIM?

As for nonionized matter, dust is known to occur in the cometary atmosphere and has been recognized as a hazard to the spacecraft. Possible effects of dust on telecommunications deserve attention. The neutral molecules of Comet Halley constitute only a tenuous atmosphere unlike those of the Earth and Venus. A brief account of effects in dense, un-ionized atmospheres like those of the Earth and Venus was included in Section 1.2.2, but it appears unlikely that such effects will be important for the Halley mission. This conclusion is supported by noting that molecular number densities for Comet Halley have been estimated as being about $10^{15}/m^3$ at a distance of 500 km from Comet Halley (Divine, 1980) compared with about $2.5 \times 10^{25}/m^3$ at the surface of the Earth, $8.6 \times 10^{24}/m^3$ at 10 km above the Earth's surface, and $2.0 \times 10^{22}/m^3$ at an altitude of 50 km (U.S. Standard Atmosphere, 1976).

With regard to ionized media, estimates of total electron content (TEC) through the Halley environment are quoted as from 10^{16} to several multiples of 10^{17} per m^2 (Levy, 1981). Values for the Earth's ionosphere range from 10^{16} to 10^{18} with 10^{19} sometimes listed as an extreme value. Thus the TEC values for Comet Halley and the Earth apparently overlap. Microwave transmissions in homogeneous plasmas having TEC values of these magnitudes are not affected significantly. Quite unexpectedly, however, it developed that microwave transmissions experience significant scintillation after sunset and before midnight near the Earth's geomagnetic equator, because of the inhomogeneous nature of the equatorial ionosphere. Cometary ionospheres are probably highly turbulent and inhomogeneous, and possible propagation effects due to the anticipated inhomogeneous nature of cometary ionospheres need attention. These effects include amplitude and phase scintillation, doppler frequency fluctuation, angular broadening, and spectral broadening. It is of interest that spectral broadening in Jupiter's ionosphere has been thought to be due to the high flyby velocity as it was accompanied by only weak scintillation (Woo and Armstrong, 1980).

4.2 ESTIMATES OF EFFECTS ON TELECOMMUNICATIONS

4.2.1 Dust

The relation

$$A = KM \quad dB \tag{5}$$

for the attenuation due to dust particles was presented in Section 2. A value of K of 3×10^{-4} was estimated for frequencies of about 9 or 10 GHz, based on measurements and calculations relating to terrestrial sandstorms. A value of M for a 600 km flyby of Comet Halley (and more distant flybys) can be obtained from data supplied by Divine (1980). He has provided fluences of f_i (mass loading in a 1 m^2 cross section along the length of the path) for dust particles in the ith size range. From his Table 2, the total fluence $F = \Sigma f_i$ is 1.12×10^{-4} kg/m^2 = 1.12×10^{-1} g/m^2. This is the total amount of matter encountered per unit area during the flyby.

Reference to Figure 2 shows the direction of the Earth with relation to the spacecraft and Halley trajectories. Taking into account this direction, it appears that a maximum of roughly one half of the total fluence would lie between the spacecraft and the Earth at any time. Therefore one can let $M = F/2 = 5.59 \times 10^{-2}$ g/m^2. Using this value for M and the value given above for K yields

$$A = (3 \times 10^{-4})\ (5.59 \times 10^{-2})$$

$$= 1.68 \times 10^{-5} \text{ dB}$$

This value is sufficiently low that dust can be said to pose no problem for telecommunications.

The estimate given above is very rough, but most of the roughness is on the conservative side. The DSN X-band frequency of about 8.5 GHz is slightly lower than the frequencies used in obtaining the estimate, and the attenuation at 8.54 GHz would be somewhat less than at 9 or 10 GHz. The attenuation at 2.3 GHz would be considerably smaller. In obtaining the value of K, a density of 1 g/cm^3 was assumed in Section 2. If a value of 10 g/cm^3 had been assumed, K would have been 3×10^{-5} and A would have been 1.68×10^{-6} dB. The assumption that M = F/2 is not necessarily accurate, but the actual condition should not differ greatly. Fluence values given by Hughes (1979) were also used as a check. From his data, $M = 3.77 \times 10^{-2}$ g/m^2 and $A = 1.1 \times 10^{-5}$ dB.

The dust near Comet Halley should present no problems for telecommunications at microwave frequencies. Note that the effects of dust are judged to be very small at microwave and lower frequencies but that no analysis has been made of possible effects on optical transmissions. While further studies of the dust hazard to the spacecraft may yield somewhat different values of fluence, the values would have to be drastically different to change the conclusion reached here.

Dust may present a problem for terrestrial communications but the loading of the terrestrial atmosphere can apparently be much higher than the levels in the vicinity of Comet Halley, around 1 g/m^3 for the terrestrial case versus about 10^{-7} g/m^3 near Comet Halley.

