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UHF-SHF Satellite Communications Link Calculations

July, 1975

UHF-SHF Satellite Communications Link Calculations

final report

Study Contract No. PL 36100-4-0995
Department of Communications
Government of Canada

Final Report

Submitted by
Satellite Systems Planning

Bell-Northern Research
Ottawa-Canada

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ABSTRACT

This study was carried out for the Department of Communications to perform the link calculations for the UHF-SHF Multipurpose Satellite System.

The satellite system would operate in two basic configurations:

- *(i) a double hop configuration for communicating between a wide variety of government field users including field parties, aircraft and ships, and*
- *(ii) a single hop configuration for good quality voice communications between commercial users.*

Configuration (i) provides 100 channels in the UHF (300-400 MHz) band with a satellite SHF (4/6, 7/8 or 12/14 GHz) back haul system to a central station. Configuration (ii) uses 12/14 GHz in the FDM or SCPC mode.

This study was carried out in three steps:-

- *a) A detailed examination was made of current papers on the propagation statistics for Canada in these frequency bands, including scintillation and multipath fading and the effects of man-made noise, intentional as well as unintentional. Link margins and noise budgets were then established.*
- *b) Current modem techniques were examined, analog and digital, and the merits of each system compared against the satellite system requirements.*
- *c) The link calculations were then performed and curves plotted of the results indicating the expected performance of the various services for various reliability requirements.*

The conclusions of the study show that the proposed UHF-SHF Multipurpose satellite system is technically quite feasible and no major problems were found in the system design. However, the UHF band presents some serious multipath fade and man-made interference problems which need careful consideration before the system design is finalized.

The modem survey indicates that adaptive narrowband FM (ANBFM) should be considered for field quality voice and 32 kb/sec adaptive delta modulation (ADM) with coherent PSK for good quality voice or data transmission.

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1.0 INTRODUCTION

1.2 OBJECTIVES AND TERMS OF REFERENCE OF STUDY

This section describes the four tasks to be carried out in this study.

The Statement of Work for the Study carried out under Contract PL.36100-4-0995, for the Department of Communications (DOC), details four tasks as given below. The total effort in terms of technical man-power resource was 25 man-weeks. The Design Authority for this contract was the Director General, Space Program (DOC) and the Project Officer supervising the work was Mr. H.L. Werstiuk, assisted by Mr. C. Oakes.

The four tasks were specified as follows:-

Task 1 (Ref. CS 3.1): Link Margins and Noise Budgets

The contractor shall review the available documentation outlined in the references. The review shall be for the purpose of establishing the adequacy and completeness of the link margin and noise budget work outlined therein. The contractor shall take into account additional work which has been carried out since the above mentioned references were prepared. Calculations of link margin and noise budgets will then be carried out, and the sensitivity of these margins and budgets to the desired reliability and earth station parameters will be examined. Links at UHF will be examined first, with further appropriate work in other frequency bands (12 - 14 GHz, L-band) being carried out as directed by the project officer. The contract shall suggest appropriate budgets (if necessary) to take into account interference in the various bands, and to take into account the projected intermodulation interference.

Task 2 (Ref. CS 3.2): Modem Evaluation/Selection

The contractor shall survey modulator/demodulator (modem) technology and coding techniques which would be appropriate to the UHF multi-

1.0 INTRODUCTION

1.1 REASONS FOR STUDY

The reasons for this study and overall objectives are summarized.

The Department of Communications (DOC) has been conducting a series of studies over the past few years on the feasibility of UHF/SHF Satellite systems to serve the Canadian Government civilian and military needs. These studies have reached a point where reasonably definitive technical system parameters have to be derived. This study formed part of this latter continuing effort. The primary objectives of this study was to carry out the satellite system link calculations and to evaluate and recommend suitable modulators/demodulators (modems) for these satellite systems.

purpose satellite system. The basic philosophy of inexpensive and reliable transportable and mobile earth stations meeting a wide range of user needs with the same hardware should be kept in mind.

The objective will be to identify the commonality in the range of user requirements which could be met by a single or small number of different modems.

The contractor shall consider the following generic types of modems:

(a) NBFM, ANBFM, PDM, DM/PSK or DM/FFSK for mobile quality voice.
(b) FM with companding, DM/PSK or DM/FFSK for toll quality voice.
(c) PSK or FFSK for data of all bit rates.

The ease of including voice activation in the candidate modems shall be considered. The contractor shall then prepare his recommendations on the modem approach for this system, and shall include information on the expected or proven performance characteristics of both the surveyed and recommended modems. Performance specifications for the selected modem types will be prepared.

Task 3 (Ref. CS 3.3): Power Budgets, EIRP Levels, Bandwidth Requirements

The contractor shall calculate and establish uplink and downlink power budgets, space and earth segment EIRP levels, and bandwidth requirements for the identified system links. These parameters will be sensitive to desired link reliability and ground station parameters, and this sensitivity shall be explored. The contractor shall take into account the concept that EIRP and bandwidth will be allocated to the individual user as required to meet the type and quality of the desired communications.

Task 4

The contractor shall present the total findings of his work in a report and supply 20 copies.

2.0 BASELINE SYSTEM

A baseline system configuration for carrying out the link calculations has been assumed based upon the user requirements contained in the DOC Report$^{(2.1)}$ entitled "Multipurpose UHF Satellite Communication System Feasibility Study (Dec, 1974)", henceforth referred to as the Feasibility Study Report (Dec, 1974).

2.1 USER REQUIREMENTS

This subsection outlines the different requirements of the potential users of the multipurpose UHF/SHF satellite.

The users of the multi-purpose UHF Satellite as identified in the Feasibility Study Report (Dec, 1974) would be the Department of National Defence (DND) and various civilian government departments. Their needs are defined as:

(a) communication to field parties and to aircraft and ships,
(b) data retransmission from environmental platforms (DRP), and
(c) emergency beacon monitoring.

The service requirements include voice, teletype (75 b/s), data (2.4 kb/s and 4.8 kb/s) and facsimile carried over low capacity channels, to mobile and transportable UHF stations. For DND users, encrypted signal transmission with anti-interference capability is also required. Details of the user requirements are given in Table 2.1.

Towards the end of this study a further need was included for single channel per carrier and multi-channel per carrier services in the SHF satellite band for public and commercial use with multibeam Canadian coverage. This need was in general terms and no specific details were given.

TABLE 2.1

User Requirements

CLASSIFICATION	TACTICAL			CIVILIAN					
AGENCIES	DND			Other civilian governments					
TRAFFIC MODE	Secure			Clear					
TYPE OF TRAFFIC	Voice, Facsimile, Data			Voice, Facsimile, Data, Teletype, DRP, Beacons					
QUALITY*	Field or Good Quality			Field (simplex) Good Quality (duplex)					
		MOBILE			MOBILE				
GROUND STATION TYPES	Regional	Sea, Air	Portable	Regional	Sea	Air	Portable	DRP	Beacons
QTY OF GROUND STATIONS (Approximate)	9	142	7	7	41	2	295	fixed: 3050 Moving 1877	?
NUMBER OF CHANNELS	A total of 100 VF two-way circuits.								

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* Note: See Footnote on Page 3-2.

2.0 BASELINE SYSTEM

2.2 SYSTEM CONFIGURATION

Different system configurations which will likely satisfy the users' needs are briefly presented.

A variety of transponder configurations may be used to satisfy the user requirements. Basically, the configurations fall into three categories:

(a) UHF transponder,
(b) UHF/SHF transponder, and
(c) SHF transponder.

In the second configuration (b) the SHF link is used between the satellite and the central control station or regional ports. This eases the assignment of UHF frequencies and allows some anti-interference capability by utilizing SHF spot beams.

This configuration, however, requires a double-hop system for communication between two remote (UHF) stations.

In the case of the UHF system (a), the Feasibility Study Report (Dec. 1974) states that in the period of maximum traffic, about 270 frequency assignments for both uplink and downlink will be required. The bandwidth in each channel is about 20 kHz with 25 kHz channel spacing, and the 270 frequency assignments will most likely be spread over a 15 MHz band in both the uplink and downlink.

2.0 BASELINE SYSTEM

2.3 BASELINE DESIGN

Various system configurations are outlined.

To carry out the present study, the most probable transponder configuration - UHF/SHF - was taken as the baseline design. In this configuration, the UHF band lies between 300 MHz and 400 MHz and the SHF band may be from any one of the following: 4 - 6 GHz, 7 - 8 GHz or 12 - 14 GHz. The links between the satellite and Central Control Station (CCS) or Regional Ports (RP), utilize frequencies in the SHF bands while the links between the satellite and other types of stations (including mobile or transportable stations, data retransmission platforms and emergency beacons) utilize frequencies in the UHF bands. Some cross-strapping of SHF and UHF subsystems in the satellite allows a limited number of direct communication links between the CCS's and RP's (SHF-SHF) and among mobile or transportable stations (UHF-UHF). (See Figure 2.1)

To respond to an additional request towards the end of this study to include a multi-spot beam satellite system, a 12 - 14 GHz transponder configuration is also considered(2.2). The 12 - 14 GHz channels may carry single channel per carrier and multi-channel per carrier services for public and commercial use.

A summary of the various configurations are given in Table 2.2.

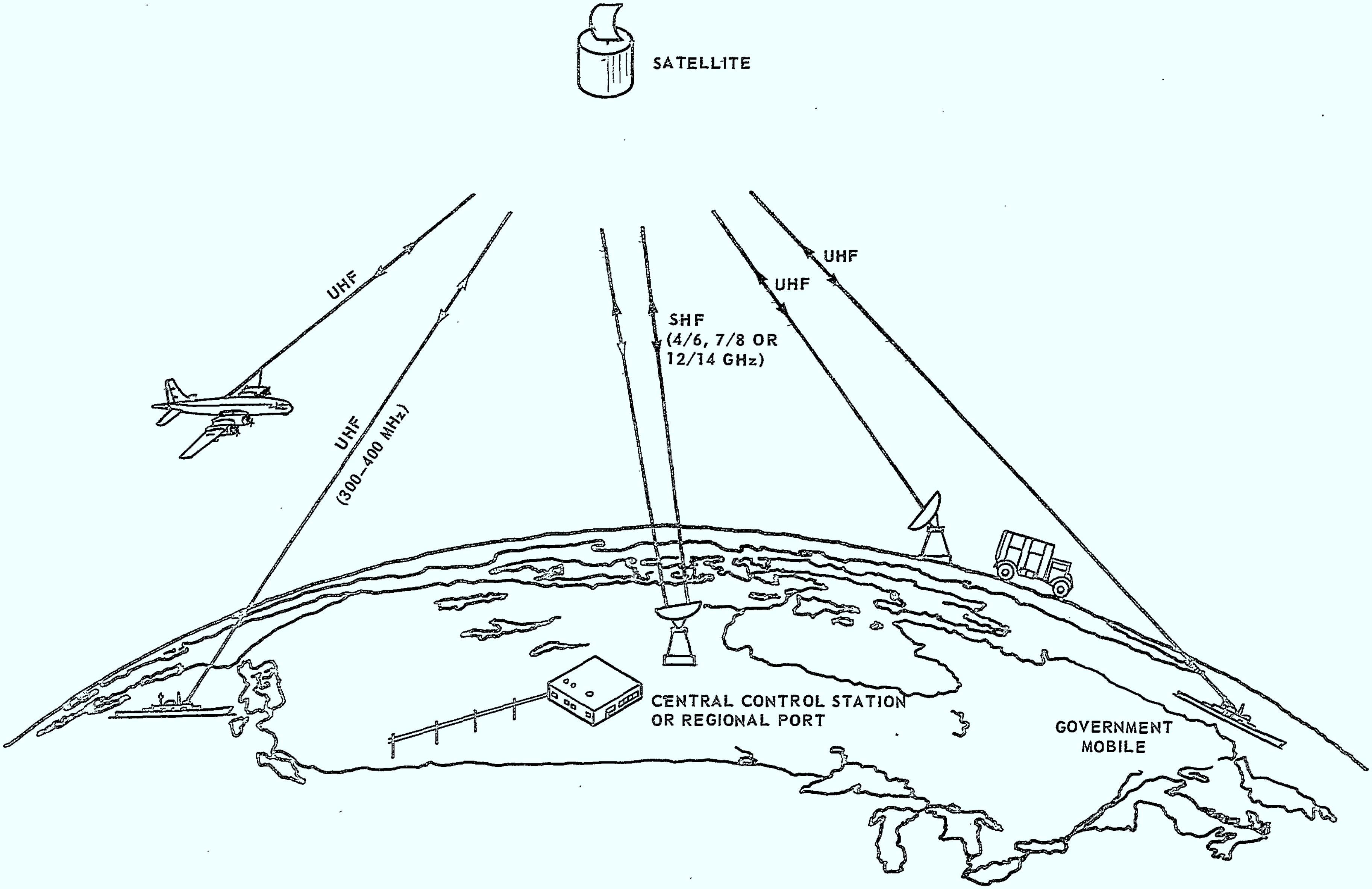

FIGURE 2.1

UHF–SHF System Configuration

TABLE 2.2

Various Configurations

USERS	LINK BETWEEN GROUND STATIONS	LINK FREQUENCY UPLINK/DOWNLINK
Government	(Central Control/regional) to (Mobile/portable)	SHF/UHF
	(Mobile/portable/DRP/Emergency Beacons) to (Central Control/regional)	UHF/SHF
	Central Control to/from regional (limited number of links)	SHF/SHF
	(Mobile/portable) to/from (Mobile/portable) (limited number of links)	(a) Single Hop - UHF/UHF (b) Double Hop - UHF/SHF/SHF/UHF
Public	Community to Community	SHF/SHF

2.4 REFERENCES

2.1 'Multi-purpose UHF Satellite Communications System Feasibility Study', Department of Communications, Government of Canada, December, 1974.

2.2 'Guidelines for the 12-14 GHz/UHF Transponder Model', Issue 1, Department of Communications, Government of Canada, March 30, 1975.

3.0 SYSTEM CONSTRAINTS AND PERFORMANCE OBJECTIVES

3.1 TECHNICAL CONSTRAINTS

The technical constraints are discussed with reference to the mobility requirement in the ground segment and the weight limitations in the space segment. Parameters considered are the antenna size, intermodulation noise, man-made noise, fading, jamming, etc.

The DND use will be mostly of a tactical nature, and the types of stations involved will be mainly mobile and transportable. For civilian use fixed as well as transportable stations will be required. Stations may be classified as ship mobile, air mobile and transportable. All stations will be modular in design for ease of maintenance and installation. Depending on the mobility and mounting requirements of each station type, the antenna size and thus the antenna gain, could be limited. Also, to ease alignment and acquisition problems, low gain omi-directional antenna are necessary for small aircraft applications.

In the Feasibility Study Report (Dec. 1974), it is stated that the UHF satellite will be in a geostationary orbit and a Thor-Delta 3914 launch vehicle would be used. This puts a limit on the maximum payload which can be carried, and hence on the antenna gain (due to the antenna size limitation) and the available power (due to the limitation on the size of the solar cell array).

Other technical constraints imposed on the multi-purpose UHF satellite system include:

- intermodulation noise caused by the nonlinearities of the UHF class C transistor amplifiers and SHF TWT amplifiers;
- man-made noise which is particularly severe in the UHF frequency band for wide antenna coverage;
- multi-path fading in the case of mobile stations; and
- jaming interference

3.0 SYSTEM CONSTRAINTS AND PERFORMANCE OBJECTIVES

3.2 SYSTEM PERFORMANCE REQUIREMENTS

The requirements of voice quality and data error probability are discussed.

For voice communications, the transmission quality required by the various users falls into two groups: field quality and good* quality. Field quality transmission requires low satellite power or small ground stations and the majority of the users (remote, mobile and military) specify this requirement because of cost and mobility considerations. Field quality voice can be described as intelligible voice, probably with a noisy background (see Section 5.2). A small percentage of users specify the need of good quality voice which requires voice signal fidelity as well as speech intelligibility. This quality approaches the performance required by a public telephone system, so that users may be interconnected with a commercial network.

For digital data communications, the bit error probability (Pe) required by the users varies between 10^{-4} and 10^{-5}. In the present study, 10^{-5} is taken as the desired performance objective.

Note:* In order to avoid any controversy in the definition of toll quality, a term used in the Feasibility Study Report (Dec. 1974), the term good quality is adopted for the purpose of this study. Refer to Section 5.2.

4.0 PROPAGATION CONSIDERATIONS

4.1 GENERAL

An overview of propagation problems on the UHF and the SHF bands is presented. Factors affecting the SHF link are rain attenuation and scintillation. Ionospheric scintillation and multipath fading are the dominant factors in the UHF link.

Free-space propagation loss, multipath fading, precipitation attenuation, scintillation, and received noises are the major design parameters in considering the space-earth communication link. Aside from the free-space propagation loss, propagation factors that are significant for the SHF link may have negligible effect in the UHF link and vice versa. It is of prime importance to obtain accurate values for various propagation parameters at the system design stage in order to realize a cost effective communication system. Unfortunately, the propagation factors are dependent not only upon the operating frequency but also on the antenna characteristics and the environment in which the transmitters and the receivers are located. Owing to the complexity of the problem and the limitations of available data, there is a certain amount of uncertainty in the data used in this report.

The square-law frequency dependence for free-space propagation loss is well known and there is no observed propagation anomaly in the space-earth link. Atmospheric attenuations due to water vapour and gases are very small for frequencies below 15 GHz. However, rain and cloud attenuations at frequencies above 7 GHz become severe and a proper link margin must be allocated.

Because of refractive index irregularities in the atmosphere and the ionosphere, large received signal fluctuations from the satellite have been measured both in the UHF and SHF bands. The ionospheric scintillation phenomenon in the UHF band is well known and extensive scintillation index statistics have been accumulated in the previous decades. Canada in general, and the northern part of Canada in particular, are in the area where severe ionospheric scintillation in the UHF band is experienced. The cause of received-signal fluctuations in the SHF band is, however, not well understood. In the overall UHF and SHF bands, three factors are emerging from various measured results: that the SHF scintillation zone and the UHF scintillation zone approximately cover the same area, that the amplitude fluctuation increases with decreasing antenna elevation angle, and that the scintillation index is approximately proportional to the wavelength squared.

The far-field antenna pattern beamwidth is usually very wide in the UHF band and this could have a significant effect in multipath fade problems. Multipath fadings due to specular and non-specular components from the ground reflected waves have been measured in mobile platform receivers. The fading magnitude distribution depends on the receiving antenna characteristics and the reflecting surfaces. There is very little published data in the open literature, aside from the description of the multipath fading phenomenon and some special data. In the case of a stationary receiver, the multipath fading phenomenon is usually neglected and the ionospheric scintillation is the major effect. However, in high latitude locations (with low antenna elevation angles) the received signal amplitude fluctuations could be due to a combination of ionospheric scintillation and multipath fading.

Another important consideration in the design of a satellite system is the noise environment. Aside from the basic receiver thermal noise and the effective antenna noise, unintentional man-made noise and lightning noise are also significant noise sources for the UHF receiver. Both these latter noise sources behave in bursts and vary from one place to another. Most of the man-made noise data is derived from measurements in the metropolitan areas of the U.S.A.; there is no experimental data from the Canadian environment. Unintentional man-made noise in the urban areas, in the UHF band, could reach as high as 30 dB above the 'ambient' thermal noise level.

Detailed discussions of fading and noise are given in the sections that follow.

4.0 PROPAGATION CONSIDERATIONS

4.2 ATTENUATION IN THE TROPOSPHERE

The tropospheric attenuation in the UHF band is very small. In the SHF band the precipitation attenuation is one of the major considerations in the link calculation.

Tropospheric attenuation experienced by radio waves is the result of two effects: (1) absorption and (2) scattering. In the SHF band, although there is some rain scattering it is reasonably accurate in the system calculation to treat all tropospheric attenuation as pure absorption.

There are two types of absorption in the troposphere; absorption by atmospheric gases and by precipitation. The major atmospheric gases that need to be considered as absorbers are water vapor and oxygen. The resonant absorption frequencies for water vapor and oxygen are 22.2 and 60 GHz, respectively.

Atmospheric gas absorption depends on the density of water vapor and oxygen along the path, or equivalently, the absolute humidity and pressure. Representative data (North Dakota, U.S.A.) are used to estimate the total gaseous attenuation which is shown in Fig. 4.1.

Precipitation absorption is a function of frequency and becomes more pronounced as the wavelength is comparable to the rain drop size. Because of the difficulty in obtaining precise rain intensity information along the propagation path, the total precipitation attenuation in the satellite-earth link cannot be accurately predicted.

Rain attenuation is a dominating factor in determing the reliability of a communication system in the SHF band. Rainfall varies greatly in frequency of occurrence and in intensity from one region to another.

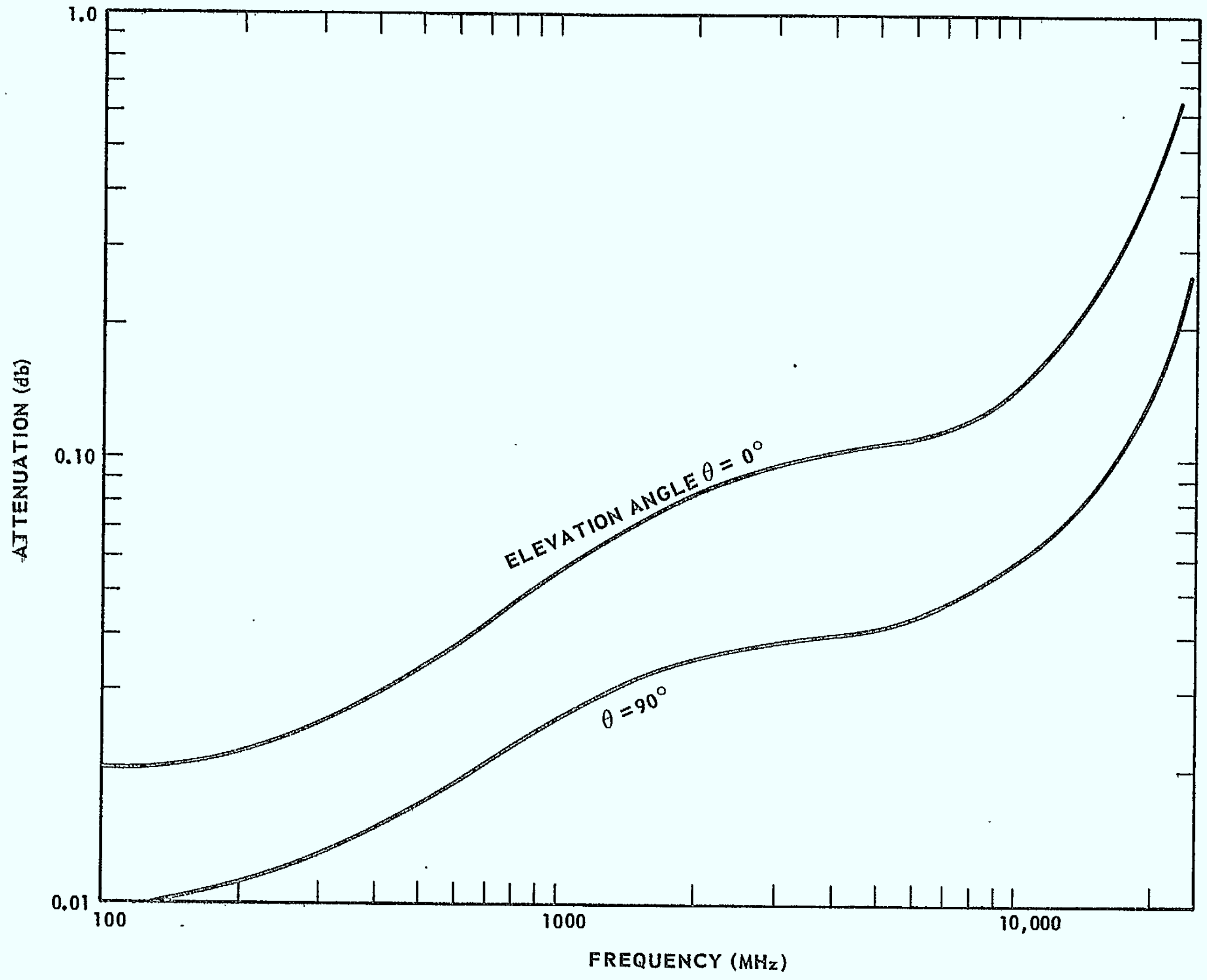

FIGURE 4.1

Typical Atmospheric Attenuation Versus Frequency

At present the exact relationship is not clear between the rainfall data at any particular location and the total rain attenuation in the satellite-earth link. The time correlation between attenuation and instantaneous rain rate is also poor. However, it has been observed that the correlation between the long term attenuation statistics and the rain rate statistics is reasonably good. The relationship between the rain attenuation α (db/km) and the rainfall intensity R (mm/hr) is usually expressed in the following form.

$$\alpha \text{ (db/km)} = aR^{b}$$

where a and b are constants depending upon the operating frequency. Various constants have been reported as shown in Table 4.1, and a set of nominal values is used in this report.