4.2.2 Impact of Gas Molecules and Dust

The effects of the impacts of gas molecules and dust on the spacecraft have been analyzed by Barengoltz (1981), and the discussion here is based on his treatment.

One phase of the analysis is concerned with estimating the rate of production of electrons by impact, and a second phase involves estimating electron density and total electron content (TEC) along the propagation path, given the electron production rate.

For gas molecules, the electron production rate S_o in units of electrons per second (el/s) is assumed to be given by

$$S_o = \phi A_{sc} \tag{7}$$

where ϕ is the flux of gas molecules [molecules per square meter per second or molecules/$(m^2 s)$] and A_{sc} is the area of the spacecraft on which the molecules impinge. The expression is based on the assumption that every molecule becomes singly ionized. The kinetic energy of an impinging molecule, $1/2\ mv^2 = 6.58 \times 10^{-17}$ J for molecules with a mean molecular weight of 22, for which m = 22/A where A is Avogadro's number for a kg mol (6.025×10^{26}/kg mol). The velocity v is the flyby velocity of about 60 km/s. Converting to energy in electron volts (eV) by equating 6.58×10^{-17} J to the charge of the electron (1.6022×10^{-19} C) times voltage, the energy in eV is 410 eV. Some of this energy will be used to excite electrons of the molecules to higher energy states and some will be used to produce ionization. It is possible that some molecules will be more than singly ionized, but, on the other hand, some recombination will take place. The assumption of complete single ionization seems to be reasonable.

Having estimated the electron production rate, the next step is to estimate the resulting electron content along the path. One approach is to determine the density as it would be if the electrons moved out uniformly with spherical symmetry so that

$$N(r) = \frac{S_o}{4\pi r^2 v} \tag{8}$$

Here N(r) is the density at the distance r from the center of the sphere for electrons moving with velocity v. Note that

$$N(r)\ 4\pi r^2 v$$

has units of

$$\left(\frac{el}{m^3}\right)\ (m^2)\ \left(\frac{m}{s}\right) = \frac{el}{s}$$

It is obvious that the assumption of spherical symmetry is not entirely correct but the actual situation will not be drastically different and the approach seems reasonable for purposes of estimation. From the above expression for N(r), the total electron content (TEC) is obtained from

$$\mathrm{TEC} = \int_a^{\infty} \frac{S_o}{4\pi r^2 v}\, dr = \frac{S_o}{4\pi v a} \tag{9}$$

where a is the radius of the original surface. It might seem questionable that the TEC would increase as "a" decreases but note that S_0 will also decrease as a and A_{sc} decrease.

To this point the value of TEC has been based on the instantaneous production of electrons, but the electrons previously generated are said to be accounted for by replacing Eq. (8) by

$$N(r) = \frac{S_o}{4\pi r^2 v}\left[1 + \left(\frac{V}{v}\right)^2\right] \tag{10}$$

where V is the spacecraft velocity and v is the electron velocity.

It is necessary to make an assumption about the velocity v of the electrons. A value that has come out of discussions for the energy of the electrons is 3 eV, and this corresponds to a velocity of 10^6 m/s which can be compared to the spacecraft flyby velocity of 6.2×10^4 m/s (or about 6.0×10^4 m/s). The higher the velocity of the electrons the faster they move away, the lower the electron density (Eq. 8), the lower the TEC (Eq. 9), and the lower the correction factor of Eq. (10). An additional consideration that tends to increase the electron density, however, is the occurrence of space charge resulting in a positive potential of about 20V for the spacecraft (Neugebauer, 1980). An increase by a factor of 26, above what would otherwise be the density, has been adopted by Barengoltz.

For dust the approach is similar to that for molecules, and S_0 is given by

$$S_0 = \frac{N_0}{A} A_{sc} \sum m_i \tag{11}$$

where Σm_i is the mass per square meter per second of dust, N_0 is Avogadro's number, and A is the molecular weight of the dust material. Thus $N_0 \Sigma m_i/A$ gives the number of molecules, as N_0/A is the number of molecules per unit mass. If Avogadro's number is taken as 6.025×10^{26}, referring to a kg mol, Eq. (11) can be used as it is. If Avogadro's number is taken as 6.025×10^{23}, referring to a g mol, an additional factor of 1000 can be introduced into Eq. (11) if SI units are used otherwise. Use of Eq. (11) involves the assumption that each molecule of dust becomes singly ionized, as was assumed for the gas molecules. It is pointed out that the kinetic energy of a molecule under the assumption of a molecular weight of 50 is 917 eV but that only a part of the energy (perhaps 81 eV) is available for ionization as energy also goes into electron excitation and heating. Furthermore some recombination takes place. Using values for m_i from Divine (1980) but not including the $[1 + (V/v)^2]$ factor of Eq. (10), Barengoltz has obtained results which are summarized in Tables 2 and 3.