Assuming the rain cloud height is 2.3 km and the typical antenna elevation angle is 30° the total path length is approximately 4.6 km. By using 10 minute rainfall rate data it can be shown that the rainfall rate with probability of occurrence of 10^{-4} in Ottawa and Toronto is 50.3 and 42.7 mm/hr, respectively. Since the 10 minute rainfall rate can be considered equivalent to the instantaneous rainfall rate(4.9) and the localized rainfall rate is approximately equal to the path rainfall rate for short path lengths(4.10) the rain attenuation in the space-earth link for Ottawa and Toronto can be estimated as shown in Table 4.2.

Another method for estimating the rain attenuation in the space-earth link is from measurements of the variations of the solar flux density. Such statistical data are very rare. There are only a few long term attenuation statistics available; Bell Telephone Laboratories, Crawford Hill, New Jersey, U.S.A.(4.8) and Science Research Council, Slough, Bucks, England(4.6). The rain attenuation statistics at these two locations are completely different and cannot be applied to the Canadian environment.

TABLE 4.1

Constants Used in the Calculation of Rain Attenuation

Frequency (GHz)	a	b	Source
7.5	0.00459	1.06	R.K. Crane
9.4	0.00870	1.10	
16.0	0.0374	1.10	
15.3	0.035	1.155	L.J. Ippolito
31.65	0.2	1.	
15.	0.15	1.	K.N. Wulfsberg and E.E. Attshuler
35.	0.60	1.	
11.2	0.0143	1.24	G. Drufuca
12.7	0.0212	1.2	
18.7	0.0607	1.1	
8.4	0.019	0.97	B.C. Blevis, R.M. Dohoo and K.S. McCormick
14.9	0.057	0.9	
7.5	0.00459	1.06	Nominal Value
12.7	0.023	1.1	
14.5	0.031	1.1	

TABLE 4.2

Fade due to Rain Attenuations (dB) at Ottawa and Toronto

Location		Ottawa			Toronto		
Probability %		0.01	0.1	1.0	0.01	0.1	1.0
Frequency GHz	7.5	1.35	0.25	0.05	1.1	0.18	0.05
	12.2	7.9	1.35	0.24	6.6	1.0	0.24
	14.5	10.6	1.82	0.32	8.9	1.35	0.32

A promising technique for measuring long term rain attenuation statistics is the use of radiometer. Work is progressing in this area at the Communications Research Centre, Ottawa.

Cloud attenuation statistics on the space-earth link is often contaminated by the rain attenuation statistics. There is only one report(4.11) dealing with cloud attenuation statistics published in the open literature. Cloud attenuation can be ignored if enough rain attenuation margin is implemented. However, cloud attenuation may become a limiting factor if space diversity technique is used in the system design.

4.0 PROPAGATION CONSIDERATIONS

4.3 EFFECTIVE ANTENNA NOISE TEMPERATURE

4.3.1 EXTRATERRESTRIAL NOISE

Sky background and solar noise are the major extraterrestrial noise sources. The extraterrestrial noise temperature is approximately 140K and 10K in the UHF and SHF bands, respectively.

The radio frequency emission from the background sky is in general nonthermal and the magnitude of the received radiation noise depends on the characteristics of the receiving antenna, the operating frequency and the antenna's pointing direction. Since most of the ground based receiving antennas in the satellite communication system have large far-field pattern beamwidths compared to the solid angle of radio stars (except the sun), it is sufficiently accurate in the system calculation to assume that all radio star emissions (except the sun) are part of the sky background noise.

Assuming that the receiving antenna has a 100 percent beam efficiency concentrated in the main beam (not aperture efficiency) and a beamwidth of less than a few degrees, the sky noise temperature is then as shown in Fig. 4.2. The sky background noise is approximately proportional to the wavelength in the UHF band. An average value of 140K is used at 300 MHz. In the case of the SHF band, the sky background noise is approximately 10K.

The mean brightness temperature of solar radio emission is in the order of 10^6 K in the UHF band and the effective temperature variation with respect to frequency is shown in Fig. 4.3. If the sun is within the main beam of the receiving antenna, as is likely for most of the operational time in the UHF Satellite system, the effective antenna temperature due to solar noises can be calculated as follows.

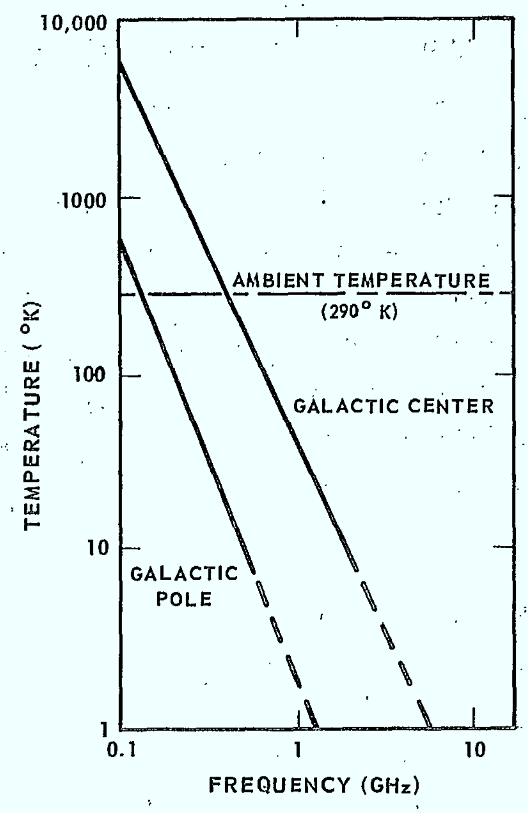

FIGURE 4.2

Background Sky Noise Temperature Observed on Ground

The flux density of radio emission, S (watt/m^2/Hz), is related to the averaged brightness temperature T as follows:

$$S = \frac{2kT}{\lambda^2}\ \Omega \tag{1}$$

where λ is the wavelength in meters

Ω is the effective solid angle of the visible disk in steradians

k is Boltzmann's constant 1.38×10^{-23} Watt/Hz/K

The effective antenna temperature (T_e) due to the noise source is

$$T_e = \frac{SA}{k} \tag{2}$$

where A is the effective receiving antenna aperture. By combining Equations (1) and (2) and using the standard antenna gain formula, i.e.,

$$G = \frac{4\pi}{\lambda^2} A$$

we have

$$T_e = \frac{G}{2\pi}\ T\ \Omega \tag{3}$$

Substituting the mean brightness temperature ($T = 9 \times 10^5$ K) of the sun at 300 MHz and the effective radiating disk ($\Omega = 1.28 \times 6.8 \times 10^{-5}$ steradians) into Equation (3), we obtain

$$T_e = 12.5\ G \tag{4}$$

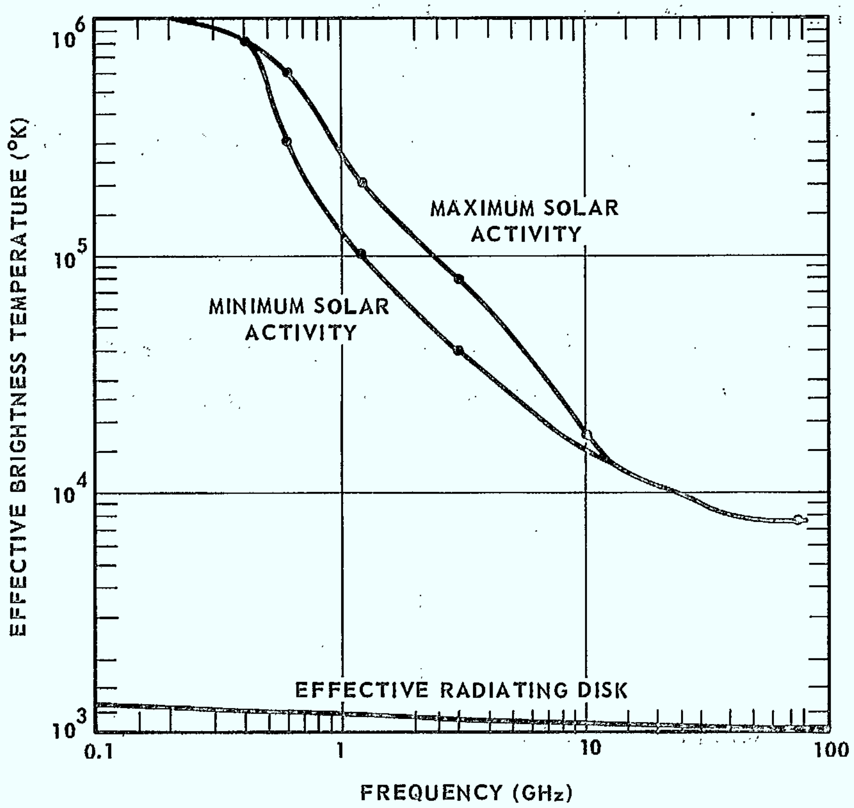

FIGURE 4.3

Effective Solar Noise Temperature

The mean solid angle of the sun is 6.8×10^{-5} steradians (0.22 deg^2)

For instance, the effective antenna noise temperature at 300 MHz with 3 and 10 dB antenna gain is 25K and 125K, respectively. The constant 12.5 in Equation (4) will be different for frequencies other than 300 MHz; it becomes 0.167 at 12 GHz.

The received noise level, at the UHF earth station receiver, from the moon and radio stars is very low - and may be neglected in the system calculation.

4.3 EFFECTIVE ANTENNA NOISE TEMPERATURE

4.3.2 TROPOSPHERIC NOISE

The thermal noise introduced by the tropospheric gaseous absorption in the microwave region is calculated.

Good absorbers of radiation are also good emitters, and vice versa. It has been shown that both oxygen and water vapour are good absorbers in the microwave region and therefore emit radio waves. The noise received from the atmosphere by an idealized antenna with an infinitely sharp beam is kTB where k is Boltzmann's constant, B is bandwidth and T effective sky temperature. If there is no precipitation and the sky background noise temperature is excluded, the effective tropospheric noise temperature is

$$Ts = \int_0^\infty \alpha \, T \exp\left(-\int^r \alpha \, dr\right) dr$$

where T is the actual temperature at the given point P, r is the distance between the observing point and point P and α is the power absorption coefficient.

It is apparent that the effective tropospheric noise temperature will depend upon the antenna elevation angle, the frequency and the atmospheric conditions along the path. The typical tropospheric noise is shown in Fig. 4.4.

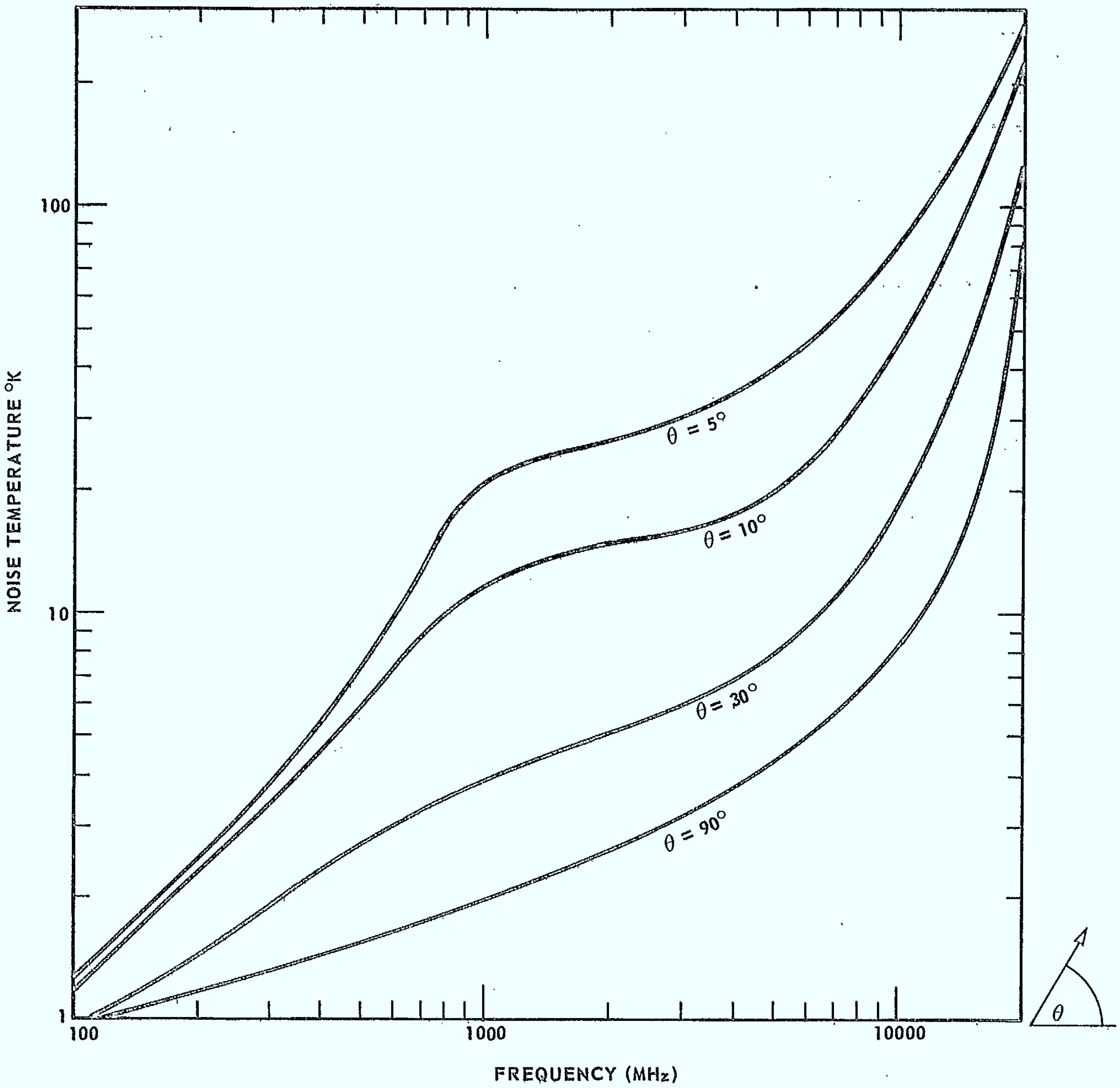

FIGURE 4.4

Thermal Noise vs Frequency for a Typical Tropospheric Condition
(θ is the antenna deviation angle)

4.3.3 ANTENNA NOISE TEMPERATURE

The effective antenna noise temperature is calculated for various antennas. The importance of various noise sources with respect to the antenna size and the frequency are discussed.

The effective antenna noise temperature is given by

$$T_a = \alpha T + T_o (1-\alpha)$$

where T is the antenna noise temperature

α is the transmission factor due to ohmic losses in the antenna and associated components in front of the reference point

T_o is the physical temperature of the lossy element.

The effective antenna noise temperature can be calculated easily if the external antenna noise temperature T is known. This value T is the total, weighted temperature 'observed' by the antenna in its environment, and it can be expressed in the following form:

$$T = \frac{1}{4\pi} \iint T(\Theta,\phi)G(\Theta,\phi) \sin\Theta \, d\Theta, d\phi$$

where $T(\Theta,\phi)$ is the noise temperature at the direction Θ,ϕ

$G(\Theta,\phi)$ is the normalized antenna directivity

There are three distinctive noise sources which contribute to the antenna noise temperature calculation: extraterrestrial noise, tropospheric noise and ground noise. Extraterrestrial noise is the dominant factor in the UHF antenna system, as shown in Section 4.3.1. Therefore, for system design purposes the UHF antenna system noise is taken as substantially independent of elevation angle. Tropospheric noise and ground noise are the dominant factors in the SHF band, and the antenna noise temperature will increase if the antenna elevation angle decreases.

For antennas with low gain (10 dB or less), the visual subtended angle of the sun is very small compared to the antenna beam width, therefore, the effective antenna noise temperature due to solar noise is small. On the other hand, for the high gain antenna, the effective antenna noise temperature due to solar noise is very high if the sun is within the main beam. For instance the excessive solar noise temperature for an antenna with a boresight gain of 17 dB (or 27 dB) is 625K (or 6250K). However, the percentage of the time that the sun is in the main beam of the high gain antenna is very small, and for this study the outages due to the sun being in the main beam were ignored. Typical antenna noise temperatures at various frequencies are shown in the following two tables.

TABLE 4.3(a)

Typical Ground Station Antenna System Noise Temperature (T) at 300 MHz (Substantially independent of elevation angle)

ANTENNA GAIN	3 dB	10 dB	17 dB	27 dB
Antenna Noise Temperature (T)	220°K	250°K	300°K	860°K

TABLE 4.3(b)

Typical Ground Station Antenna Noise Temperature (T) at the SHF Band

ELEVATION ANGLE	>30°	10°	5°	1°
7 GHz	30K	60K	80K	100K
12 GHz	70K	90K	120K	200K

4.4 NON-THERMAL NOISE

4.4.1 LIGHTNING NOISE

The general characteristics of lightning noise are discussed. The UHF receiver will experience a momentary outage due to excessive noise if there is a lightning discharge in its vicinity.

Because of environmental variations, uncertainties of distance between the discharge and the measuring equipments, variations of measurement set-ups and types of discharge, it is very difficult to characterize the discharge parameters. Most of the radiation noise is emitted during the return strokes in the discharge. The duration of discharge is in the range of 200 - 550 msec.

From various measured data, it has been shown (4.15) that the radiation component of the vertically polarized field at 300 MHz and at 10 km from the discharge is about 0.03 (μV/m) sec. The equivalent mean power over 200 msec in a bandwidth of 1 kHz is 16 μW. The received noise power from an isotropic antenna at a distance of 10 km is -106 dBm in a bandwidth of 25 kHz. This noise power is approximately 10 to 20 dB higher than the nominal received signal level of the proposed UHF satellite system.

Under this condition a momentary outage of the received path is to be expected. However, since the number of lightning discharges per year in Canada is small, therefore the probability of a receiver system outage due to a nearby lightning discharge is expected to be extremely small and would have little effect in the overall system reliability.

4.0 PROPAGATION CONSIDERATIONS

4.4 NON-THERMAL NOISE

4.4.2 UNINTENTIONAL MAN-MADE NOISE

The magnitude of unintentional man-made noise at the UHF band is extremely high in the suburban and metropolitan areas. Published experimental data are presented.

In this section, attention is restricted to unintentional man-made noise and so excludes interference produced by licensed or non-licensed transmitters. The noise is usually 'broadband' (i.e. its power being proportional to the bandwidth of the receiver) and is often highly impulsive in nature. The noise sources include power transmission lines, automotive ignition systems, rotating electrical machines, arcing devices, etc.

Much measured data has been published in the literature and large differences among experimental data have been observed. According to the ITT Handbook(4.2), there is approximately 15 dB difference in power level between urban and suburban areas, and the man-made noise in the suburban areas at 300 MHz is approximately 12 dB above thermal noise (i.e. equivalent man-made noise is -174 dBm/Hz). However, recent published data(4.12, 4.13) indicates that the noise level at 300 MHz in the range of 15 to 35 miles from the city center is approximately -162 dBm/Hz. Since the unintentional man-made noise is a function of time, location and frequency, a large data base is required to predict the level of man-made noise in different locations. The task of predicting the man-made noise level in the Canadian environment is very difficult due to lack of experimental data. Because of this difficulty, a nominal value of -168 dBm/Hz (1148K) (i.e. an arithmetic average between -162 and -174 dBm/Hz), has been assumed.

The characteristics of unintentional man-made noise are not known and their effects on communication systems are not clear. Although the validity of treating unintentional man-made noise as white noise may be questionable, it is used in this report because the calculations are simple and there is no point in being too precise as the noise data themselves are full of uncertainties.

The radio frequency interference (RFI) environment near synchronous orbital altitude in the UHF band has been measured by using LES-5 and LES-6 satellites(4.14)

It has been shown that the average received interference signal level was -130 dBm with spikes at levels of -100 dBm (receiver bandwidth was 120 kHz). The equivalent noise temperature for these two levels of interfering signal is 60K and 60,000K, respectively. Because of the measuring equipment inaccuracy at low signal level the measured average man-made noise (60K) at the synchronous orbit may have a large error. This has been indirectly proven by Ploussios(4.14). Perhaps a more reliable method of measurement at present is the use of aircraft. By measuring the effective airborne antenna noise temperature at the UHF band, the magnitude of the noise power density distribution was computed(4.14) to be 3×10^{-18} to 1×10^{-18} W/m^2/Hz for all the East Coast cities in U.S.A. Assuming the averaged population density in a Metropolitan area is 10,000 per square mile and the effective population within the UHF Satellite antenna beam coverage is 200 million, then the effective radiated noise power from the earth is 5.25×10^{-8} W/Hz which is less than 60K and can be neglected.

On the other hand, the radio frequency interference problem due to the higher spikes (60,000K) in the UHF band at the synchronous orbit is serious. However, there is not enough published data and a special study on this RFI problem in the UHF band is warranted.

4.0 PROPAGATION CONSIDERATIONS

4.4 NON-THERMAL NOISE

4.4.3 AIRCRAFT STATIC NOISE

Aircraft static noise is reviewed. The noise may be neglected in the system calculation if proper devices are incorporated in the aircraft antenna.

Based on the noise producing mechanism, there are three types of static noise that may produce interference in the aircraft receiver. These are (1) corona discharge, (2) streamer discharge, and (3) particle impact.

The corona discharge noise is the most significant source of static noise and the discharge usually occurs at the antenna and at other extremities of the airplane. Installation of dischargers can reduce the corona noise to a negligible level. The streamer discharge noise comes from flush mounted antennas with dielectric radomes. It may be reduced by using a highly resistive coating on the dielectric radome surface and by using a non-corona producing device to discharge the airframe surface. The particle impact noise is usually very low at UHF band and can be neglected.

4.0 PROPAGATION CONSIDERATIONS

4.5 SCINTILLATION AND MULTIPATH FADING

4.5.1 IONOSPHERIC AND TROPOSPHERIC SCINTILLATIONS

Ionospheric scintillation is discussed and based on various experimental data, a typical fade margin in the UHF band is derived. Tropospheric scintillation data in the SHF band is presented.

Irregularities in the electron density distribution can cause fluctuations in the amplitude, phase and angle of arrival of a UHF signal passing through the ionosphere. The amplitude fluctuation has a range of approximately 8 dB. Ionospheric scintillation activities are functions of latitude, solar disturbance and magnetic conditions and have strong diurnal and seasonal variations(4.17).

There are two major methods for analyzing the ionospheric scintillation statistics; the scintillation index method which has been adapted by the Air Force Cambridge Research Laboratories, U.S.A. and the cumulative fading statistics which is used by the Canadian Defence Research Board. All published Canadian experimental data are in the form of the cumulative amplitude probability distribution.

By using the measured data(4.21) from the Churchill experiments*, and assuming a f^{-2} frequency dependence, Maynard(4.26) has derived the cumulative amplitude probability distributions at 300 MHz for ground stations with 22° antenna elevation angle. The fade margin is approximately 10 dB and 4 dB at a system reliability

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* The cumulative amplitude probability distribution from reference 4.27 is similar to the experimental data in reference 4.21 if proper adjustments are taken into account.

of 99.9% and 99%, respectively**. There is approximately a further 2 dB in the fade margin for ground stations with 1° antenna elevation angles. If the system is designed for the regions where the elevation angle of the ground station antenna is greater than 5°, the fade margins in the UHF band due to ionospheric scintillation are shown in the following table:

TABLE 4.4

UHF Band Fade Margins Due to Ionospheric Scintillations

Propagation Reliability %	95	97	99	99.7	99.9
Fade Margin (dB)	2	2.5	4.2	7	10.5

In the SHF band, scintillations caused by irregularities of the refractive index in the troposphere have been reported(4.23). The amplitude fluctuation is a function of the antenna elevation angle and the local climatic conditions. Ionospheric scintillations have also been reported at 4 and 6 GHz bands(4.22). The causes of scintillations are not fully understood and it is beyond the scope of this study to carry out a thorough investigation. However, reasonably good data is available to make an estimate of the scintillation fade margins. The best available data of the fade margin in the SHF band is given in reference 4.23 and the cumulative amplitude probability distribution for an antenna with 5° elevation angle is shown in the following table. (In the case of 1° antenna eleva-

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** Assuming all the extreme fade margins are in the period with high scintillation index and if a $f^{-2.93}$ frequency dependence is used(4.18), then the fade margin with 99.9% probability is 6 dB.

tion angle, approximately 10 dB fade margin is required at 12 GHz for a 90% propagation reliability.)

TABLE 4.5

Scintillation Fade Margins For Canada in SHF Bands
(5° Elevation)

PROPAGATION RELIABILITY %		99	99.7	99.9
Fade Margin	7.3 GHz	3	4.2	4.7
	12 GHz	4.2	6	8.2

4.0 PROPAGATION CONSIDERATIONS

4.5 SCINTILLATION AND MULTIPATH FADING

4.5.2 MULTIPATH FADING

Multipath fading statistics in the UHF band is presented and a diversity system which will reduce the multipath fading margin is proposed.

In satellite communication links, if the ground station antenna pattern has a wide beamwidth so that both the direct satellite signal and the ground reflected signal are received with little discrimination, serious destructive interference between the two signals can take place and the received signal can fade to the receiver thermal noise level. Such phenomenon may exist in the airborne, shipborne and man-pack systems with a low gain antenna and any ground station system in which the antenna half beam width is compatible with the antenna elevation angle.

The effects of multipath fade on a communication system are to reduce the received signal level and introduce intersymbol interference or intermodulation noise. In this section only the multipath phenomenon will be presented. The effect of intersymbol interference is discussed in Section 5.3.4.

By using a top mounted blade antenna (omnidirectional antenna) on an aircraft, Bergemann and Kucera(4.28) obtained the cumulative amplitude probability distribution due to multipath fading at 135.6 MHz. The required fade margin is 7 and 12 dB at 99% and 99.9% propagation reliability, respectively. Assuming an f frequency dependence, the fade margin will be 8.5 and 14 dB at 99% and 99.9% reliability, respectively, at 300 MHz. The fade margin can be reduced considerably by using a properly designed antenna.

In the case of shipborne receiver systems(4.24), the required multipath fade margin for a half-wave dipole antenna at 254 MHz is approximately 19 and 29 dB at the propagation reliability of 99% and 99.9%, respectively. However, a 6 dB fade margin may be achieved by using an antenna with a modest amount of directivity in the vertical plane. The fade margin(4.25) may be reduced to 8 dB (99%) and 13 dB (99.9%) if a Yagi antenna is used.

There is no experimental data for the man-pack system or the land mobile system. It is considered that the fade margin for the land mobile system will be less than the shipborne system, on account of the generally poorer conductivity of soil.

In view of the excessive fade margins required for the airborne and shipborne system, it is extremely important to find a practical receiving system which may reduce the required fade margin for the mobile platform in the multipurpose satellite communication system. It has been shown(4.24, 4.29) that the fade margin can be reduced if a space diversity system is used. The system usually consists of more than one antenna and either an IF combiner, or a baseband combiner/switching system. If such a system is used properly, the fade margin may be reduced to 5 dB (99%) and 8 dB (99.9%) which is in the same order as the ionospheric scintillation fade margin. In the system calculations of Section 6 it is assumed that a proper receiving system* is used for the mobile platform and the required multipath fade margin is less than or equal to the ionospheric scintillation fade margin. There is, therefore, no additional multipath fade margin for the communication systems on mobile platforms. There may, however, be a slight decrease in system reliability (e.g. a decrease of system reliability from 99.9% to 99.8% at most).

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* The required mobile to satellite fade margin in the up-link path is assumed to be the same as the down-link path.

4.6 SPACE-DIVERSITY AND HOT STANDBY SYSTEMS

A space diversity and hot standby system for the central control station is recommended to increase the system availability.

Since the UHF satellite system is a double-hop communication system, the reliability of the central control station is extremely important. Redundant subsystems are generally used in the central station to reduce the equipment failure outage (Hot Standby System). Further, two control stations may be employed to give added protection. The scheme could therefore be quite expensive. The space-diversity and hot-standby system suggested in this report can meet all requirements and has low maintenance cost without compromising the system reliability.

The system consists of a central station, a space diversity station and a terrestrial microwave link between them. The space diversity station is located approximately 30 miles away from the central station and consists of a ground station antenna and various microwave subsystems. All baseband equipments are located at the central station. (The frequency bands between 1 and 8 GHz are the best for the microwave system). No redundant microwave subsystems such as the low noise amplifier, the microwave transmitter, etc. are required in the central and the space diversity stations.

In the central station, two received signals, one from the main antenna and another from the space diversity antenna via the terrestrial microwave link, are always available. The best signal will be chosen by the switching equipment. The transmitter in the space diversity station is operated in the hot-standby mode and is controlled by the switching system. A schematic diagram is shown in Fig. 4.5. The space diversity station may not be manned.

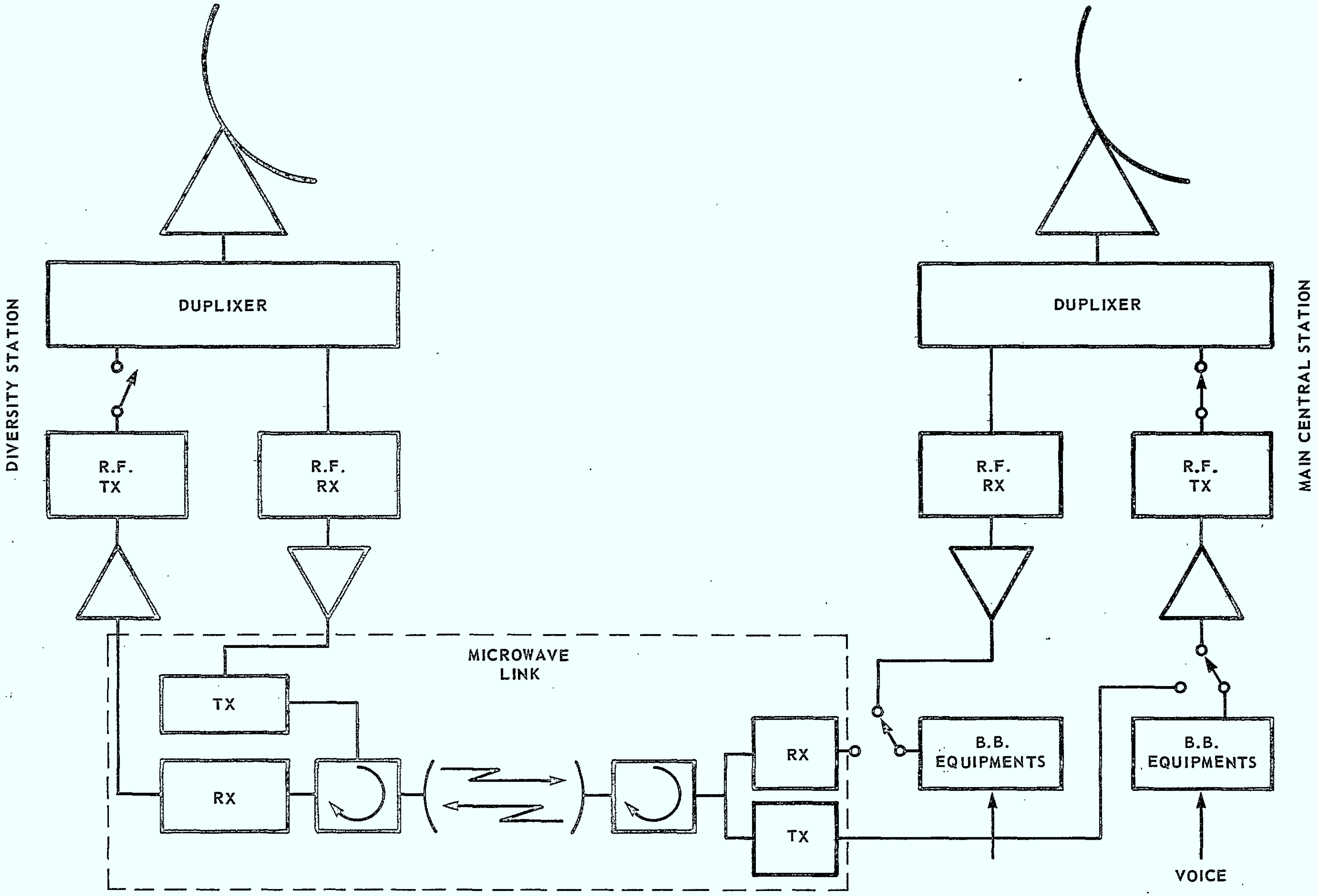

FIGURE 4.5

Diversity Scheme for Central Station

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5.0 MODULATION TECHNIQUES

5.1 MODEM REQUIREMENTS

The system requirements which affect the choice of the modulation techniques are highlighted.

The requirements of the users and the proposed system for the multi-purpose UHF Satellite are extracted from the statement of work and from the given reference materials. They are listed below and are interpreted to form the general design guide-lines for the modem evaluation and selection.

5.1.1 Traffic Modes and Qualities

There are four traffic modes required by the users: voice, facsimile, teletype (75 b/s) and data (2.4 kb/s and 4.8 kb/s). The voice transmission may be of field and good quality. Because of the cost factor, only a very small percentage of the users will require good quality transmission.

In the modem study, the transmission requirement for facsimile is taken to be similar to that for voice. (Note that the facsimile signal contains more low-frequency components than the voice signal. Some caution should be taken in the practical design of the modem when it is used for facsimile transmission.) In order to minimize the number of modem types, the one modem should be capable of being adapted for either voice or data transmission by some suitable means, such as front-panel switches or plug-in circuit modules. The user survey indicates that the data traffic is only a small fraction of the voice traffic, and is mostly from remote stations to the control station or regional ports. Moreover, 80% of the civilian government communications is between fixed stations and transportable or mobile platforms where equipment with low complexity (thus resulting in small size, low power consumption, low cost and high reliability) is of prime consideration. Thus, it is envisaged that a simple modem which provides field quality voice transmission together with some data transmission capability (e.g. teletype only) would satisfy a majority of users' needs.

5.1.2 Compatibility With Encryption

Although this requirement is not listed in the statement of work, there is a definite need for this as indicated from the survey results given in the Feasibility Study Report (Dec. 1974) and from meetings with DOC. In this respect, a digital modulation technique is favoured since in general it is easier and less expensive to incorporate encryption in digital form.

5.1.3 Other System Requirements

To provide the low-capacity channels for voice and low bit rate data, the Feasibility Study Report (Dec. 1974) proposes the following:-

(a) to use a frequency-division multiple access (FDMA) system in which each voice/data channel is assigned its own frequency (i.e. single channel per carrier, SCPC)

(b) to use a uniform channel spacing of 25 kHz

(c) Voice channels can be either simplex with 'push-to-talk' feature or duplex with voice-activation.

Thus, the selected modem must be capable of working with the SCPC/FDMA system, and if coherent detection is used, it must have a short synchronization acquisition time so that together with the response time of the voice-activating switch, it will not clip any significant part of the voice signal. Furthermore, the 25 kHz channel spacing appears to impose a bandwidth constraint on the digitized voice transmission, especially in the good quality case.

5.0 MODULATION TECHNIQUES

5.2 CHOICE OF PERFORMANCE CRITERIA

Parameters are required to provide a reference for comparing the performance of different types of modems and for assigning operation limits under adverse transmission conditions. These parameters are considered under the power-limited constraint of the satellite channel.

5.2.1 Voice Transmission

For the evaluation of different types of modems used for voice transmission, no single parameter alone can provide sufficient measure of the voice quality. In the case of voice communications between field parties and headquarters, speech intelligibility may be of primary concern and the articulation index (A.I.) would be a useful figure of merit.

The principle of A.I. as developed by French and Steinberg(5.1) consists of dividing the speech frequencies into 20 unequal bands and the assignment of 5 percent weighting to each of the bands. Within each of the frequency bands, the speech power is allowed to vary over a range of speech-peak-to-speech-minimum ratio. Thus, an A.I. of 100% corresponds to a voice communications system in which all the 20 frequency bands allow the full speech dynamic range. The use of A.I. as a parameter for comparing the different voice modulation techniques should be done with caution, since the calculation of A.I. depends on the speech and noise spectra. Also the idle noise during speech pauses plays a strong roll in the subjective quality of voice signal. Thus, the A.I. results could be misleading unless some listening tests are also done when comparing different voice modulation techniques. Nevertheless, for lack of a better, simpler and computable parameter, the A.I. is used in this study as a performance figure of merit for speech intelligibility. To establish an operating A.I. value and to gain some insight into the performance limit, a typical plot of intelligibility score for various texts as a function of A.I. is shown in Fig. 5.1. Again, one must note that these results are approximate because they depend on the type of text, the talkers' skill and the listeners' capabilities. In this study, a nominal A.I. value of 0.45 is taken as giving acceptable intelligibility and 0.35 is taken as the threshold value below which the performance is not acceptable.

The voice channels dealt with are both power and bandwidth limited. Thus, the best voice modulation system is the one which will fit the allocated r.f. bandwidth and the lowest carrier-to-noise spectral density ratio (C/No).

In the case of a good quality voice transmission, speech intelligibility is not the only requirement. Some form of voice recognizability or fidelity is also needed. For good quality voice systems the signal-to-noise ratio (SNR) is used as the parameter to evaluate the different modulation techniques. The use of this parameter is cautioned with the following comments:

(a) SNR must be characterized in terms of the baseband truncation bandwidth, the shape of the background noise spectrum (pre-emphasis considered) and the amount of clipping employed.

(b) the standard frequency modulation equation is applied and the voice signal is treated as noise-like baseband signal with the r.f. bandwidth determined by Carson's rule.

In this study, a subjective signal-to-noise ratio of 28 dB is used for the nominal value of acceptable good voice quality as suggested in CCIR Report 508(5.2).

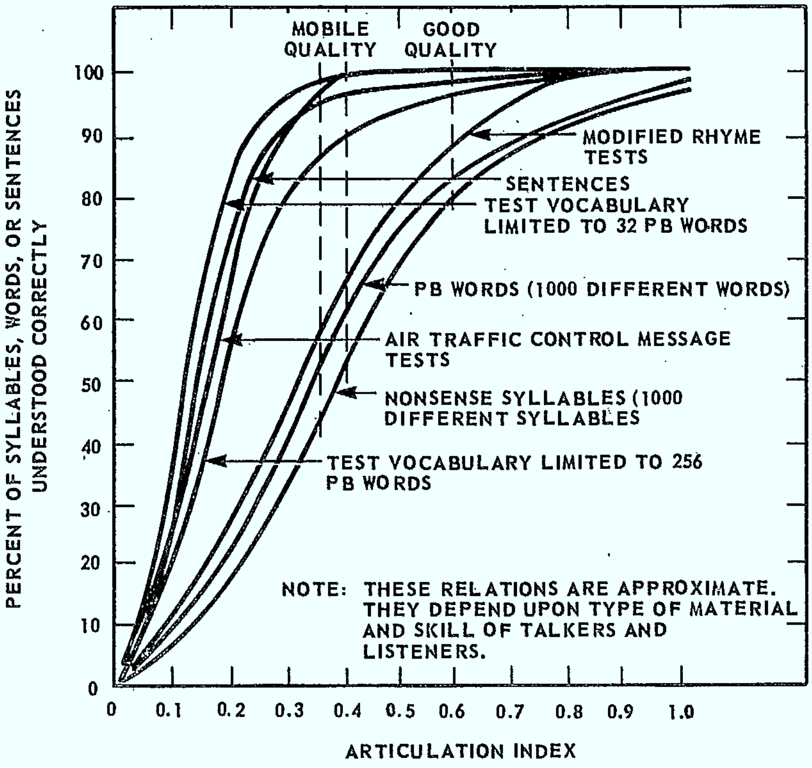

FIGURE 5.1

Relation between Articulation Index
and Various Measures of Speech Intelligibility

5.2.2 Data Transmission

For data transmission, the bit error probability, P_e, is taken as the performance criterion with the threshold value for acceptable performance set at 10^{-5} (one bit error out of 10^5 bits). (See Section 3.2.) The relative efficiency of different digital modulation techniques is measured by the required energy per bit-to-noise spectral density ratio (E/N_o) for maintaining this threshold bit-error probability. For the data channel, because of the low data rate (4.8 kb/s maximum), the 25 kHz channel spacing imposes no constraint on the bandwidth requirement of the modulation techniques considered. However, for the power limited satellite transponder, it is necessary to select a modem which requires the smallest E/N_o at the bit error probability of 10^{-5}. Furthermore, as will be shown later, the channel is intermodulation noise limited, and the carrier-to-noise ratio $(\frac{C}{N})$* requirement must not exceed the carrier-to-intermodulation noise ratio $(\frac{C}{IM})$.

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*Note: $\frac{C}{N} = \frac{C}{N_o B}$

where C = carrier power (Watt)

N_o = noise spectral density (Watt/Hz)

B = r.f. bandwidth in Hz.

5.3 EVALUATION OF MODEMS

In this section, the various modulation techniques to be evaluated are briefly described and their performances in terms of the chosen parameters are given. A selected number of modulation techniques which meet the requirements is recommended.

The generic types of modems listed for consideration in the statement of work may be broadly classified into analogue and digital modems. The analogue modems include Narrow Band FM (NBFM), Adaptive NBFM (ANBFM), FM with companding and Pulse Duration Modulation (PDM). The digital modems include Phase Shift Keying (PSK) and Fast Frequency Shift Keying (FFSK). For digitized speech processing, only delta-modulation (DM) is required to be considered. From the viewpoint of minimizing the modem types and maximizing operational flexibility, it would be advantageous to use the same modem for both voice and data transmission. Table 5.1 lists the possible ways in which the different modulation techniques can provide these services.

The different modems are briefly described in Sections 5.3.1 and 5.3.2 for analogue and digital modulation, respectively. Their performances are compared in Sections 5.3.3 and 5.3.4.

TABLE 5.1

Summary of Modem Techniques

VOICE	DATA	REMARK
ANBFM	FSK	Using Bell Aerospace FM Modem; for teletype transmission clipping, pre-emphasis/de-emphasis networks are bypassed, and the teletype signal is modulated onto a subcarrier in the baseband frequency.
FM with companding	FSK	For data transmission, clipping, pre-emphasis/de-emphasis, compandor/expander networks are bypassed; low frequency removal effect considered.
PDM/PSK	PSK	Modem provided with multi-rate capability. Data to PSK modem is differentially encoded.
DM/PSK	PSK	DM is used for voice processing; the PSK modem allows the selection of bit rate to suit the different requirement in voice quality and data rate.
DM/FFSK & DM/OFFSET PSK	FFSK & OFFSET PSK	DM is used for voice processing. Trade-off between bandwidth & C/N; implementation margin, r.f. envelope, etc. considered.

5.3 EVALUATION OF MODEMS

5.3.1 ANALOG MODEMS

NBFM, ANBFM, PDM, and FM with companding are briefly examined.

NBFM, with a modulation index ($\beta = \frac{\Delta f}{f_m}$) less than 1, provides intelligible voice (field) quality with reasonable RF bandwidth and satellite power requirements. Because of the inherent characteristics of the voice signal spectrum, and the noise spectrum at the output of the FM demodulator, pre-emphasis may be applied to obtain improvement in signal-to-noise ratio. Bell-Aero System Inc. has developed an ANBFM modem which is capable of providing field quality (intelligibility requirement only) voice transmission at low C/N_o values. A pre-emphasis network is used to avoid the masking of signal by high frequency noise at the input of the modulator. At the output of the demodulator, a de-emphasis network restores the original signal spectrum while flattening out the demodulated FM noise. A peak clipping of 12 dB is used to avoid overdeviation while producing no detectable degradation effect. Threshold extension is provided by using a phase-locked loop demodulator. The bandwidth of the phase-locked loop is dependent on the received signal power. Thus, the loop is adaptable to varying $\frac{C}{N_o}$ conditions, and the threshold at which it will lose lock is extended with decreasing C/N_o. To avoid distortion resulting from varying loop bandwidths, the closed loop response is optimized for the average power spectrum giving optimum performance at low C/N_o. No significant improvement in signal-to-noise ratio can be achieved by using a companding technique for the Bell-Aero ANBFM modem because of the inherent low S/N resulting from low frequency deviation. This low S/N would be near the threshold of a conventional compandor making the compandor ineffective. The r.f. bandwidth required for ANBFM is about 10 kHz. In the absence of speech, a squelch tone can be included in the low frequency portion of the spectrum to gate out the idle noise. This could improve the subjective quality of the voice transmission.

Magnavox Research Laboratories developed a modem which processes the voice signal using PDM techniques with a selectable sampling clock(5.3). The binary signal which carries the voice information in the zero crossover is then PSK modulated with a varying RF bandwidth commensurate with the sampling clock rate. In the modulator, the voice signal is processed using pre-emphasis and compression before it is sampled at a rate satisfying the Nyquist sampling principle. The sampled voice signal amplitude is encoded by the pulse width of the binary waveform. The pulse leading edge, carrying the clock information, is suppressed to reduce the number of pulse transitions. The resulting binary waveform is then transmitted on a ±90° PSK carrier. The RF bandwidth required is in excess of three times of the sampling rate. The received PSK signal is coherently demodulated using a Costas loop for the carrier recovery, and an integrate-and-dump filter for optimum pulse shaping. A locally recovered clock signal is added to the demodulated signal to regenerate the original PDM signal which is then filtered and processed through de-emphasis and expansion networks to recover the audio signal.

As in the NBFM case, the subjective quality of the PDM voice transmission can be improved by squelching the noise on the absence of speech. The squelch tone is provided by the inherent component at half the sampling rate.

For the good quality voice system, the use of syllabic companding in processing the voice signal improves the subjective signal-to-noise ratio for the FM system by reducing the transmitted dynamic range of the speech signal and attenuating the intersyllabic noise. The syllabic compandor is a voice-activated device. A voice-activated compressor in the transmitter compresses the range of the speech signal, and a voice-activated expandor in the receiver restores the speech signal to its original range. Boudreau and Davies(5.4) reported that the subjective improvement in signal-to-noise ratio with the use of companding technique may amount to more than 18.8 dB. This results in a reduction of C/N_o in the order of 5.5 to 8.5 dB depending on the frequency deviation of the FM system being considered. The use of compandors, together with a threshold extension demodulator, provides soft thresholding and better voice recognizability. However, the benefits of companding are only fully realizable in a basically fairly good quality transmission system, as a threshold signal-to-noise ratio is required. The use of a linked compandor-expandor (lincompex) system may overcome some of the problems of the conventional compandor. The lincompex, however, would need further development to make it relatively low cost.

5.3.2 DIGITAL MODEMS

DM/PSK and DM/FFSK are examined for digitized voice transmission. The voice quality is reviewed with respect to the required transmission bit rate.

For data transmission, PSK, FSK and FFSK are considered. Only factors which may affect the selections are discussed.

A digital voice system consists of a digitized voice processor, a digital modem and probably some form of forward error correcting coder. The first two subsystems are discussed here. Error correcting codes will be discussed in the addendum.

Delta Modulation is the only type of digitized voice processing covered in this study. It is a special form of differential pulse code modulation in which the analog signal (in this case, the voice signal) is transmitted by the difference signal between successive samples. If the quantized step size is fixed, slope overloading will result when the signal changes too rapidly; similarly, a train of alternating positive and negative pulses is produced if the step size is larger than the changes in the signal. In either case, the modulator output fails to follow the signal. An adaptive or companded delta modulator may be used to adjust the step size according to the past history of the analog signal and to improve the dynamic range of the coder. From the known voice spectrum, it is possible to design the codec on the principle of prediction through the use of integrating networks or sequence detector/level stepper. This would minimize the slope-overloading condition.

The signal-to-quantization noise (SNR) of an adaptive delta modulation codec is dependent on the sampling rate. Fig. 5.2 shows plots of SNR at the output of the decoder as a function of the sampling

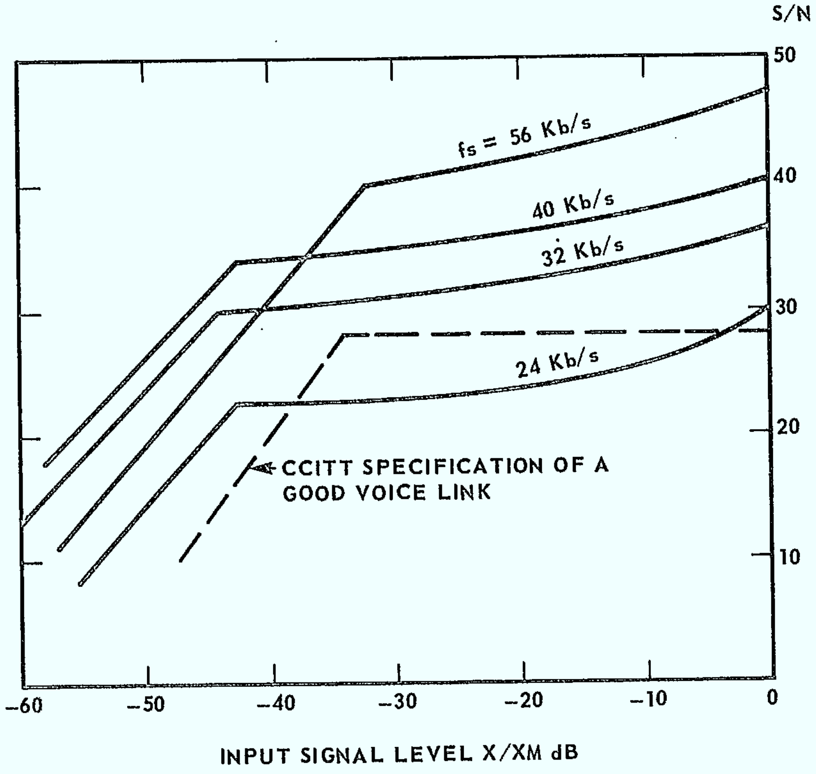


FIGURE 5.2

Signal/Noise Ratio vs Input Levels
at Various Sampling Rates of Delta Modulation Codecs

rate and the input signal level. It can be seen that the quality of the voice system may be varied by varying the sampling rate with corresponding changes in C/N_o and RF bandwidth. From the view point of hardware implementation, different input/output lowpass filters for truncating the voice signals, and different clock rates have to be provided. For simplicity of equipment, it is preferred that the clock rates be related by a small multiple. From Fig. 5.2, it appears reasonable to choose 32 kb/s for good quality voice and, as it will be shown later in Section 5.3.3, 16 kb/s for field quality voice.