The values of the tables indicate that even for an approach as close as 300 km, the TEC values are several orders of magnitude below estimates for TEC due to the comet itself. It appears that the ionization induced by impact of gas molecules and dust particles should not be a problem.

Table 2. Dust Impact Ionization

Flyby Distance km	S_o electrons/s	n_{max} electrons/m^3	TEC electrons/m^2
300	2.1×10^{19}	1.6×10^{14}	1.5×10^{13}
600	5.3×10^{18}	4.0×10^{13}	3.8×10^{12}

Table 3. Neutral Gas Impact Ionization

Flyby Distance km	S_o electrons/s	n_{max} electrons/m^3	TEC electrons/m^2
300	2.4×10^{19}	1.8×10^{14}	1.6×10^{13}
600	5.1×10^{18}	3.8×10^{13}	3.4×10^{12}

Some environmental results are available for comparison. In terms of electrons produced per kg of mass (el/kg) of dust particles, Barengoltz predicts an upper limit of 8.4×10^{24} el/kg, whereas Dietzel, Neukum, and Rauser (1972) obtained a value of 6.25×10^{24} el/kg in an experimental program. The highest velocity, achieved with a Van de Graff generator, was about 40 km/s compared to 62 km/s for the Comet Halley flyby.

4.2.3 Inhomogeneous Plasma Effects

The plasma generated by Comet Halley can be expected to be highly turbulent and inhomogeneous and to have some effect on radiowave transmissions. The intensity of the effect will vary inversely with a power of frequency. It is likely to be significant for frequencies of several hundred MHz. In the case of the occultation by Comet Kohoutek of 327 MHz transmissions, a scintillation index S_4 of 0.2 to 0.3 was recorded. If amplitude scintillation varies as $1/f^{1.5}$ (Fremouw et al., 1978), the index at 2.3 GHz should be only about 0.02, which is not significant. Furthermore the observed scintillation was for a path through the comet's tail and appeared to diminish when the path was near the nucleus. However a high degree of variability from one comet to another can be expected, and one observation does not constitute a reliable base for making decisions.

If propagation impairments result in a maximum degradation in signal-to-noise ratio of 1 or 2 dB, providing a margin of 1 or 2 dB is probably the efficient means of coping with the problem, to maintain the same data rate. Use of more sophisticated coding techniques may be advisable if impairments are more serious. In assessing the effects of fading or amplitude scintillation on bit error rate (BER), knowledge of the probability distribution of the amplitude fluctuations is highly desirable. The probability p_B of a given BER is a function of the ratio of bit energy E_b to noise power density N_o, i.e.

$$p_B = f(E_b/N_o) \tag{12}$$

For a Viterbi coded channel for example, p_B is given approximately by

$$p_B \cong e^{-(\alpha_0+\alpha_1 E_b/N_o)} \tag{13}$$

with $\alpha_0 = -4.4514$ and $\alpha_1 = 5.7230$ (Koerner, 1981). If signal amplitude is reduced by a factor "a" with a = 1 corresponding to the design value and a < 1 representing a degradation in performance, E_b/N_o in Eq. (12) can be replaced by $a^2 E_b/N_o$. In practice a will ordinarily not be reduced by a fixed amount but will vary in accordance with a probability density function p(a). In that case p_B will be given by

$$p_B = \int_0^\infty f\,(a^2 E_b/N_o)\; p(a)\, da \tag{14}$$

Thus if p(a) is known one can determine what increase in margin or change in coding or reduction of data rate is needed to retain a satisfactory BER. Lacking knowledge of p(a) or of the mean value of a or of any bounds on a for Comet Halley, one is reduced to making an educated rough estimate, but the above discussion is pertinent in that it shows what information the design engineer would like to have. It suggests also that an effort should be made to determine the probability density function of the amplitude fluctuations during the HIM, so as to accumulate a data base for future use.

It is understood that present plans for the HIM telecommunications system call for a margin of 2 dB, and it is recommended that the HIM proceed on the basis of retaining the 2 dB margin. The one observation of occultation by a comet (Comet Kohoutek) suggests that the effect may be less than 2 dB. As stated, however, one observation does not constitute a reliable data base. Furthermore, the path through the coma was in a much different direction for Comet Kohoutek than it will be for Comet Halley. Also the unexpected amplitude scintillation at 4 and 6 GHz due to the earth's equatorial ionosphere suggests a degree of caution. Therefore, it is concluded that a margin of no less than 2 dB should be retained.