For the transmission of delta-modulated voice signals and other digital data in the SCPC/FDMA satellite mode, the angle modulation (phase or frequency modulation) appears to be most suitable. Only those which are potential candidates are considered in this report. They include PSK, FSK and FFSK. From the theoretical performance aspect, these modulation techniques can be evaluated in terms of the required E/N_o to support a given error probability and the required RF bandwidth expressed as a function of bit rate. In the practical aspect, one has to consider,

(a) the amount of excessive bandwidth (defined as the amount of bandwidth in excess of the Nyquist bandwidth) necessary to give insignificant degradation due to intersymbol interference,

(b) the implementation margin,

(c) the C/N requirement,

(d) the synchronization time, and

(e) the amount of degradation in the presence of interference signals.

The most efficient of the angle modulation techniques is PSK when coherent detection is used (CPSK). The need to provide a carrier reference for coherent reception requires a relatively complex receiver. Different techniques have been used; e.g. phase multiplication, I-Q loop, remodulation, etc. The "push-to-talk" and

A Digital FM or FSK signal has constant RF envelope and in a low deviation system, is quite efficient in its power spectral occupancy. With a modulation index (defined as the peak-to-peak frequency deviation to bit rate ratio) of 0.7, 98% of its modulated signal power is contained in a RF bandwidth of approximately 1.2 times its bit rate. The FSK signal can be detected non-coherently using an FM discriminator with an E/N_o degradation of about 3.6 dB over the PSK system, at an error probability of 10^{-5}.

The Fast FSK (FFSK) is a binary, continuous-phase FSK signal with a modulation index of 0.5. Because of the continuous modulation phase, the power spectral density decreases as the fourth power of frequency and 98% of the modulated signal power is contained in a RF bandwidth of slightly over the Nyquist bandwidth. The generation of the FFSK signal requires holding the modulation index to precisely 0.5 and long term phase stability. One practical implementation scheme has been proposed by deBuda(5.5) and Brady(5.6). The fact that FFSK may be treated as bi-orthogonal coherent phase modulation (i.e. pulses transmitted on orthogonal phase being staggered) allows the use of coherent phase detection. To extract the carrier and timing information, the received signal passes through a times 2 multiplier, resulting in two strong components at twice the mark ($2f_M$) and space (2fs) frequencies, respectively. The carrier (fc) and the clock ($\frac{1}{T}$) frequencies can then be recovered by taking the sum and difference of these frequencies, respectively. The carrier and clock signals can be used for conventional coherent demodulation and detection. Thus, FFSK has about the same performance as the coherent four phase PSK system with a somewhat simpler receiver configuration. As in the four phase PSK case, FFSK is penalyzed for a higher C/N requirement. One advantage FFSK has over the four phase PSK is that it can also be demodulated (with approximately 3 dB degradation) by means of a frequency discriminator as in the case of non-coherent FSK system.

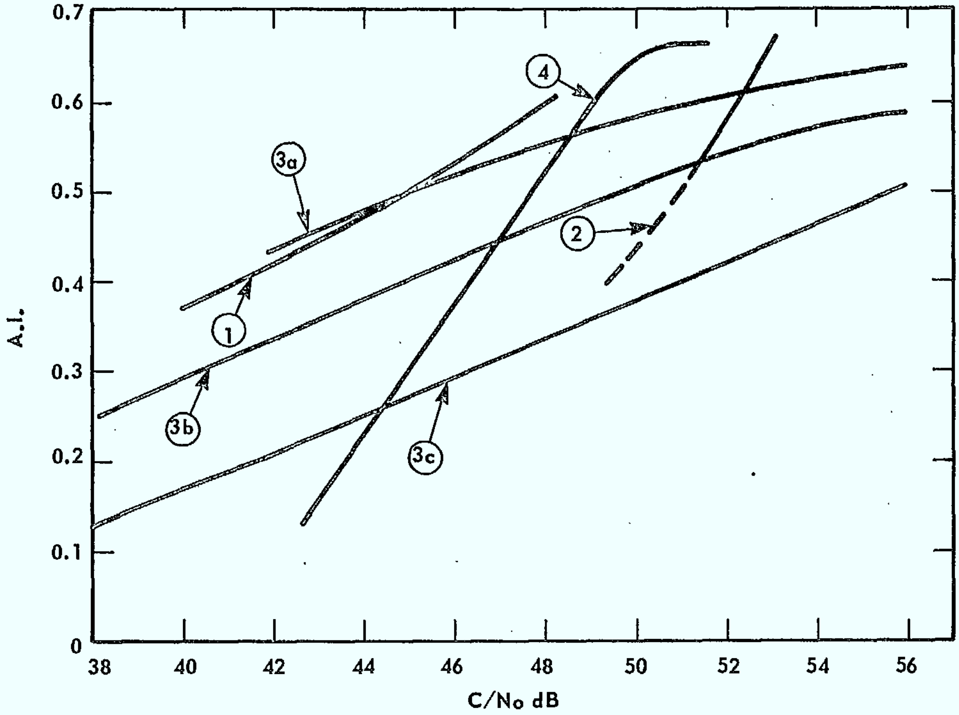
5.3.3 COMPARISON OF MODEM PERFORMANCE

The different modems considered in the preceeding subsections are compared using A.I. or SNR as figures of merit for voice transmission, and P_e for data transmission. Comparisons on the required bandwidth and C/N_o are also made.

5.3.3.1 MODEMS FOR VOICE TRANSMISSION

The A.I. values for the various voice modems can be obtained by first calculating the test tone-to-noise (TTN) performance, and then relating TTN to A.I. taking into consideration the speech power spectrum(5.7). The TTN for FM systems can be calculated from the well known FM equation with the C/N_o at threshold(5.8). The TTN for DM/PSK can be calculated by considering the quantization noise and the noise due to the error rate. The effect of slope overload on A.I. is unknown and has not been taken into account here. (A.I. for the digitized voice system can also be directly obtained by calculating the signal-to-noise ratio in each of the speech frequency bands(5.9). For the delta-modulated voice transmission, A.I. is shown only for the PSK system. The A.I. performance for other than the PSK modulation system can be readily obtained by relating to the bit error probability performances.

With some reservation on the adequacy of using A.I. as a figure of merit for comparing the voice intelligibility as discussed in Section 5.2, we may use the curves of A.I. vs C/N_o shown in Fig. 5.4 for the various voice modulating techniques. Some of the important parameters for the various modems are tabulated in Table 5.2.



CURVE

① ANBFM B.W. = 10 kHz; FROM BELL AEROSPACE MODEM

② CONVENTIONAL FM WITH COMPANDING B.W. = 23 kHz; DERIVED FROM BOUDREAU & DAVIES

③ a. PDM/PSK B.W. 40 kHz TAKEN FROM CAMPANELLA & SCIULLI
b PDM/PSK B.W. 20 kHz
c PDM/PSK B.W. 10 kHz

④ DM/PSK B.W. 23 kHz WITH 3dB MARGIN (16 Kb/SEC)

FIGURE 5.4

Articulation Index (AI) vs C/No

TABLE 5.2

Modem Parameters for A.I. Curves Shown in Fig. 5.4

VOICE MODULATION METHODS	A.I. CURVE REF.	MODEM PARAMETERS
ANBFM (BELL AERO)	Ref. (5.15)	Voice Band 300 Hz to 3 kHz Pre-emphasis at 6 dB/octave 12 dB clipping Peak Deviation ±1500 Hz IF Bandwidth = 10 MHz Adaptive Bandwidth PLL Demodulator
FM with companding	Ref. (5.4) using 8 dB & 9.4 dB for de-emphasis and expandor improvement respectively	Voice Band = 300 Hz to 3.4 kHz Pre-emphasis at 6 dB/octave 10 dB clipping Peak Deviation = 8 Hz IF Bandwidth = 23 kHz Conventional FM discriminator
PDM/PSK (Magnovox, suppressed clock PDM system)	Ref. (5.7)	Voice Band = 200 Hz to 2.5 kHz Clock rate = 6 kHz IF Bandwidth = 20 kHz
DM/PSK	Ref. (5.9)	Voice Band = 300 Hz to 2.5 kHz Clock Rate = 16 kHz IF Bandwidth = 23 kHz Budgeted error probability = 5 x 10^{-2}

As seen from Fig. 5.4 each of the techniques considered has somewhat different A.I. curves. From the viewpoint of efficient usage of the satellite power, the modulation technique which gives the greatest A.I. for the lowest C/N_o is the most desirable one. Also, techniques whose A.I. performance does not degrade drastically with varying C/N_o are preferred. For transmitting field quality voice, ANBFM (curve 1) and PDM (40 kHz bandwidth, curve 3a) both give an A.I. of 0.45 (nominal value for field quality voice used in this study) for C/N_o = 43 dB-Hz. Their performance appears reasonably linear for C/N_o between 40 dB-Hz and 48 dB-Hz. DM/PSK (curve 4, implementation margin excluded) requires a C/N_o of approximately 47 dB-Hz to give A.I. of 0.45. Also, the steeper slope of its A.I. performance makes the voice quality unacceptable for C/N_o below 45 dB-Hz. Other PDM/PSK systems (curves 3b and 3c for IF bandwidth of 20 kHz and 10 kHz, respectively) have comparatively inferior A.I. performance. A conventional FM voice system with companding (curve 2) requires about 4 to 6 dB more power compared to the ANBFM system, but will give voice recognizability in addition to intelligibility.

For good quality voice which requires more than mere intelligibility, SNR is used as the figure of merit. In Fig. 5.5, the performance of FM with companding is given in terms of SNR vs $\frac{C}{N_o}$. The signal-to-quantization noise ratios for companded DM/PSK system are also plotted in the same figure for comparison purposes. Table 5.3 summarizes the modem parameters which are used for Fig. 5.5. From this figure, it is seen that DM/PSK with sampling rate of 32 kb/s gives a SNR of 32 dB for C/N_o of 55 dB-Hz (a 3 dB implementation margin is assumed at an error probability of 10^{-3}). FM with companding requires 54.5 dB-Hz for the same SNR value. However, since the performance requirements of the proposed system calls for a SNR of only 28 dB, an FM system with companding can meet this requirement at a C/N_o of 53.5 dB-Hz.

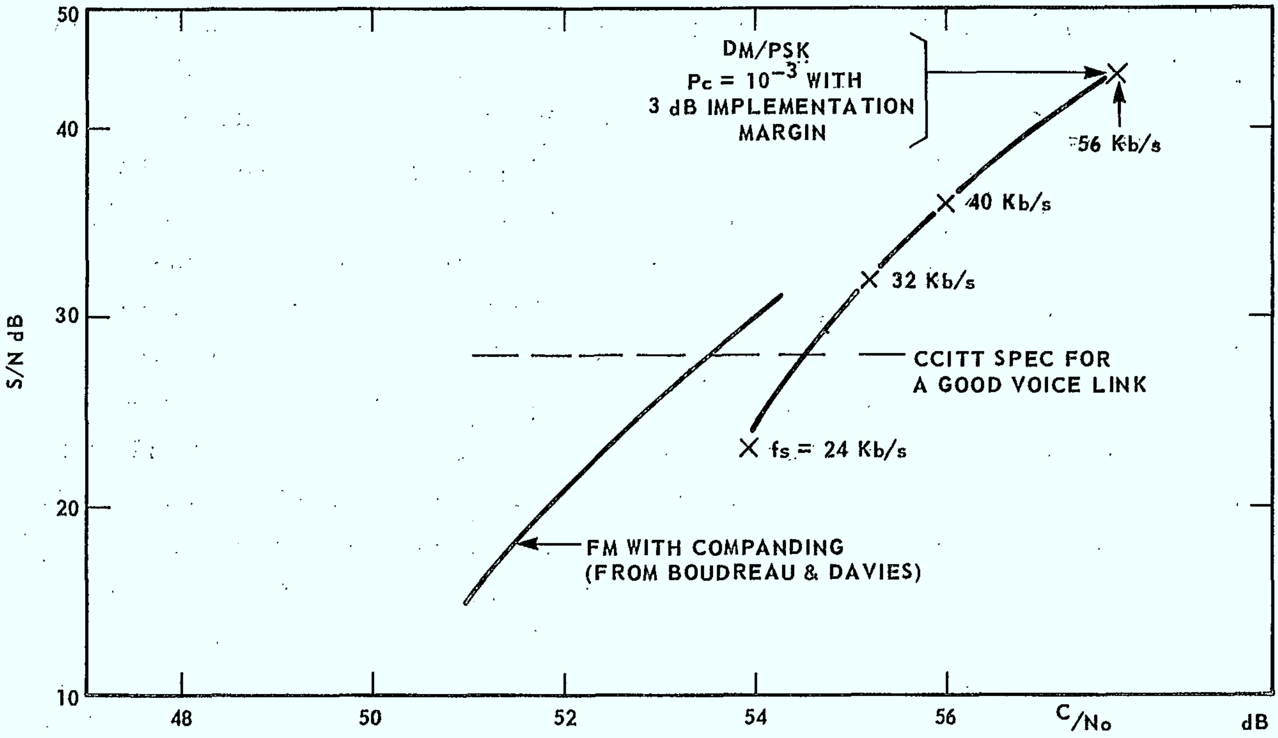


FIGURE 5.5

Signal/Noise Ratio vs C/No for Good Quality FM and Digitized Voice

TABLE 5.3

Modem Parameters for S/N Curves Shown in Fig. 5.5

VOICE MODULATION METHOD	S/N CURVE REF.	MODEM PARAMETERS
FM with Companding	Ref. (5.4)	Voice Band = 300 Hz to 3.4 kHz Pre-emphasis of 6 dB/octave 10 dB clipping Peak Deviation = 8 kHz IF B.W. = 23 kHz Conventional FM discriminator
DM/PSK	Ref. (5.9)	Voice Bandwidth = 300 Hz to 3 kHz clock rate as indicated I.F. Bandwidth = 1.4 (clock rate) Budgeted error probability = 10^{-3} Implementation Margin = 3 dB

5.3.3.2 MODEMS FOR DATA TRANSMISSION

The digital modulation methods considered in this study include binary CPSK, DPSK, binary FSK (non-coherent detection), four phase (offset) CPSK, and FFSK. Theoretical error-probability performance curves are shown in Fig. 5.6. In a peak power limited channel, binary CPSK, four phase CPSK and FFSK require the same E/N_o to operate at a given error probability. However, the different bandwidth occupancies of the various modulation methods and different implementation margins impose different C/N requirements. Thus, the four-phase CPSK and FFSK require higher C/N but require lower bandwidth.

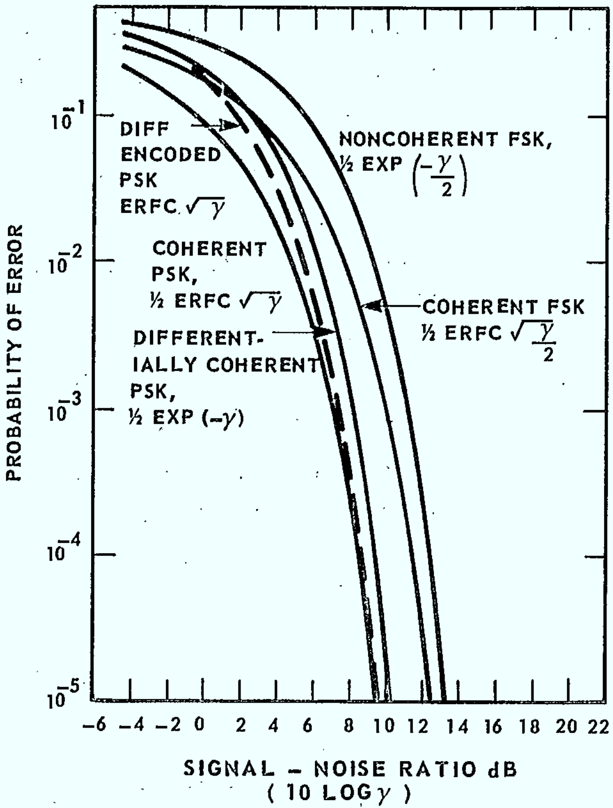


FIGURE 5.6

Error Rate of Ideal Digital Systems

The implementation margin assigned to the different modems consists of two portions: equipment imperfection and channel degradation. The portion contributed by the imperfect equipment includes expected degradations from the modulator and demodulator and takes into account the frequency instabilities of oscillators used in the transmission path. The second portion includes degradation contributed by intersymbol interference due to non-linear devices in the transmission channel. For the different modems considered the implementation margin ranges from 2.8 dB (DPSK, FSK) to 3.3 dB (4 phase CPSK and FFSK). The equipment implementation margin for FSK is higher than normally expected because the FM modem is designed for analog voice transmission and is modified for data transmission only.

Table 5.4 summarizes the theoretical error probability performance, RF bandwidth requirement, implementation margin, and the relative equipment complexity. It is noted that the carrier phase recovery circuits cause the major complexity in the demodulator, and that four phase CPSK requires a more complex carrier recovery circuit than FFSK.

TABLE 5.4

Summary of Digital Modem Types

DIGITAL MODEM TYPES	ERROR BIT PROBABILITY (Theoretical) $\gamma = \frac{E}{No}$	R.F. BANDWIDTH R = BIT RATE	IMPLEMENTATION MARGIN		RELATIVE EQUIPMENT COMPLEXITY	
			EQUIPMENT	ISI DEGRADATION THRU TRANSPONDER	MOD	DEMOD
BINARY CPSK	$\frac{1}{2}\ \text{erfc}\ \sqrt{\gamma}$	1.4R	1.5 dB	1.5 dB	1	3
BINARY DCPSK	$\frac{1}{2}\ \exp\ (-\gamma)$	1.4R	1.3 dB	1.5 dB	1	2
BINARY FSK (Noncoherent)	$\frac{1}{2}\ \exp\ (-\ \frac{\gamma}{2})$	1.2R	2.0 dB*	0.8 dB	1	1
4 Ø CPSK (offset)	$\frac{1}{2}\ \text{erfc}\ \sqrt{\gamma}$	0.9R	2.5 dB	0.8 dB	2	4
FFSK	$\frac{1}{2}\ \text{erfc}\ \sqrt{\gamma}$	1.1R	2.5 dB	0.8 dB	2	4

Definition of relative equipment complexity: 1 = least 2 = moderate 3 = significant 4 = most

*Note: This takes into account that the modem is designed for voice transmission and adapted for data.

5.0 MODULATION TECHNIQUES

5.3 EVALUATION OF MODEMS

5.3.4 SYSTEM IMPLICATIONS

Related problems for the various modems are discussed.

5.3.4.1 EFFECT OF INTERFERENCE

In evaluating the various modem performances it was assumed that through careful channel assignments with spacing of 25 kHz, no significant degradation is caused by adjacent channel interference. However, radio frequency interference (RFI) is generally one of the limiting factors in the performance of any communication system. In the link calculation, RFI is treated as another source of additive white Gaussian noise. This may give conservative results for digital modulation and in some cases for analog voice modulation. The following provides some insight into the effect of interference on analog and digital signals.

Analog Voice Signal

For the single voice channel per carrier system considered in this study, most of the RFI (man-made) will appear as wide-band interference. The model of additive white Gaussian noise for RFI is applicable. If the interference is narrow-band (or tones), the hard limiter in the ANBFM demodulator prior to the detector will give the familiar suppression effect. If the desired signal is above the interference signal, this effect helps to reduce the interference degradation. However, if the desired signal is below the interference signal, the same effect will enhance the interference degradation. Fig. 5.7 taken from reference(5.10) shows the effect of interference on the A.I. performance of the ANBFM system for different C/I values.

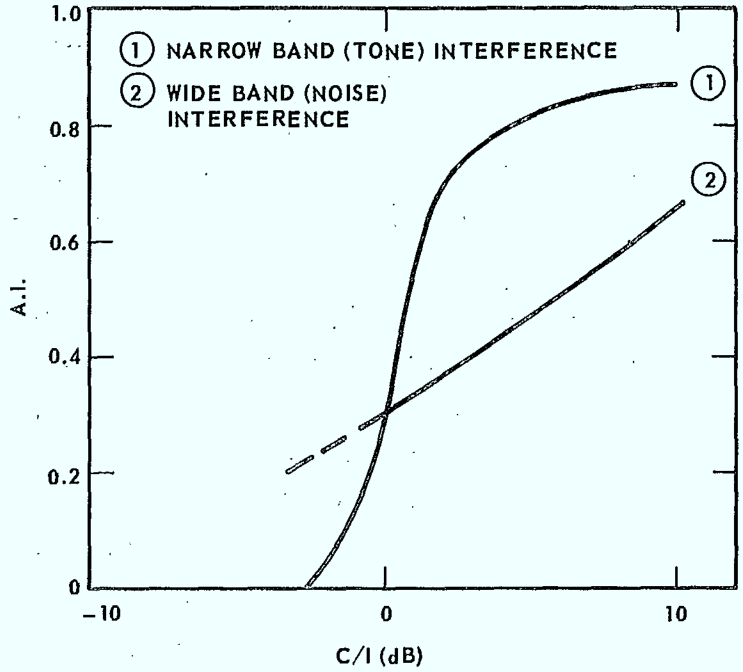


FIGURE 5.7

Performance of ANBFM with RFI

Digital Data

Rather than attempting to evaluate separately the performance of the digitized voice and data signal in the presence of interference signal, results are given in terms of increased E/N_o requirements for the various digital modulation methods.

For the coherent PSK system, Rosenbaum and Glave$^{(5.11)}$ derived the limited peak bound for circular symmetric interference (i.e. the envelope and phase functions of the interference signal are independent with uniformly distributed phase). Curves of error probability vs E/N_o are given in families of C/I with different peak factors (ratio of peak envelope to rms envelope of the interference signal). For ease of comparison with other modulation systems, degradations in E/N_o are derived from the given results for a peak factor of 0 dB (i.e. a single, constant amplitude in-band, additive interferer). Curves for binary PSK and Quadrature PSK (QPSK) are shown in Fig. 5.8. Because of the similarity in the coherent detecting configuration, the degradation for FFSK is assumed to be similar to that of QPSK. In general, QPSK is much more susceptible to interference than binary PSK especially for low C/I (less than 16 dB). For DPSK system the interference signal in two adjacent sample times are correlated so the degradation is dependent on the relative phase slip of the interference from one sampling instant to the next$^{(5.12)}$. This phase slip is defined by

$$\Theta = 2\pi\,(fi-fs)T$$

where fi = interfering carrier frequency
fs = wanted signal frequency
T = bit interval

In the binary system, Θ is 0° for the best case and 90° for the worst case. The spread is dependent on C/I. At C/I = 8 dB, this amounts to 2 dB. In general, binary DPSK performs about as well with interference at best-case Θ as binary CPSK. For four phase DPSK, the spread in performance degradation due to Θ is less, but the overall large degradation prohibits its consideration in the present study.

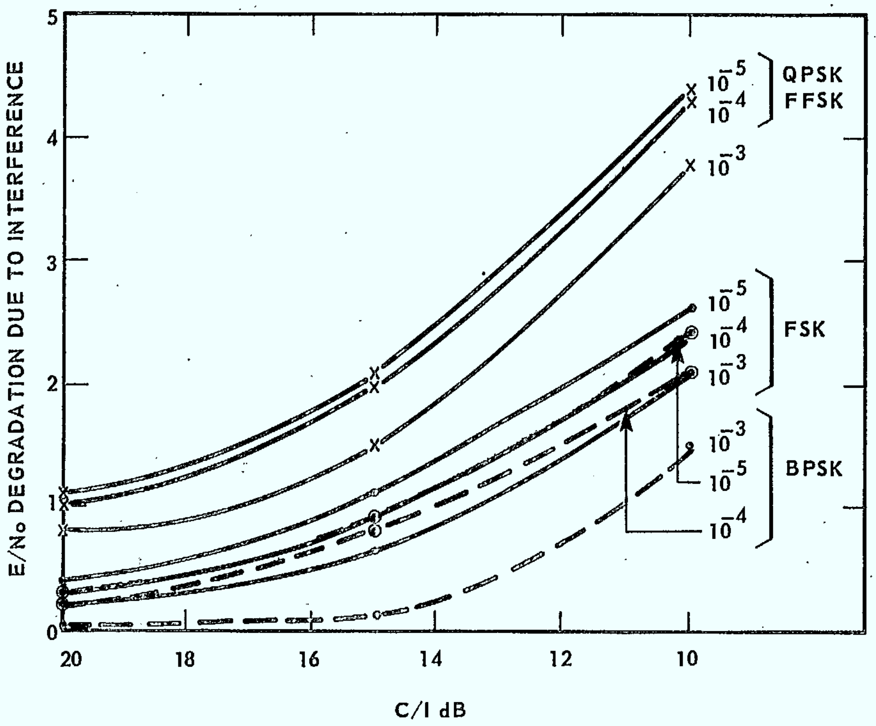


FIGURE 5.8

E/No Degradation Due to Interference

The error probability of a binary noncoherent FSK system in the presence of tone and narrow band interference has been dealt with by Jones(5.13) and Wang(5.14). The E/N_o degradation is again plotted in Fig. 5.8 for different C/I and is seen to be somewhat greater than that for the binary CPSK system.

Thus, from comparisons of the E/N_o degradation among the different modulation methods, it is evident that the choice of binary CPSK system is an appropriate one for the power-limited channel in the presence of interference. For negligible degradations (smaller than 0.3 dB), C/I has to be greater than 20 dB:

5.3.4.2 EFFECT OF IMPERFECT TRANSPONDER CHARACTERISTICS

In the SCPC/FDMA system considered in this study, it is necessary to amplify many modulated carriers through TWT amplifiers in the SHF portion and class C transistor amplifiers in the UHF portion of the satellite transponder. The intermodulation due to the non-linear amplitude characteristic and AM-PM conversion effect of TWT have been considered by many authors(5.15, 5.16). The intermodulation product contributed by TWT with various degrees of back-off can be obtained(5.17). For the transistor class C amplifiers, there is an optimum operating power for optimum C/IM(2.1) due to the amplitude saturation characteristic similar to TWT as well as an additional 'turn-on' nonlinearity in low driving level. Since no definite AM-AM and AM-PM characteristics are available yet for the probable class-C amplifiers the approach taken in this study is to assume a range of probable C/I values, and to evaluate the C/N_o requirement at the demodulator input for the various modem types when the intermodulation noise is treated as an additional source of thermal noise. The results are given in Tables 5.5 and 5.6 for voice and data transmission, respectively, for three levels of C/IM: 12dB, 16 dB and 20 dB. From the $\frac{C}{N_o}$ requirement, it is apparent that C/IM should be at least 16 dB. The link calculation for the satellite channels is given in Section 6.

TABLE 5.5

Summary of Modem System Requirements for Voice

REQUIREMENT FOR VOICE TRAFFIC			REQUIRED AT DEMODULATOR I/P			$(C/No)_{Total}$ in dB-Hz REQUIRED AT DEMODULATOR FOR			
MODULATION METHOD	PERFORMANCE	BANDWIDTH	$\frac{E}{No}$ dB	$\frac{C}{No}$ dB	$\frac{C}{N}$ dB	$C/_{IM}$ = 12 dB	$C/_{IM}$ = 16 dB	$C/_{IM}$ = 20 dB	REMARK
ANBFM	A.I. = 0.37	10 kHz	---	40	0	40.3	40.1	40.0	
	= 0.45	10 kHz	---	43	3	43.6	43.2	43.1	
	= 0.53	10 kHz	---	46	6	47.4	46.6	46.2	
FM with Companding	A.I. > 0.65	23.0 kHz	---	53.5	10.0	57.8	54.8	54.0	
DM/CPSK; 16 kb/s BW = 1.4R	A.I. = 0.38	22.4 kHz	5.3 dB @ 10^{-2}	46	2.5	46.5	46.2	46.1	Implementation margin = 1.5 dB Transponder ISI degradation = 1.5 dB $P_e \leq 10^{-2}$
	= 0.52			48	4.5	48.9	48.3	48.1	
	= 0.65			50	6.5	51.4	50.6	50.2	
DM/CPSK; 32 kb/s BW = 1.4R	A.I. > 0.65 S/N + 32 dB	44.8 kHz	7.4 dB @ 10^{-3}	55.4	8.9	58.3	56.4	55.8	Implementation margin = 1.5 dB; Transponder ISI degradation = 1.5 dB $P_e \leq 10^{-3}$
DM/FFSK; 16 kb/s BW = 1.1R	A.I. = 0.38	17.6 kHz	5.3 dB @ 10^{-2}	46	3.5	46.7	46.3	46.1	Implementation margin = 2.5 dB; Transponder ISI degradation = 0.8 dB
	= 0.52			48	5.5	49.1	48.4	48.1	
	= 0.65			50	7.5	51.9	50.7	50.3	
DM/FFSK; 32 kb/s	A.I. > 0.65 S/N + 32 dB	35.2 kHz	7.4 dB @ 10^{-3}	55.4	9.9	59.6	56.6	56.0	Implementation margin = 2.5 dB; Transponder ISI degradation = 0.8 dB

TABLE 5.6

Summary of Modem System Requirements for Data

REQUIREMENT FOR VOICE TRAFFIC			REQUIRED AT DEMODULATOR I/P			$(C/No)_{Total}$ in dB-Hz REQUIRED AT DEMODULATOR FOR			
MODULATION METHOD	PERFORMANCE	BANDWIDTH	$\frac{E}{No}$ dB	$\frac{C}{No}$ dB	$\frac{C}{N}$ dB	$C/_{IM}$ = 12 dB	$C/_{IM}$ = 16 dB	$C/_{IM}$ = 20 dB	REMARK
CPSK 75 b/s	$P_e \leq 10^{-5}$	105 Hz	9.8 + 3	31.5	11.3	40.2	33.3	32.2	Implementation margin ≈ 1.5 dB; Transponder ISI degradation ≈ 1.5 dB B.W. = 1.4R
750 b/s	$P_e \leq 10^{-5}$	1.05 kHz	9.8 + 3	41.5	11.3	50.2	43.3	42.2	
2.4 kb/s	$P_e \leq 10^{-5}$	3.36 kHz	9.8 + 3	46.6	11.3	55.3	48.4	47.3	
4.8 kb/s	$P_e \leq 10^{-5}$	6.72 kHz	9.8 + 3	49.6	11.3	58.3	51.4	50.3	
FFSK 75 b/s	$P_e \leq 10^{-5}$	82.5	9.8 + 3.3	31.8	12.6	N.P.*	34.5	32.7	Implementation margin ≈ 2.5 dB; Transponder ISI degradation ≈ 0.8 dB B.W. = 1.1R
750 b/s	$P_e \leq 10^{-5}$	825	9.8 + 3.3	41.8	12.6	N.P.	44.5	42.7	
2.4 kb/s	$P_e \leq 10^{-5}$	2.64 kb/s	9.8 + 3.3	46.9	12.6	N.P.	49.6	47.8	
4.8 kb/s	$P_e \leq 10^{-5}$	5.28 kb/s	9.8 + 3.3	49.9	12.6	N.P.	52.6	50.8	
FSK 75 b/s	$P_e \leq 10^{-5}$	90.0	13.2 + 2.8	34.7	15.2	N.P.	42.7	36.5	Implementation margin ≈ 2 dB; Transponder ISI degradation ≈ 0.8 dB B.W. = 1.2R
750 b/s	$P_e \leq 10^{-5}$	900		44.7	15.2	N.P.	52.7	46.5	

* N.P. = Not Possible

The tabulated $(\frac{C}{N_o})_{Total}$ requirements shed some light on the modem recommendation to be given in Section 5.4. For example, for voice transmission, if C/IM = 16 dB, ANBFM has an advantage ranging from 1.7 dB to 6.1 dB over DM/PSK (16 kb/s) for A.I. of 0.52 and 0.38, respectively. Because of the relatively low C/N requirement compared to the available C/IM, the dependence of $(\frac{C}{N_o})_{Total}$ on C/IM is only slight. Similar observation can be made for DM/PSK and DM/FFSK.

For data transmission which requires an error probability of 10^{-5}, the effect of C/IM could be very pronounced. For binary CPSK, FFSK, and binary non-coherent FSK, the C/N required is 11.3 dB, 12.6 dB and 15.2 dB, respectively. Thus, a channel with C/IM less than 12 dB cannot support reliable data transmission if FFSK and non-coherent FSK are used. Even at C/IM = 16 dB and a data rate of 4.8 kb/s, using the FFSK modem requires a $\frac{C}{N_o}$ = 52.6 dB-Hz which is difficult for the link budget to meet. For the FSK modem, data rates higher than the teletype signal is almost not possible.

Apart from the degradation due to the intermodulation noise, as the digital modulated signals pass through the satellite transponder, intersymbol interference and phase distortion produced by the AM-PM conversion will all contribute to the increase of bit error rate. In the previous comparison of different digital modulation methods some degradation margins are allowed (Table 5.4), and depends on the amount of RF envelope variation$^{(5.18)}$.

5.3.4.3 EFFECT OF MULTIPATH FADING

In the communications link between the satellite and a moving platform (a probable application in this study), fading and multipath transmission due to the signal reflection will be encountered. The fading will be most severe in the case of aircraft with wide antenna beam width and flying over water plus viewing the satellite at a low inclination angle. The reflective signal may consist of a specular component, (a replica of the transmitted signal with a differential delay and a certain reflection coefficient) and a diffuse component (an aggregate of reflected signals from multiple reflection points within the line of sight of the aircraft, resulting in random-noise like signal). To predict the degree of reliability of a communications link, analyses have been made with the assumption of different fading models, the most common of which are Rayleigh (reflected signal consisting of diffuse component only), and Rician (reflected signal consisting of both specular and diffuse components.). The accuracy of the model depends on the geometry and the relative motion between the satellite and the moving platform. Much effort on fading measurement has been made, but mostly on the amplitude characteristics of the faded signal. This gives information on the net loss of signal level during fading, and allows the assignment of fading margin in the link calculation. To find out other degradation effects of fading, it is necessary to know the relative magnitudes of specular and diffuse components and of direct and reflected signals.

In analog voice transmission using FM, the differential time delay* of the reflected signal is short compared with the top modulating frequency. The resulting distortion is negligible apart from the loss of signal strength accompanying the fading. However, extremely low fading rates (lower than 2 Hz) and high fading rates (higher than 20 Hz) will affect the voice intelligibity due to psycho-accoustical effect(5.10).

For digital signal transmission, intersymbol interference may be caused by the multipath fading. Smith(5.20) et al, analyzed the performance degradation for the coherent PSK transmission. They modelled the binary PSK signal with bit duration T and carrier frequency having an identical multipath component with differential

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*Note: The differential time delay depends on the aircraft's latitude, longitude, altitude, the flying speed, and the carrier frequency. For a synchronous equational satellite and an aircraft flying due North - 600 mph at 30,000 ft, with frequency at 300 MHz, the differential delay may have a maximum of 60 μsec at 0° latitude(5.19).

time delay γ, phase shift and relative amplitude α. For $f = \alpha \cos (2\pi f_0\gamma + \Theta)$ less than zero, intersymbol interference is negligible; for f greater than 0, the intersymbol interference effect becomes significant when $\frac{\gamma}{T} > 0.5$. With the differential time delay encountered in the aircraft/satellite communications link normally below 80 μsec, and the relatively low data rate (4.8 kb/s maximum) considered in this study, the performance degradation will therefore only be due to the signal loss associated with the fading. However, for digitized voice transmission, the performance degradation caused by intersymbol interference resulting from multipath fading may become significant. There is insufficient information available at present and some field experiments in this respect will be useful.

5.4 RECOMMENDATIONS OF MODEMS

Recommendations are given based on the results obtained in Section 5.3.

Based on the results obtained in Section 5.3 recommendations of modem types appropriate to the UHF multipurpose satellite system are now catagorized for two major groups of users:-

(1) Users of field quality voice and teletype transmission, and

(2) Users of field quality and good quality voice (including encryption) and high rate data transmission (up to 4.8 kb/s).

GROUP (1): FIELD QUALITY VOICE CHANNEL USERS:-

ANBFM IS RECOMMENDED

- lowest C/No and $\frac{C}{N}$ requirements
- lowest bandwidth requirement (10 kHz)
- performance degrades less rapidly with decreasing C/No.
- meets remote/remote or remote/central user communication requirement with teletype capability
- low cost, high reliability, low power consumption
- high immunity to intermodulation noise
- good FM suppression of interference signal
- graceful deterioration under severe fading conditions
- less susceptable to multipath differential delay
- alternatively suitable for 75 b/s data transmission.

GROUP (2): FIELD AND GOOD QUALITY VOICE CHANNEL USERS:-

DM/PSK IS RECOMMENDED

- compatibility with encryption for DND users
- capability of trade off between power (up to 4 dB) and Bandwidth by using forward error correcting codes; this may be advantageous for transmitting data and digital control/supervisory signals which require $P_e < 10^{-5}$
- consideration of future all digital network.

5.0 MODULATION TECHNIQUES

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6.0 SYSTEM CALCULATIONS

6.1 SATELLITE TRANSPONDER CONFIGURATIONS

Various system parameters of the satellite transponder and the transponder configurations are presented. Critical transponder design objectives are listed.

During the study period, two types of transponder configurations(6.1, 6.2) were given by the design authority, Department of Communications, Government of Canada. The initial configuration consists of two transponders; a UHF-SHF and a SHF-UHF transponder. For simplicity, this will be referred to as the UHF system. It is basically a double-hop system and the SHF band is 4 - 6 GHz, 7 - 8 GHz or 12 - 14 GHz. A second configuration consists of the above two transponders and six SHF-SHF transponders, the SHF band being 12 - 14 GHz. A simplified schematic diagram is shown in Fig. 6.1.

The system parameters of the various transponders are as follows:-

(1) UHF

Polarization	circular
Minimum Antenna gain within coverage zone	19 dB
Receiving Frequency	370 - 406 MHz
Received signal level	-107 dBm/channel
Receiver system Noise Figure	2 dB
Transmitting power level	29 dBm/channel
Transmitting Frequency	300 - 329 MHz

(2) SHF (Part of UHF/SHF System)

Polarization	Linear
Bore-sight Antenna gain	
(a) Broad Beam	29.5 dB
(b) 1° x 1° spot beam	44.5 dB
Receiving Frequency	8 GHz (or 14 GHz or 6 GHz)

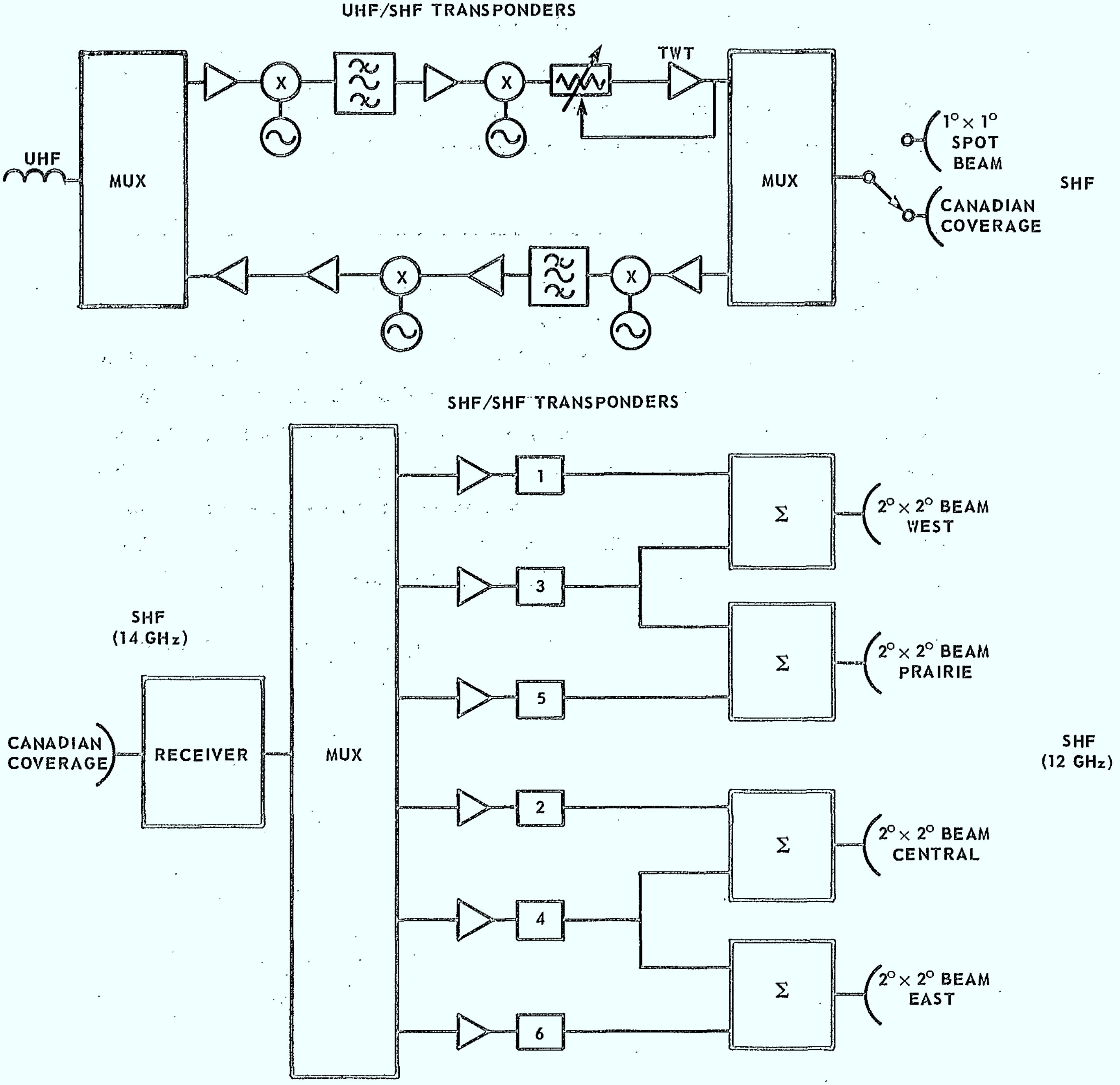


FIGURE 6.1

Simplified Schematic Diagram of Satellite Transponders

(a) Initial configuration: UHF/SHF transponders only,

(b) Second configuration: UHF/SHF and SHF/SHF transponders.

Receiver System Noise Figure	4 dB
Saturated Transmitting power level (Single Carrier)	37 dBm
Transmitting Frequency	7 GHz (or 12 GHz or 4 GHz)

(3) SHF (Second Configuration)

Polarization	Linear
Bore-sight Receiver Antenna gain (Broad Beam)	29.5 dB
Receiver Frequency	14 GHz
Saturated Flux density (Single Carrier)	-50 dBm/m^2
Receiver G/T	-8 dB/K
Bore-Sight Transmitter Antenna Gain (2° x 2° spot beam)	38.6 dB
Beam Edge Saturated EIRP (Single Carrier)	76 or 73 dBm (See below)
Transmitting Frequency	12 GHz

There are three communication systems which the satellite may provide; one UHF system and two SHF systems. The UHF system provides 100 voice or data channels with SCPC (single channel per carrier) service. The SHF system with 73 dBm minimum saturated EIRP carries SCPC service for remote communications and the SHF system with 76 dBm EIRP provides MCPC (multi-channel per carrier) services for communications between centers.

6.2 EARTH STATIONS

Various types of earth stations are discussed. Earth station parameters are presented.

Since the service objectives of various communication systems are different, the requirements of the earth stations are completely different. In the following, the major earth station parameters for each system are presented and various constraints are discussed.

(1) UHF System

There are basically four types of UHF stations and two types of SHF stations in the system, namely

(a) data retransmission platform (UHF),
(b) portable station (UHF),
(c) airborne station (UHF),
(d) transportable station (UHF),
(e) central control station (SHF),
(f) regional station (SHF).

The data retransmission station is not considered in this report (by direction of the Design Authority). From the view point of link calculations, the major differences among the various stations are the antenna size, the required transmitting power and the receiver system noise figure. Because of the high antenna noise in the UHF band, within certain limits, the receiver noise figure is not a very sensitive parameter in the system. For instance, by changing the receiver system noise from 300°K to 100°K, the total system improvement is less than 2 dB but the receiver system reliability, cost, size, weight, etc. would increase considerably.

The UHF earth station parameters are as follows:-

UHF EARTH STATION

Antenna gain	Range of:	3, 10, 17, 27 dB
Receiver system Noise Figure		3 dB (290°K)
Transmitting power		up to 1000 Watts

The Control and Regional earth station parameters are as follows:

SHF EARTH STATION

Antenna Diameter	up to 60 ft.
Receiver system Noise Temperature	180 to 600K
Transmitting power	5 to 100 Watts

(2) SHF System:

There are two types of earth stations in the system, Single channel per carrier (SCPC) stations and multichannel per carrier (MCPC) stations. The earth station parameters are:

	SCPC	MCPC
Antenna Diameter	6.5 ft.	16.4 ft.
Receiver Noise Temperature	600K	200K
G/T	17.2 dB/K	28 dB/K

6.0 SYSTEM CALCULATIONS

6.3 UHF SYSTEM

6.3.1 GENERAL DISCUSSION

The system configuration of the UHF communication system is discussed and the link equation is given.

The system is not symmetrical and consists of many different links which have completely different constraints. There are five different message paths which the system can provide, namely SHF-UHF, UHF-SHF, UHF-UHF, SHF-SHF and UHF-SHF/SHF-UHF. (SHF-UHF means that the message is originated at the ground station with SHF band and terminated at the UHF station). In the following sections, all message paths will be discussed.

In the link performance assessment the carrier to noise density ratio C/N_o is the most effective parameter and the total system C/N_o (thermal) is computed as follows:-

$$(C/No)^{-1} = (C/No)_u^{-1} + (C/No)_D^{-1} \tag{1}$$

where $(C/No)_u$ and $(C/No)_D$ are the carrier-to-noise density power ratios in the up-link and the down-link, respectively.

For either the up link or the down link, the C/No values (in dB) can be calculated as follows:

$$C/N_o = P + G_t - L + (G/T) - k \tag{2}$$

P	is the transmitting power in dBm
G_t	is the transmitting antenna gain (dB)
L	is the path loss in dB
(G/T)	is the receiver G/T dB/K
k	Boltzman's constant (-198.6 dBm/K/Hz)

In Eq. (1) above, the intermodulation noise is not included. In the final availability and sensitivity analysis, the required C/N with specified bandwidths must be compared to the available C/N which is made up of thermal and intermodulation components. It is just a matter of convenience whether intermodulation noise is included in the available system C/N or in the required C/N. In the discussions that now follow, the intermodulation noise is included in the required carrier to noise ratio.

Since there are no system reliability objectives defined for this contract study, the fade margins have been treated as a variable in order to test the system sensitivity.

The primary SHF band used in the UHF system is the 7/8 GHz frequency band. Two other frequency bands, namely 4/6 GHz and 12/14 GHz, will be discussed by comparing with the results from the 7/8 GHz frequency band calculations.

6.3.2 SHF-UHF CHANNELS (CENTRAL-TO-REMOTE)

The channel is down-link limited. High gain UHF ground station antenna or high satellite EIRP is required to achieve a reliable communication channel.

The up-link equation is

$$(C/No)_u = EIRP - Lu + (G/T) - k$$

Substituting the effective path loss of 204.2 dB (see Table 6.1) and the Boltzman's constant into above equation, we have

$$(C/No)_u = EIRP + (G/T) - 5.6$$

Since the most demanding system C/No requirement in the UHF system is due to the good quality voice service, and the required system C/No with 16 dB intermodulation noise is 56.4 dB-Hz (DM/PSK, 32 kb/s) as shown in Table 5.5, then, assuming $(C/No)_u$ is 10 dB better than the system C/No,

$$EIRP + (G/T) = 72 \text{ dBm}$$

Assuming that the typical satellite receiver G/T = -2 dB/k, then the required ground station EIRP is 74 dBm/channel which can be obtained easily by using a 60 ft. diameter antenna with less than 50 Watts transmitting power. (The SHF ground station antenna size is determined by the interference condition as shown in Section 6.3.3). The detailed link calculation is shown in Table 6.1 and the relationship between the UHF ground station G/T and the down link C/No is shown in Fig. 6.2(a).

Figures 6.2b and 6.2c indicate the available C/No (thermal) for various values of propagation reliability and various UHF antenna gains; 6.2b without unintentional man-made noise and 6.2c with unin-

TABLE 6.1

SHF-UHF Channels (Central-to-Remote)

(a)	UP-LINK (8 GHz)		
1.	Ground Station Effective Transmitting Power		
	TWT Output	50 Watts (single carrier, saturated)	
	TWT Output backoff	10 dB	
	Number of Channels	100	
	Transmission Line Loss	1 dB	
	Effective transmitting power per channel		16 dBm
2.	Ground Station Effective Antenna Gain		
	Antenna Gain (60 ft.)	61 dB	
	Pointing Error	0.5 dB	
	Effective Antenna Gain		60.5 dB
3.	Ground Station EIRP	76.5 dBm	
	Transmitting System Margin	2 dB	
	Ground station EIRP		74.5 dB
4.	Free Space Loss and Fade Margin		
	Free Space Loss	202.7 dB	
	Atmospheric Attenuation	0.1 dB	
	Precipitation and Scintillation Fade Margin (99.99%)	1.4 dB	
	Effective path loss		204.2 dB
5.	Effective Satellite Receive Antenna Gain		
	Antenna Gain (Broadbeam)	29.5 dB (boresight)	
	Antenna pointing error	0.1 dB	
	Central station location error	1.0 dB	
	Multipath degradation	0.5 dB	
	Polarization Misalignment	0.1 dB	
	Transmission line loss	0.5 dB	
	Effective receive Antenna Gain		27.3 dB
6.	Satellite Receive System Noise Temperature		
	Background Noise	220K	
	Receiver Noise	440K	
	Receiver system Noise		660K
7.	Effective Satellite Receiver G/T		-0.9 dB/K
8.	Up-link C/No		68 dB-Hz

..........Cont'd.