Spectral broadening, discussed in Section 3.3, is a possibility because of the high flyby velocity. In considering the effects of spectral broadening, broadening of a few Hz may not necessarily be harmful in itself, but if it is due to amplitude scintillations the amplitude variations may cause a problem. If the broadening is due to doppler shifts of signal components scattered from electron density irregularities and is unaccompanied by significant amplitude scintillation, the potential for a harmful effect is considerably reduced. The possibility of spectral broadening should be kept in mind and a strategy should be devised so that it will have been worked out in advance if broadening becomes a problem, but no known basis exists for predicting that the problem will be serious.

5. RECOMMENDATIONS FOR MEASUREMENTS DURING MISSION AND FOR FURTHER WORK

The information base concerning turbulence, electron density and its distribution, and effects on the propagation of electromagnetic waves in cometary atmospheres is exceedingly meagre. The Halley mission provides an opportunity to remedy that condition by making measurements which will be valuable to telecommunications and radio science. It is recommended that measurements be made of electron content, amplitude scintillation, and spectral broadening, as a minimum program.

Whereas the X-band is preferable to the S-band for minimizing plasma effects, the more sensitive S-band is superior for measuring plasma effects. Having both S- and X-downlinks would satisfy both purposes. Furthermore the combination of S- and X-downlinks provides higher accuracy and sensitivity for recording electron content and scintillation than use of the S-band alone. It is recommended that the Halley spacecraft have both S- and X-downlinks.

Estimates of the electron content of Comet Halley are extremely rough but values of 10^{16} to 10^{17} el/m^2 have been mentioned by Levy (1981). This content is comparable to that of the Earth's ionosphere, which has values generally between 10^{16} and 10^{18} el/m^2. The electron density in the interplanetary medium between the earth and spacecraft is very low, about 10^7 el/m^3, but as the path length is about 0.7 AU or 10^{11} m, the interplanetary content is approximately 10^{18} el/m^2. The electron content of the comet's atmosphere may thus not constitute a large fraction of the total electron content along the path. On the other hand $\Delta(\overline{TEC})$, where the overbar indicates a mean value, for a given count time T_c will be higher when the spacecraft is passing through the cometary atmosphere than when in interplanetary space. This condition may allow a determination of cometary electron content. It is also possible that the electron content of the cometary atmosphere may be lost in noise and too low to measure, but that result would allow putting an upper bound on the content, and would be valuable.

Determination of the probability density function of amplitude scintillation would be valuable for telecommunications, and scintillation data would provide information about turbulence in the comet's atmosphere. Amplitude scintillation in particular would be suitable for obtaining information on the small-scale structure of turbulence. The high flyby velocity of 62 km/s may well result in spectral broadening, and monitoring and recording of spectral broadening is important to telecommunications. In the process of determining electron content and recording amplitude scintillation and spectral broadening, phase scintillation and doppler frequency data would presumably be utilized or at least be available. It would seem desirable to retain this data as well.

Understanding of the propagation medium has become increasingly important as missions have become increasingly sophisticated, and an opportunity to increase the understanding at a reasonable cost should not be lost. The dual-frequency (S- and X-) technique for determining electron content has already been developed, and it is recommended that it be used on the Halley mission. Employing this technique will provide increased understanding of propagation effects, as opposed to proceeding on the basis of empirical experience only.

It is realized that the recommendation for employing a dual S- and X-system must be considered in the light of cost. Having only one downlink available would present a dilemma. An X-band link would provide greater protection against unexpectedly large plasma effects but at the expense of the sensitivity needed for a good measurement of the effects. An S-band link alone would provide higher sensitivity for measuring plasma effects than an X-band link and could be used in a DRIVD mode (differenced range versus integrated doppler) but would not be completely satisfactory, as compared to a dual-frequency S-X system.

Richard Woo and John Armstrong have developed a program for analyzing propagation effects for Starprobe. This same program could be applied to the Comet Halley environment, and it is recommended that it be so applied. It appears that the program could be employed at rather small cost. The results should be very interesting and would provide another input to be weighed, concerning possible effects on telecommunications and effects that would be useful to radio science.

6. CONCLUSIONS

Three phenomena - dust, ionization produced by impact, and plasma irregularities and inhomogeneities - are considered to be most likely to affect telecommunications on the Halley mission. Analysis of the effects of dust and ionization produced by impact indicates that they should cause no problem. Reaching a conclusion concerning inhomogeneous plasma effects is more difficult. No basis exists for recommending a larger margin than 2 dB, and caution suggests that a 2 dB margin should be retained.

To increase the understanding of the propagation medium, it is recommended that both S- and X-band downlinks be employed to measure electron content, amplitude scintillation, and spectral broadening. The results would be pertinent to telecommunications and radio science.

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