TABLE 6.1 (Cont'd)

(b) DOWN-LINK (300 MHz)

9. Satellite Transmitting Power (per channel) 29 dBm

10. Effective Satellite Antenna Gain within coverage zone 19 dB

11. Free Space Loss

Free Space Loss 174 dB

Atmospheric Attenuation 0.2 dB

Effective path loss 174.2 dB

12. Ground Station Antenna G/T range of -27.8 to -5.7 dB/K

Antenna Gain	3	10	18	27	(dB)
Polarization Misalignment Loss	3	1	1	1	(dB)
Antenna Pointing Error	0.	0.3	0.5	0.5	(dB)
Transmission Loss	0.5	1	1	1	(dB)
Antenna Noise	200	250	320	860	(K)
Receiver System Noise	290	290	290	290	(K)
Effective G/T	-27.8	-19.7	-12.3	-5.7	(dB/K)

13. Down-Link C/No* (without fade margin) range of 44.6 to 66.4 dB-Hz

14. Total C/No* (combined up and down link) range of 44.6 to 64.2 dB-Hz

* UHF down link fade margin not included, as this is a function of propagation reliability. See Figures 6.2b and 6.2c.

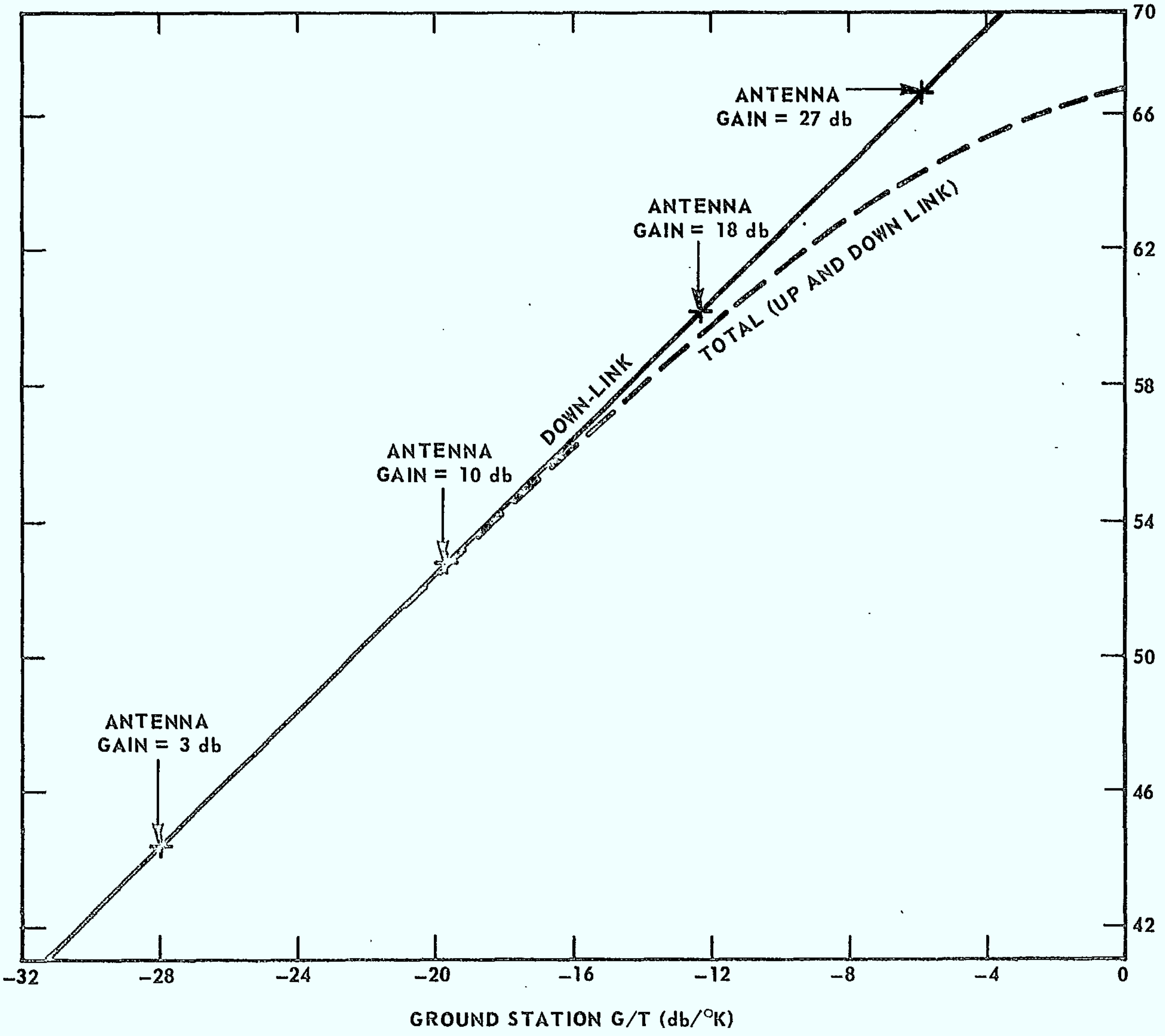
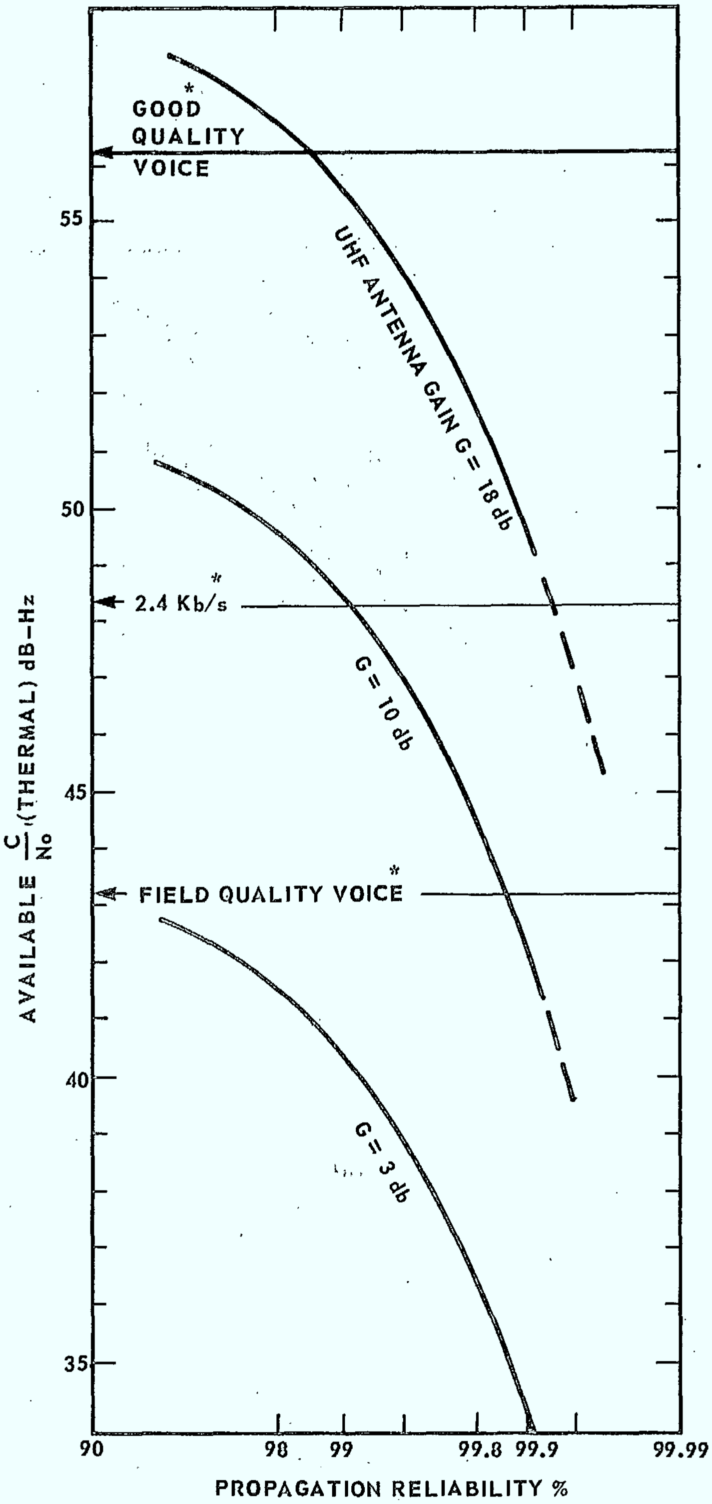


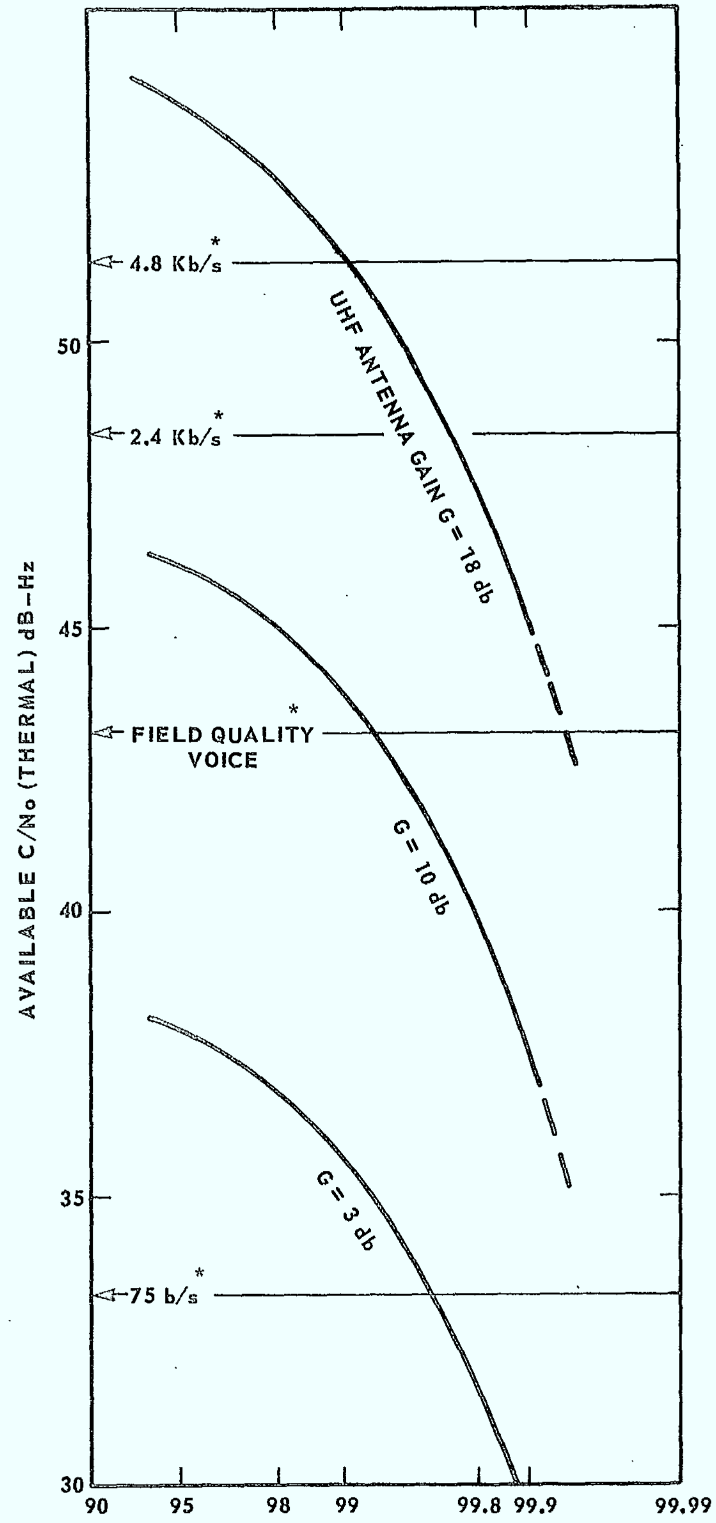
FIGURE 6.2a

C/No (Thermal) for SHF/UHF Channels vs Effective Ground Station System G/T, for UHF Channels, without UHF Propagation Fade Margins.



* With 16 dB C/I

FIGURE 6.2b
Available C/No (Thermal) versus Propagation Reliability, without Unintentional Man-made Noise, for the SHF-UHF System



* With C/I 16 dB

FIGURE 6.2c

Available C/No (Thermal) versus Propagation Reliability, with Unintentional Man-made Noise, for SHF-UHF System tentional man-made noise (-168 dBm/Hz). Superimposed on top of these curves are horizontal lines indicating the required C/No (thermal) ratio for various types of service, when the C/I of the UHF transponder is 16 dB, and the modem requirements are as stated in Tables 5.5 and 5.6.

The corresponding required UHF ground station antenna gain is shown in Table 6.2.

TABLE 6.2

Required UHF Ground Station Antenna Gain for Various Services
(The receiver system noise figure is 3 dB)

	REQUIRED UHF ANTENNA GAIN (dB)			
PROPAGATION RELIABILITY	99%		99.9%	
	WITHOUT MAN-MADE NOISE	WITH MAN-MADE NOISE	WITHOUT MAN-MADE NOISE	WITH MAN-MADE NOISE
Field Quality	2.8 dB	9.3 dB	8 dB	15.8 dB
Good Quality	19 dB	25.0 dB	27.6 dB	29.1 dB
75 b/s Data	-4.3 dB	0.7 dB	1.1 dB	5.7 dB
4.8 kb/s Data	13.1 dB	17.9 dB	20.0 dB	24.2 dB

6.0 SYSTEM CALCULATIONS

6.3 UHF SYSTEM

6.3.3 UHF-SHF CHANNEL (REMOTE-TO-CENTRAL)

The channel is interference limited and power limited. High ground station EIRP is required to support a reliable communication channel.

There are three basic calculations for the UHF-SHF channel; the required UHF ground station effective transmitting power, the effects of the Satellite AGC system on the faded signal, and the effective SHF ground station antenna size. The detailed procedure and various assumptions in each calculation are as follows:-

(A) Required UHF Ground Station Transmitting Power

The relationship between the ground station transmitting power and the satellite received signal level is

$$C = EIRP - L_u + G_s$$

where C = the effective satellite received signal
= -107 dBm;

G_s = the satellite receiving antenna gain
= 19 dB; and

L_u = total path loss (without fade margins)
= 178.1 dB.

then EIRP = 178.1 - 19 - 107
= 52.1 dBm

Taking into consideration transmission line loss, pointing error loss, polarization misalignment loss, etc., a nominal 3 dB and 10 dB UHF ground station antenna has a net antenna gain measured at the transmitter output point of -0.5 dB and 7.7 dB, respectively.

The corresponding required transmitting power is 52.6 dBm (162 Watts) and 44.4 dBm (28 Watts), respectively. (See Table 6.3).

(B) Effects of the Satellite AGC System on Faded Signals

The satellite UHF/SHF transponder incorporates an automatic gain control (AGC) system as an anti-interference feature. This AGC system has a detrimental effect on a faded up-link signal to the extent of about 1.9 dB as indicated below.

The up-link signals arrive at a satellite from different locations and from ground stations with different EIRP's. The signals suffer different scintillation and multipath fades.

Assume that the received signals can be divided into three effective levels; that is, the nominal level, 6 dB above the nominal level and 6 dB below the nominal level. Also assume that the effective distribution function of the carriers is 50% at the nominal level, 25% at 6 dB above the nominal level and 25% at 6 dB below the nominal level. Due to the AGC system keeping the satellite total output power constant, it can be shown that from purely the division of power consideration the stronger signals would suppress the weaker signals by approximately 1.9 dB.

The SHF transponder TWT output backoff is determined from a number of conflicting considerations. On the one hand it is obvious that as little back off as possible should be incorporated so as to get the maximum output power. On the other hand with multi-carrier operations inter-modulation products can be a very severe constraint unless adequate output backoff is used. The issue is complicated by the fact that the multiple carriers going through the transponder are not of equal magnitude and some of these carriers would be part of a double hop satellite system where additional intermodulation noises are introduced in the second satellite link. Further, the capacity and performance for the various services are not yet fully defined. Because of these difficulties it is not possible to conduct an accurate computation of the optimum backoff and therefore the output backoff used in this study has been arrived at from a qualitative argument as follows:

On examing Tables 5.5 and 5.6 it can be seen that the carrier to intermod ratio must be better than about 16 dB in order to cater for all the service demands. Bearing in mind that in a worst case situation a double hop transmission involving a UHF class C transponder amplifier whose carrier to intermodulation products are not expected to be better than about 16 dB, it is considered that the C/IM of the SHF transponder TWT amplifier should be appreciably better than 16 dB. In this study, therefore, a C/IM of 20 dB has been chosen as a minimum requirement. The TWT output backoff corresponding to this C/IM value is approximately 5.6 dB.

In order to utilize the TWT in the satellite effectively, TWT output backoff of 5.6 dB is assumed and the inter-modulation noise introduced by the TWT is -20.2 dB. The effective satellite transmitting power is 5.3 dBm (99% reliability) or -1.0 dBm (99.9% reliability) as shown in Table 6.3 (item 4).

(C) SHF Ground Station Antenna

In the link performance assessment the following relations hold,

$$(C/No)^{-1}_{\text{Thermal}} = (c/No)^{-1}_{u} + (C/No)^{-1}_{D}$$

and $$(C/No)_D = EIRP - L_D + (G/T)_R - k - D_I$$

where the satellite EIRP for the 7 GHz down-link is 26.3 dBm (99.9% reliability) as may be deduced from Table 6.4 (items 4 and 5). The effective path loss (L_D) is 203 dB and the effective down-link interference degradation D_I due to an "Extraordinary Interfering" CW signal 50 dB above the nominal received signal level is 14.1 dB as shown in Table 6.4 (item 11), (1° x 1° spot beam is assumed).

Substituting the values discussed, we have:-

$$(C/No)_D = 26.3 - 203 + (G/T)_R + 198.6 - 14.1$$
$$= 7.8 + (G/T)_R$$

Assuming field quality voice is required under interference conditions, the required $(C/No)_{Thermal}$ with 20.2 dB intermodulation noise is 43.1 dB-Hz. Since $(C/No)_u = 54.9$, then

$$(C/No)_D = 43.5 \text{ dB-Hz}$$

and

$$(G/T)_R = 35.7 \text{ dB/K}$$

TABLE 6.3

UHF - SHF Channels (Remote-to-Central)

(a) UP-LINK (370 MHz)

1. Ground Station
Required Transmitting power

Satellite receiving signal level		-107 dBm			
Effective Satellite Antenna gain		19 dB			
Ground Station Antenna gain:	Range of	3	10	18	(dB)
Net ground station antenna gain		-0.5	7.7	15.5	(dB)
Total path loss without Fade Margin		178.1 dB			
Required Transmitting Power (dBm)		52.6	44.4	36.6	
(Watts)		162	28	4.6	

2. Satellite Receiver
System Noise

Earth Temperature	200°K	
Solar Noise	30°K	
Receiver System Noise	170°K	
Transmission line Ambient Temperature	300°K	
Total Receiver System Noise (1 dB Insertion Loss)		414°K

3. Up-Link C/No

Scintillation & Multi-path Fade Margin (dB)		4.2 (99%)	10.5 (99.9%)
Worst Channel C/No	(dB-Hz)	61.2 (99.0%)	54.9 (99.9%)

............Cont'd.

TABLE 6.3 (Cont'd)

(b) DOWN-LINK (7 GHz)

4.	Satellite Transmitting Power			
	TWT Output	37 dBm (single carrier, saturation)		
	TWT output backoff	5.6 dB		
	Carrier/Intermodulation Noise	20.2 dB		
	Number of Channels	100		
	AGC suppression effect	1.9 dB		
	Input power reduction (Due to UHF up-link fades)	4.2 dB (99%)	10.5 dB (99.9%)	
	Effective Transmitting power		5.3 dBm	-1.0 dBm
5.	Effective Satellite Antenna Gain (Broadbeam)			27.3 dB
6.	Free Space Loss and Fade Margins			
	Free Space Loss	201.5 dB		
	Atmospheric Attenuation	0.1 dB		
	Precipitation and Scintillation Fading (99.99%)	1.4 dB		
	Effective Free Space Loss			203 dB
7.	Effective Ground Station Antenna Gain			
	Antenna Gain (60 ft.)	60 dB		
	Pointing Error	0.5 dB		
	Effective Antenna gain			59.5 dB
8.	Receiver System Noise Temperature			
	Antenna Noise Temperature	70°K		
	Receiver Noise	180°K		
	Receiver System Noise Temperature			250°K
			(99%)	(99.9%)
9.	Down-Link C/No*		63.7	57.4 dB-Hz
10.	Total C/No*		59.3	53.0 dB-Hz
11.	Interference			
	Nominal Interference level	-57 dBm		
	Equivalent Interference Degradation (Ref. 6.1)	30 dB		
	Satellite Antenna Gain (Spot)	44.5 dB		
	Antenna Pointing Error (0.1°)	0.7 dB		
	Polarization Misalignment	0.1 dB		
	Insertion Loss	0.5 dB		
	Effective Interference Degradation			14.1 dB
			(99%)	(99.9%)
	Down-Link C/No* with Interference		49.7	43.3 dB-Hz
	Total C/No* with Interference		49.4	43 dB-Hz

---

*TWT intermodulation noise (C/I = 20.2 dB) is not included here but will be dealt with later.

Assuming the receiver system noise temperature is 250K, then

$$G = 56.4 \text{ dB}$$

which is equivalent to a 60 ft. diameter antenna including 0.5 dB gain reduction due to the pointing error.

The detailed link calculation is shown in Table 6. 3 and the total system C/No with and without interference versus the propagation reliability is shown in Fig. 6.3. The propagation reliability of various services is summarized in Table 6.4. Under normal (no interference) conditions the channel can support good quality voice traffic with 99.8% propagation reliability and it can support 4.8 kb/s data traffic with a propagation reliability better than 99.9%. However, the channel cannot support good quality voice traffic with reasonable propagation reliability under the stated extraordinary interference condition.

TABLE 6.4

Propagation Reliability for Various Services for the UHF-SHF Channels

INTERFERENCE LEVEL	GOOD QUALITY VOICE	FIELD QUALITY VOICE	750 b/s DATA	4.8 kb/s DATA
Without Interference	99.75%	> 99.9%	> 99.9%	> 99.9%
With Extraordinary Interference	Not Possible	> 99.9%	99.92%	98.2%

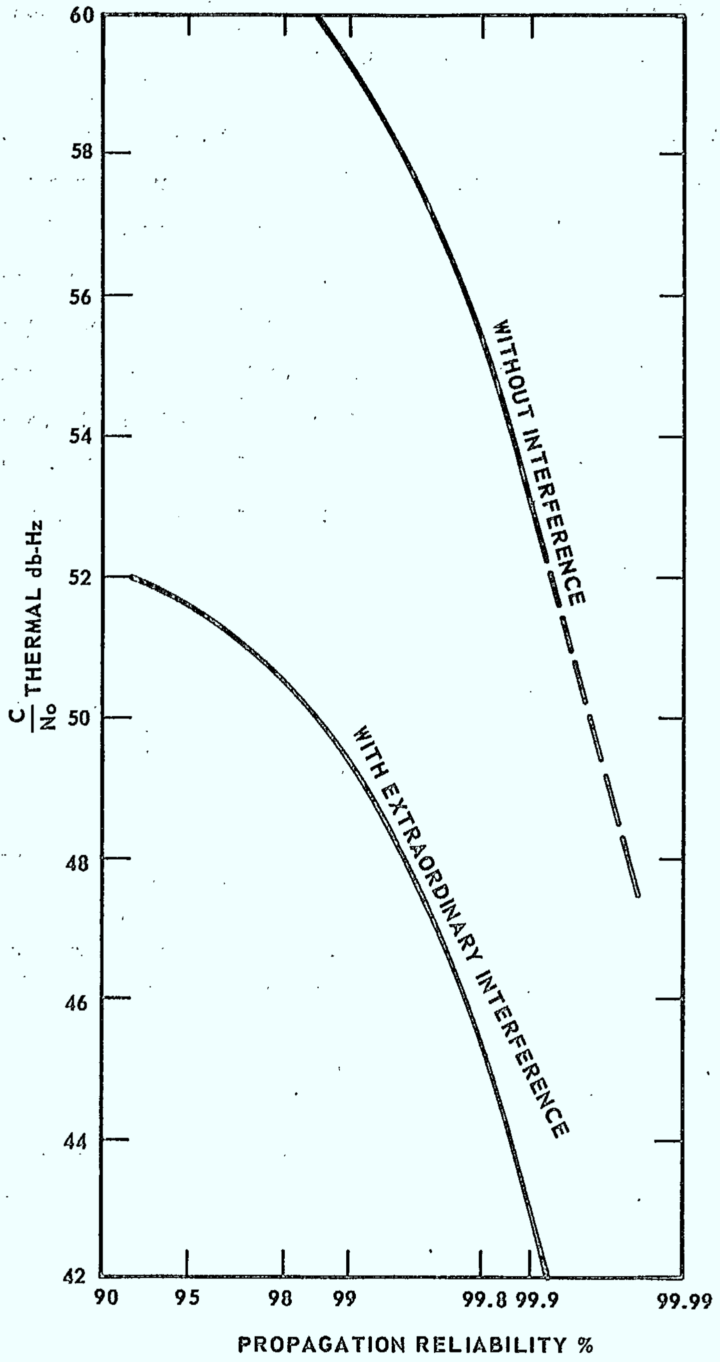


FIGURE 6.3

UHF/SHF Channel System C/No vs the Propagation Reliability

6.0 SYSTEM CALCULATIONS

6.3 UHF SYSTEM

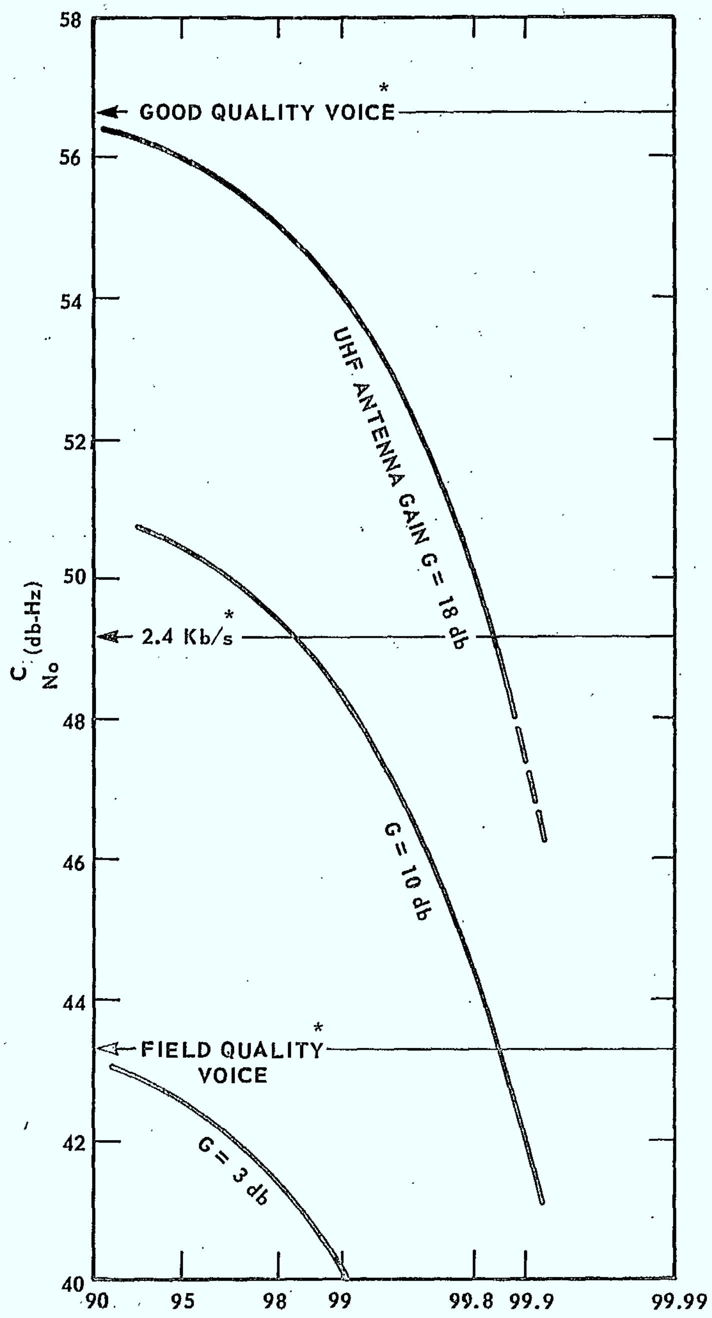
6.3.4 UHF-SHF/SHF-UHF CHANNEL

The system is forward channel (SHF-UHF) limited, and it is also interference limited. The thermal C/No at various propagation reliabilities is presented.

Various assumptions and conditions used in Sections 6.3.2 and 6.3.3 are applied in the UHF-SHF/SHF-UHF channel and the total system intermodulation noise is 14.8 dB; 16 dB being due to the satellite UHF power amplifier and 20.2 dB being due to the satellite SHF TWT. The available system C/No shown in Fig. 6.4a and 6.4b excludes the system intermodulation noise. The required C/No with 14.8 dB intermodulation noise for various services is shown as horizontal lines in Figure 6.4(a) and 6.4(b).

Assuming that there is little correlation between the UHF up-link fading and the UHF down-link fading, the total system propagation outage is approximately the sum of the UHF-SHF channel and the SHF-UHF channel propagation outages. Figs. 6.4a and 6.4b are derived based on these assumptions. Under normal conditions, the field quality voice service can be supported by a 3 dB gain UHF antenna with approximately 99% propagation reliability. The good quality voice service with 95% propagation reliability requires an approximately 19 dB gain UHF antenna. Under the extraordinary interference condition, the 3 dB gain UHF antenna system can support field quality voice services with 98.8% propagation reliability.

In the case of data traffic, the system intermodulation noise reduces the system margin by approximately 4 dB. It will be preferable to implement a data regeneration system in the central station to reduce the cumulative effects of intermodulation noise.



* WITH 16 dB C/I FOR UHFAMPLIFIER AND 20 dB C/I FOR SHF TWT AMPLIFIER, RESULTING IN C/I (TOTAL) OF 14.8 dB

FIGURE 6.4a

C/No of UHF-SHF/SHF-UHF Channels vs Propagation Reliability, without Extraordinary Interference

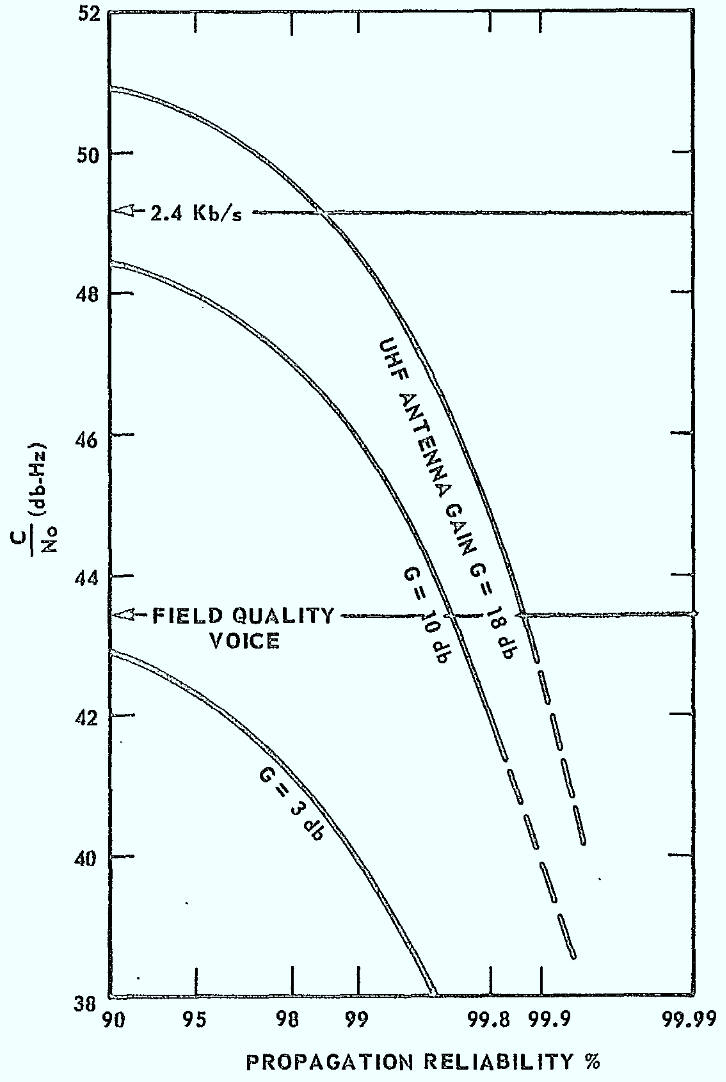


FIGURE 6.4b

C/No of UHF-SHF/SHF-UHF Channels vs Propagation Reliability, with Extraordinary Interference

Assuming no regeneration system in the central station, an 18 dB UHF antenna can support 4.8 kb/s and 750 b/s data traffic with 99.2% and 99.94% propagation reliability, respectively, under normal conditions. Under the extraordinary interference condition, 750 b/s data traffic can be supported by a UHF antenna with 10 dB and 18 dB gain with 99.2% and 99.8% propagation reliability, respectively.

6.0 SYSTEM CALCULATIONS

6.3 UHF SYSTEM

6.3.5 UHF-UHF CHANNEL

The system is down-link limited and it cannot carry any traffic under the extraordinary interference condition. The system C/No for various UHF antennas is presented.

From Table 6.4 it has been shown that the up-link C/No is as follows:

Propagation Reliability %	99.9	99	50
C/No (dB-Hz)	54.9	61.2	65.4

The down-link C/No of various ground station G/T is shown in Fig. 6.2(a). The system thermal C/No of various UHF antennas, as shown in Fig. 6.5, is calculated based on the following assumptions.

(1) There is little correlation between the up-link fading and the down-link fading.

(2) The up-link fade is directly translated to a reduction of satellite down-link EIRP.

(3) Additional 1.9 dB fade due to the satellite AGC effect has been applied to the faded channel. (See Section 6.3.3 for explanation of AGC effect.)

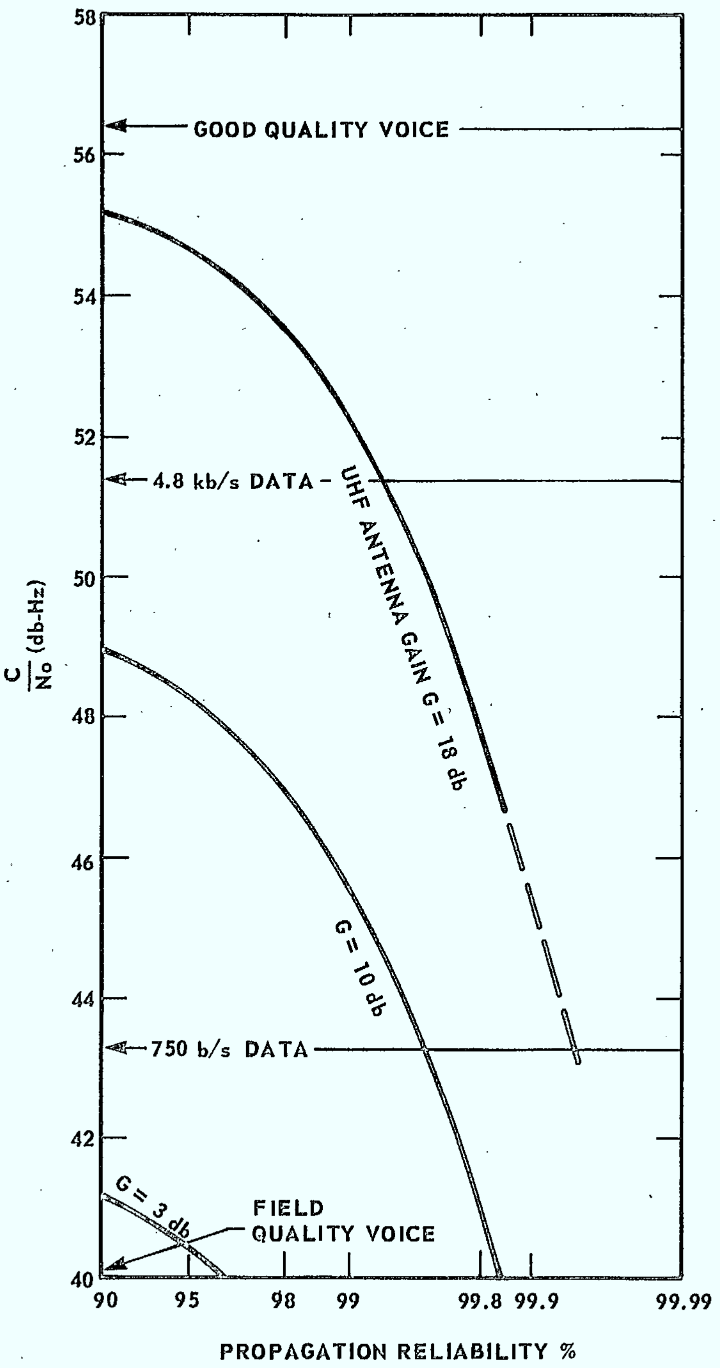


FIGURE 6.5

UHF/UHF Channel System C/No vs the Propagation Reliability, without Extraordinary Interference

6.0 SYSTEM CALCULATIONS

6.3 UHF SYSTEM

6.3.6 SHF-SHF CHANNEL

The regional office ground station parameters are determined and the system thermal C/No is calculated.

One of the possible communication channels in the UHF system is the link between the central station and the regional office in the SHF band. The up-link C/No of the system is 68 dB-Hz, as shown in Table 6.1 (item 8). There will be no satellite AGC effect on the SHF-SHF channels in the satellite output TWT, and the nominal satellite transmitting power per channel is 11.4 dBm. The transmitting power of the channel with 1.4 dB fade (see Table 6.1) is therefore 10 dBm and the regional office ground station G/T is obtained as follows:-

$$G/T = L_D - EIRP + k + (C/No)_D$$

where, L_D = 203 dB as shown in Table 6.4, EIRP = 10 + 27.3 dBm = 37.3 dBm

then, $G/T = (C/No)_D - 22.9$

The required system C/No of the good quality voice service with 20.2 dB intermodulation noise is 55.8 dB-Hz. Therefore;

$$(C/No)_D = 56.1 \text{ dB-Hz}$$

and $$G/T = 33.2 \text{ dB/K}$$

The propagation reliability of the SHF-SHF channel with good quality voice service is 99.96%. It is obvious that as the required regional office ground station G/T must be fairly high necessitating a large antenna (about 50 feet), the SHF-SHF channel is not a very attractive communication system.

6.0 SYSTEM CALCULATIONS

6.3 UHF SYSTEM

6.3.7 12/14 GHZ BACK HAUL SYSTEM

The 12/14 GHz system is discussed. A comparison between the 7/8 GHz system and the 12-14 GHz system is presented.

In a satellite communication system, if the satellite antenna gain is determined by the required beamwidth coverage then the antenna gain is independent of the operating frequency. As it is assumed that the satellite coverage and the ground station antenna size are fixed, the nominal received signal at the ground station is directly related to the satellite transmitting power and is independent of operating frequency. Hence, there is no difference in the link calculation between the 7/8 GHz and the 12/14 GHz bands except for differences in system margins and reliability, and the interference environment. The technical differences between the two frequency bands are given as follows:-

1. Satellite Antenna Size: For a specified coverage the antenna aperture area is proportional to the wavelength squared. The required antenna aperture area at the 7/8 GHz frequency band is almost three times that of the antenna aperture area at the 12-14 GHz frequency band.
2. Effective System Noise Temperature: The receiver system operating at 7/8 GHz frequency band generally has lower system noise temperature than the receiver at 12/14 GHz frequency band.
3. Fade Margins: 12/14 GHz frequency band requires higher fade margins than the 7/8 GHz frequency band.

From the viewpoint of the UHF system, the major technical considerations in the choice between the two SHF bands (7/8 GHz and 12/14 GHz) are the satellite antenna size and weight and the costs of the central station antenna systems. The fade margin of 1.4 dB (99.98%) used in the previous calculations for the 7/8 GHz frequency band may be used at the 12/14 GHz frequency band with reduced propagation reliability (99.8%). If the hot stand-by and space diversity system concept is incorporated in the central control station design (see Section 4.6), all results in Sections 6.3.2 to 6.3.6 are valid for both the 7/8 GHz and the 12/14 GHz systems.

6.3.8 4/6 GHZ BACK HAUL SYSTEM

The 4/6 GHz System is discussed. A comparison between the 7/8 GHz system and the 4/6 GHz system is presented.

If 4/6 GHz back haul is used in the UHF system instead of 7/8 GHz back haul, then the thermal C/N_o for various UHF channels will be slightly different from the results given in the earlier sections (6.3.3 and 6.3.4), due to the satellite antenna and ground station antenna gains being different. The maximum SHF satellite antenna size is 7 ft. (as directed by the Design Authority, DOC) and at 3.7 GHz has a beamwidth of 2.7° x 2.7° (compared to 1° x 1° given for 7 GHz) and a gain of 35.8 dB, some 8.7 dB less than the gain at 7 GHz. However, the ground station antenna gain could be increased by increasing the antenna size from 60 ft. to 95 ft., being an economic compromise between performance versus cost. Using the 95 ft. ground station and 7 ft. satellite antenna, a quantitative comparison was made between the 4/6 GHz system and the 7/8 GHz system.

Based on the assumptions that:-

(a) the satellite EIRP for the broad beam is the same for 7/8 GHz or 4/6 GHz

(b) the satellite G/T for the 7/8 GHz system is the same for the 4/6 GHz system

(c) the ground station receive system noise temperature is the same for 4/6 GHz and 7/8 GHz

(d) a 95 ft. ground station is used,

then, under nominal conditions, the 4 GHz down-link $\frac{C}{N_o}$ will be increased by 4.5 dB due to the lower path loss at 3.7 GHz. However, if extra-ordinary interference is present the satellite spot beam will be used for the SHF down-link, providing 8.7 dB less gain at 3.7 GHz compared to the 7 GHz system. The net down-link C/No (thermal) will therefore be reduced by 8.7 - 4.5 = 4.2 dB. As the required precipitation fade margin at 3.7 GHz is 0.5 dB less than that at 7 GHz, the resultant SHF down-link C/No at the specified reliability is reduced by 3.7 dB. The overall channel C/No (thermal) using the 4/6 GHz back haul will be different, therefore, from those given in Sections 6.3.3 and 6.3.4 by the amounts shown in Table 6.5 for the various link configurations.

TABLE 6.5

Overall $\frac{C}{No}$ (Thermal) Differences for the 4/6 GHz Back Haul System as Compared to the 7/8 GHz 'Reference' Back Haul System

LINK CONFIGURATION	CHANGE IN OVERALL $\frac{C}{No}$ (thermal) from 7 GHz SYSTEM
UHF-SHF	+1.2 dB
UHF-SHF with extraordinary interference	-3.7 dB
UHF-SHF/SHF-UHF	+0.0 dB UHF Antenna Gain 3 dB +0.3 dB UHF Antenna Gain 28 dB
UHF-SHF/SHF-UHF with extraordinary interference	-0.5 dB UHF Antenna Gain 3 dB -1.8 dB UHF Antenna Gain 10 dB -3.0 dB UHF Antenna Gain 18 dB

(Note: A positive difference in dB indicates that the 4/6 GHz system would have a better C/No)

6.0 SYSTEM CALCULATIONS

6.4 SHF SYSTEM (PART OF SECOND CONFIGURATION)

6.4.1 SYSTEM CONFIGURATION

An overview of the SHF system is presented.

The system provides two types of services; Multichannel per carrier (MCPC) FDM-FM telephony and single channel per carrier (SCPC) FM telephony. A simplified transponder configuration has been shown in Section 6.1. Multichannel communications are carried on transponders 1, 2, 5, 6 through the respective 2° x 2° antenna beams and single channel per carrier service is carried on transponders 3 and 4, with the TWT power divided between adjacent beams. The satellite receiver is connected to a Canada coverage antenna.

Both SCPC and MCPC services are intended for public and commercial use. SCPC service is for communications among remote communities and MCPC service is for communications between two urban centers. It is essential that the system should be capable of carrying toll quality voice traffic or equivalent. The voice channel noise objective of MCPC system and SCPC system are 37.5 dBrnCO and 44 dBrnCO, respectively.

Conventional FM modulator and demodulator are used in MCPC service. There are two types of FM demodulator in the SCPC service; conventional FM demodulator and threshold extension FM demodulator. Both demodulator systems are discussed. Using the given transponder and ground station data shown in Sections 6.1 and 6.2, the number of voice channels for each service is calculated and the propagation reliability is discussed in the following sections. All calculations are based on Reference (6.3), "A Super-High-Frequency Satellite Communications System for Canada (1977-1985)", Vol. 2, BNR report, 1971, a contract study carried out for the DOC.

6.0 SYSTEM CALCULATIONS

6.4 SHF SYSTEM (PART OF SECOND CONFIGURATION)

6.4.2 MULTI-CHANNEL TELEPHONY SERVICE USING FDM/FM TECHNIQUES

The number of channels per MHz RF bandwidth versus carrier-to-noise ratio are calculated.

The up-link and down-link carrier-to-noise density ratio can be calculated from the following equation:-

$$C/No = EIRP - L + G/T - k$$

where EIRP is the effective isotropically radiated power in dBm
L is the path loss in dB
G/T is the receiving antenna system gain to noise temperature ratio in dB/K
k = -198.6 dBm/Hz/K

For the down-link calculation, EIRP = 76 dBm and G/T = 28 as shown in Section 6.2, and L = 206.4 dB, we obtain

$$(C/No)_D = 96.2 \text{ dB-Hz}$$

In the case of the up-link, G/T = -8 dB/K as shown in Section 6.1, $EIRP - L - 10 \log (\lambda^2/4\pi) = -50 \text{ dBm/m}^2$, where λ is the up-link signal wavelength, we have

$$\begin{aligned} C/No)_u &= -50 + 10 \log (0.0207^2/4\pi) -8 + 198.6 \\ &= 95.9 \text{ dB-Hz} \end{aligned}$$

Assuming ground station antenna pointing error loss is 0.5 dB and polarization misalignment loss is 0.1 dB, the effective up-link and down-link C/No are 95.3 dB-Hz and 95.6 dB-Hz, respectively. Using Ottawa area rain statistics, shown in Table 4.2, and assuming there is little correlation between up-link and down-link fades, the system C/No for various propagation reliabilities is given in Table 6.6.

TABLE 6.6

System C/No versus % Propagation Reliability

% Propagation Reliability	99.99%	99.9%	99%	50.0%
System C/No dB-Hz	84.4	90.5	92.2	92.4

If the test-tone-to-noise service objective in the top channel (S/N) of 52.5 dB (Noise = 37.5 dBrnCo) is used, the relationship between the channel capacity per MHz RF Bandwidth and C/N is shown in Fig. 6.6. (This curve is derived from reference 6.3.) The figure is valid only for systems with FDM channel capacities greater than 240 channels. For system capacities of less than 240 channels, the relationship between the RF bandwidth and C/N is shown in Fig. 6.7 (obtained from reference 6.3). Assuming the system has an available RF bandwidth of 30 MHz, the system capacity with 99.9% propagation reliability is 1026 channels. In the case of 99.99% propagation reliability, the system is power limited and it can support approximately 132 channels with RF bandwidth of 10 MHz. $[(C/N)_{Total} = 11.8 \text{ dB}]$.

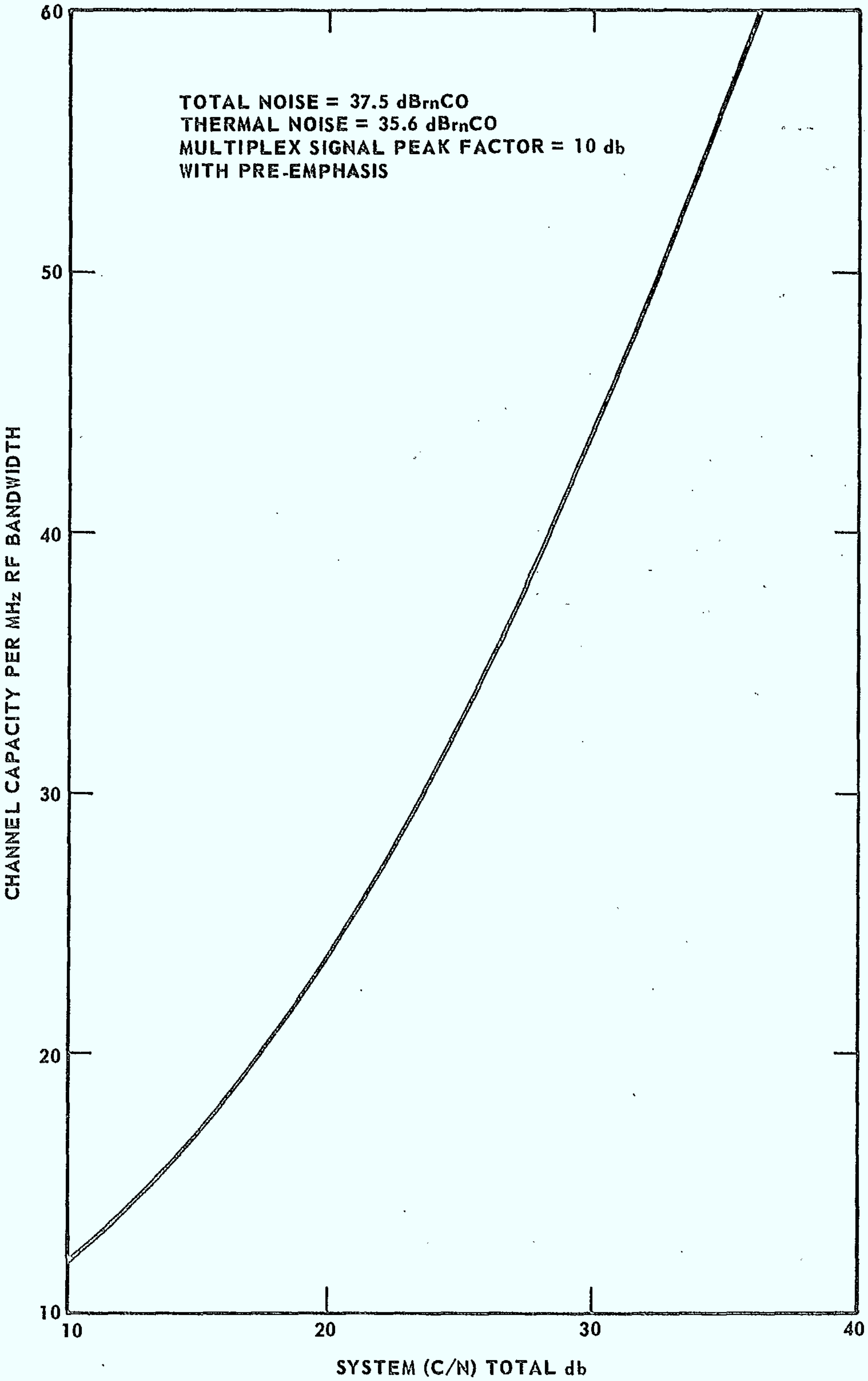


FIGURE 6.6

Channel Capacity for the FDM-FM System
(Capacity > 240 channels)

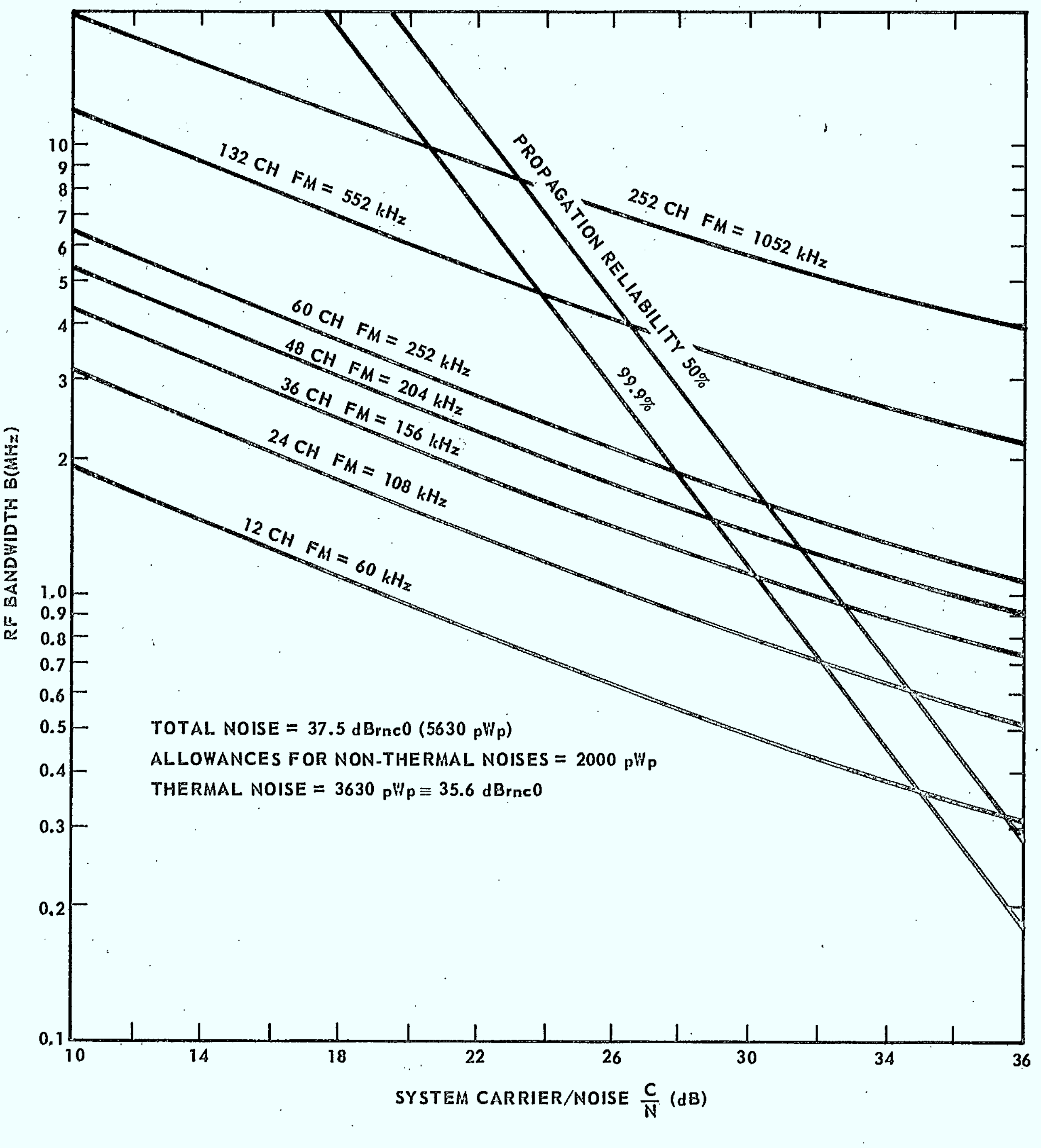


FIGURE 6.7

FDM-FM Satellite System
(Capacity ≤ 12 + 240 channels)

(7

6.0 SYSTEM CALCULATIONS

6.4 SHF SYSTEM

6.4.3 SINGLE CHANNEL PER CARRIER TELEPHONY SERVICE

The number of voice channels for a conventional demodulator system and low threshold extension demodulator system are calculated. The optimum system configuration is discussed.

The three parameters which must be determined before questions such as the number of voice channels, the propagation reliability, etc. can be answered; are the system carrier to thermal noise density ratio (C/No), the required carrier to noise ratio (C/N) and the required RF bandwidth for each carrier. All calculations are interrelated.

(1) Up-Link and Down-Link C/No

The specified up-link C/No is 95.9 dB-Hz as shown in Section 6.4.2. By using the standard link equations and data shown in Section 6.2, EIRP = 73 dBm, G/T = 17.2 dB/K and free space path loss without fading = 206.4 dB, the single carrier saturated down-link C/No is calculated as 82.4 dB-Hz. Using a total of 0.6 dB loss due to the ground station antenna pointing error and polarization misalignment, the effective up-link and down-link C/No is 95.3 dB-Hz and 81.8 dB-Hz, respectively. All the above (C/No)'s are referred to as single saturated carrier to thermal noise density ratios.

(2) Required C/N

Two possible FM demodulator systems may be used for the service; conventional demodulator and threshold extension demodulator. The threshold carrier-to-noise ratios of conventional and threshold extension demodulators are assumed to be 10 dB

and 6 dB, respectively. Additional allowance of 1 dB is made to take care the imperfections of narrow band filters and the problems of frequency stability (discussed later).
There are two possible ways of interpreting the system margin requirements - one is based on the system outage criterion and the other is based on the mimimum performance criterion. These will be referred to as "hard cut-off" and "soft cut-off" criteria, respectively. The definitions are given below:

a) Hard Cut-off: The system fade margin is allocated such that the service reliability (non outage) will exceed the specified percentage of the time.

b) Soft Cut-off: The system fade margin is allocated such that the system performance will not be worse than the specified signal-to-noise ratio for the specified percentage of the time.

As the names imply, the transition from operational service to outage is abrupt in the case of the hard cut-off and gradual in the case of the soft cut-off designs.

For a system fade margin of 4.7 dB specified in reference (6.3), the predetection carrier to noise ratios for the conventional and threshold extension demodulators for the hard and soft cut-off cases are given below.

	Conventional Demod. System	Threshold Extension Demod. System
Hard Cut-off $(C/N)_H$	11 dB	7 dB
Soft Cut-off $(C/N)_S$	15.7 dB	11.7 dB

(3) Required RF Bandwidth

Following Equation (42) in Section 8.4.2, Reference (6.3), we have

$$\frac{S}{N} = \frac{C}{N} + 10 \log \frac{Bx}{4} \left(\frac{Bx}{4} - 2\right)^2 + 15.9$$

where S/N = test-tone-to-noise ratio (unweighted) in dB

C/N = specified carrier-to-noise ratio in dB

B_x = radio-frequency bandwidth in kHz

The voice channel noise objective is 44 dBnCO which is equivalent to S/N of 44 dB (unweighted). By using the required C/N shown above, the RF bandwidth can be calculated as follows:

	Conventional Demod. System	Threshold Extension Demod. System
Hard Cut-off Bandwidth	20.6 kHz	25.8 kHz
Soft Cut-off Bandwidth	16.3 kHz	20 kHz

Assuming a total frequency drift in the system of ± 8 kHz, the required RF bandwidth for each channel with proper guardband is shown in Table 6.7.

TABLE 6.7

Required RF Bandwidth per Carrier Including Guardband

	BANDWIDTH (kHz)	
	HARD CUT-OFF	SOFT CUT-OFF
Conventional Demod.	36.6	32.3
Threshold Extension Demod.	41.8	36.

(4) Optimum System Operating Parameters

In a multiple carrier system, for each value of minimum required C/N there is an optimum point in the satellite transponder TWT output back-off which gives the maximum system capacity. By using typical transponder characteristics (6.4, 6.5), the optimum transponder operating parameters are obtained as shown in Table 6.8. Because of rapid variations in the carrier to intermodulation noise ratios in the region where the TWT backoff is less than 3 dB, the parameters for the hard cut-off cases may not be very accurate.

TABLE 6.8

Optimum Transponder Operating Parameters

	CONVENTIONAL DEMOD. SYSTEM		THRESHOLD EXTENSION DEMOD. SYSTEM	
	HARD CUT-OFF	SOFT CUT-OFF	HARD CUT-OFF	SOFT CUT-OFF
Input Back off (dB)	7.8	12.	5.0	8.4
Output Back off (dB)	3.	5.6	2.	3.3
C/I* (dB)	15.7	20.2	13.5	16.1
C/N Thermal (dB)	12.8	17.6	8.1	13.7
C/N Total (dB)	11.	15.7	7.	11.7

* A 3 dB advantage in C/I is assumed due to the voice activation scheme (6.6) considered.

A 6 dB difference between $(C/No)_u$ and $(C/No)_D$ is used as a compromise between the requirement of low ground station transmitting power on the one hand and effective utilization of satellite EIRP on the other hand. By using the single carrier saturated C/No and the transponder TWT output backoff shown in Table 6.8, the optimum ground station operating points are derived as shown in Table 6.9.

Table 6.9

Optimum Ground Station Operating Parameters

	CONVENTIONAL DEMOD. SYSTEM		THRESHOLD EXTENSION DEMOD. SYSTEM	
	HARD CUT-OFF	SOFT CUT-OFF	HARD CUT-OFF	SOFT CUT-OFF
$(C/No)_D$ dB-Hz	79.4	76.8	80.4	79.1
Required $(C/No)_u$	85.4	82.8	86.4	85.1
Total C/No Thermal	78.4	75.8	79.4	78.1
Specified $(C/No)_u$	95.3	95.3	95.3	95.3
Reduction of Transmitting Power (dB)	9.9	12.5	8.9	10.2

The total number of voice channels (active and inactive) can be calculated from the following relations:

$$(C/N)_T + F = (C/No)_T - 10 \log n - 10 \log 0.4 - 10 \log B_x$$

where $(C/N)_T$ = required C/N thermal as shown in Table 6.8.

F = Fade Margin

$(C/No)_T$ = Total system C/No thermal

n = total number of voice channels (active and inactive)

0.4 = 40 percent activity Factor (voice activation factor)

B_x = required RF bandwidth including guard band (in Hz).

The propagation reliability with a given fade margin is calculated based on the following assumptions:

(i) There is little correlation (in time) between the up-link fade and the down-link fade.

(ii) The up-link fade is directly translated to the down-link fade, due to the quasi-linear operation of the transponder.

The relationship between the total number of voice channels and propagation reliability for the hard cut-off case is shown in Table 6.10.

TABLE 6.10

Total Number of Voice Channels for the Hard Cut-off System

PROPAGATION RELIABILITY %	99.98	99.9	99.	~ 90 (Clear Day)
Fade Margin dB	9	2.3	0.6	0.
Conventional Demod. System	55	259	384	440
Threshold Extension Demod. System	131	611	904	1038

In the soft cut-off system, there are two propagation reliability figures, one is the propagation reliability when the channel meets the design noise objectives, the other is the propagation reliability when the channel can still carry intelligible communication, although it will no longer meet the noise objectives. The relationships between the total number of voice channels and propagation reliability figures for the soft cut-off system is shown in Table 6.11.

TABLE 6.11

Total Number of Voice Channels for the Soft Cut-off System

PROPAGATION RELIABILITY % (SPECIFIED NOISE OBJECTIVES)	99.98	99.9	99	~ 90 (CLEAR DAY)
PROPAGATION RELIABILITY % (OUTAGE)	> 99.99	99.976	99.97	99.96
FADE MARGIN	9	2.3	0.6	0
Conventional Demod. System	13	60	88	101
Threshold Extension System	43	203	300	344

6.5 DISCUSSIONS

Various implications of the outcome of the systems calculation for the UHF and SHF Satellite configurations are discussed.

UHF System

Owing to the high ground station EIRP, the man pack station is not feasible for the UHF system. The transportable station with a fixed antenna during operation is a possible compromise. Another alternative is using a high gain UHF satellite antenna such as a 30 foot unfurlable antenna. The trade off for an optimum design depends upon system objectives, number of ground stations, satellite weight budget, etc. It is beyond the scope of this study to investigate these further.

It has been shown that the requirement of the large multipath fade margin in the UHF links is a severe constraint for the mobile platform. A space diversity system with UHF antennas of approximately 10 dB gain or more, should be considered for the airborne or shipborne system in order to reduce the down-link fade margin to a reasonable level. However, this still does not solve the problem of multipath fading in the UHF up-link and no simple solution is available except by increasing the ground station transmitting EIRP.

Techniques used in the currently proposed system to counter the extra-ordinary interference in the UHF up-link are automatic gain control (AGC) in the satellite SHF transponder, switching from a broad beam SHF antenna to a spot beam (1° x 1°) SHF antenna and using a large SHF ground station antenna (60 ft.). The cost of implementing this scheme is high, especially that of the spot beam antenna which is approximately 70 and 120 inches in diameter at 12 GHz and 7 GHz, respectively. A better design compromise is probably to use partial channelization in the satellite UHF receiver and an AGC system in the satellite SHF transponder. A simplified transponder schematic diagram for both the currently proposed and the new proposed schemes are shown in Fig. 6.8 and are called AGC scheme and channelized AGC scheme, respectively. The AGC circuit in either scheme may be placed at any convenient place between the UHF low noise receiver and the SHF TWT output. In the case of the channelized AGC scheme, the UHF signal is divided into several channels and an AGC circuit is implemented in each channel as shown in Fig. 6.8(b). Only those UHF signals which are in the same channel as the extraordinary interfering signal will be affected by the interference. A qualitative comparison between two schemes are tabulated as follows:

(i) Required Additional Subsystems

AGC Scheme: one SHF switch, one SHF spot beam antenna and large control station Antenna

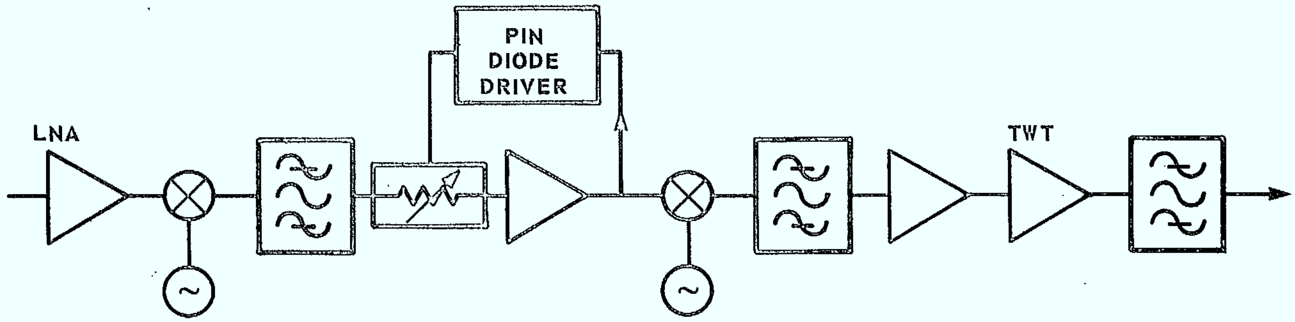
Channelized AGC Scheme: two branching networks, several AGC amplifiers.

(ii) System Performances

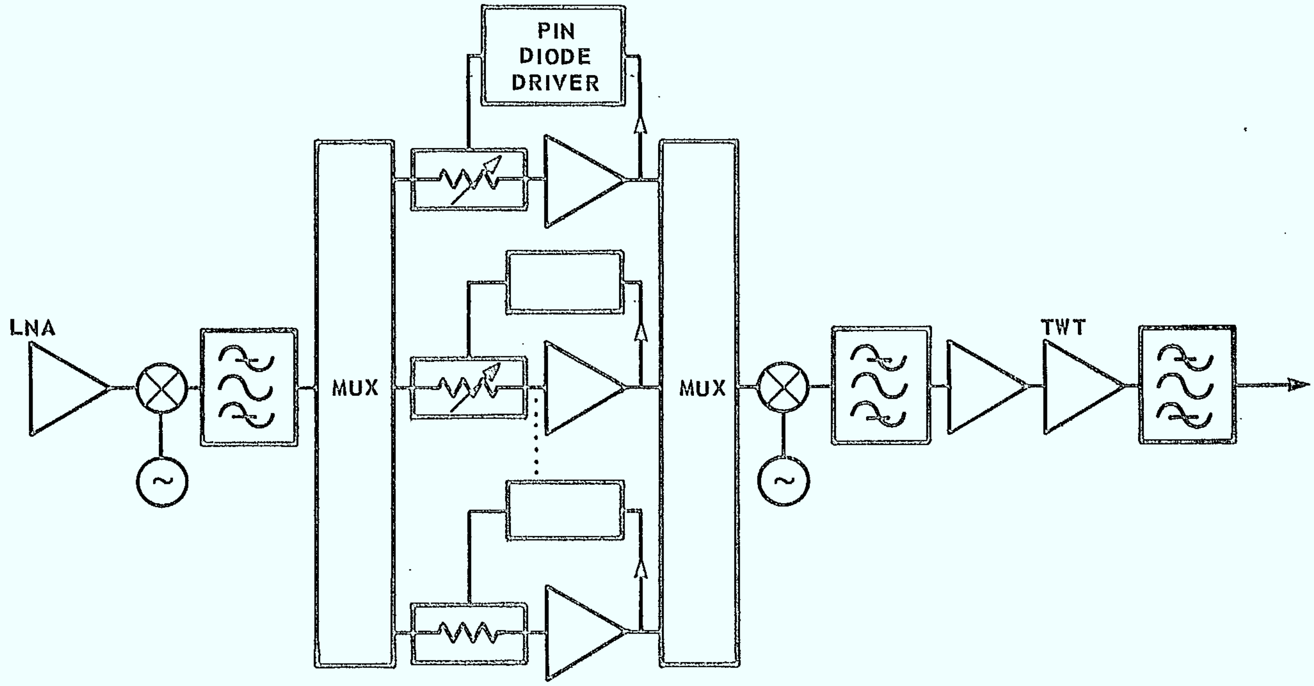
AGC Scheme: All channels are degraded and the link can support only field quality voice with reasonable propagation reliability.

Channelized AGC Scheme: The voice channels not in the same channelized band as the interfering signal are not affected. Voice channels in the same channelized band as the interfering signal are not serviceable.

In view of the above, it is suggested that a partially channelized AGC scheme should be considered to overcome the extraordinary interference.



(a) AGC SCHEME



(b) CHANNELIZED AGC SCHEME

FIGURE 6.8

Simplified Transponder Schematic Diagram

SHF System

The system consists of two parts; SCPC system and MCPC system. No detailed system tradeoff calculations have been attempted owing to the uncertainties in the traffic pattern. However, no major problem areas are foreseen.

6.6 REFERENCES

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6.4 D. Chakraborty, "Intelsat IV Satellite System - Channel Capacity versus Earth Station Performance", EASCON, p. 77, October, 1970.

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6.6 D.I. Dalgleish and A.G. Reed, "Some Comparisons of the Traffic Carrying Capacity of Communication Satellites Using Digital Techniques with the Capacity of Satellites Using Frequency Modulation", Intelsat/IEE International Conference on Digital Satellite Communications, London, 1969.

7.0 SUMMARY AND CONCLUSIONS

A summary of the study results and major conclusions are presented.

The major objectives of this study were to carry out evaluations of modems and calculations of link parameters in various combinations of UHF and SHF satellite configurations.

7.1 SUMMARY OF RESULTS

Section one of this report defined the specific study objectives in four major tasks, namely: - Task 1 - Calculate link margins and noise budgets, and test the sensitivity of these margins and noise budgets against reliability of the UHF and SHF systems;

Task 2 - Carry out a survey of Modem technology and coding techniques to meet the UHF multipurpose satellite specifications and make a recommendation of the most desirable types;

Task 3 - Calculate power budgets, EIRP levels and bandwidth required to meet the overall Satellite Specifications;

Task 4 - Present the total findings in a report.

A summary of the findings for each of these tasks are shown below:

7.1.1 TASK 1 – LINK MARGINS AND NOISE BUDGETS

(a) LINK MARGINS (Propagation)

TABLE 7.1

Summary of Single Link Fade Margins Required

FADE CAUSE	FREQUENCY (GHz)	FADE MARGINS (dB) VERSUS PROPAGATION RELIABILITY					
		95.0%	97.0%	99.0%	99.7%	99.9%	99.99%
Precipitation – Ottawa	4.0 7.5 12.7 14.5	– – – –	– – – –	0.01 0.05 0.24 0.32	– – – –	0.10 0.25 1.35 1.82	0.80 1.35 7.90 10.60
Precipitation – Toronto	4.0 7.5 12.7 14.5	– – – –	– – – –	0.01 0.05 0.24 0.32	– – – –	0.10 0.18 1.00 1.35	0.50 1.10 6.60 8.90
Ionospheric Scintillation*	0.3	2.0	2.5	4.2	7.0	10.5	–

* Multipath fading, could be reduced by careful UHF antenna design to that below scintillation fading, and is therefore covered by the scintillation fade margins. There may perhaps be a slight drop in system reliability due to this assumption.

(b) NOISE BUDGETS

TABLE 7.2

Summary of UHF Noise Budgets

FREQ. BAND	CAUSE	AMOUNT
UHF Band	Unintentional man-made noise: (Earth segment interference)	-168 dBm (average) Varies over a range ± 6 dB
	Unintentional man-made noise: (Space segment): (i) Average	< 60K
	(ii) Peak	≈ 60,000K – Frequency of occurence unpredictable

TABLE 7.3

Ground Station Antenna Noise Temperature at 300 MHz

		ANTENNA GAIN (dB)			
		3	10	17	27
UHF	Antenna Noise Temp. (°K) (Mainly due to solar source)	240	250	300	860

7.1.2 TASK 2 - MODEM TECHNOLOGY SURVEY AND RECOMMENDED SPECIFICATIONS

(a) MODEM TECHNOLOGY SURVEY SUMMARY

A summary of the modem survey is shown in Table 7.4 and Table 7.5 below.

(b) RECOMMENDED MODEM SPECIFICATIONS

(i) Far Field Quality Voice - Analog Modem

Adaptive Narrow Band FM (ANBFM)

RF Bandwidth	10 kHz
Channel Separation	25 kHz
Voice Band	300-3000 Hz
Peak FM Deviation	1500 Hz
Pre-emphasis	6 dB per Octave
Clipping	12 dB
FM Threshold C/N (using Threshold Extension Demodulation)	3 dB
System Phase Jitter Noise	< 100 Hz*

* For the SHF system, the 100 Hz max jitter allowance may be very stringent and is very dependent on the satellite and ground station short term phase jitter noise specification.

TABLE 7.4

Summary of Modem System Requirements for Voice

REQUIREMENT FOR VOICE TRAFFIC			REQUIRED AT DEMODULATOR I/P		$(C/No)_{Total}$ in dB-Hz REQUIRED AT DEMODULATOR FOR		
MODULATION METHOD	PERFORMANCE	BANDWIDTH	$\frac{C}{No}$ dB	$\frac{C}{N}$ dB	$C/_{IM}$ = 12 dB	$C/_{IM}$ = 16 dB	$C/_{IM}$ = 20 dB
ANBFM	A.I. - 0.45	10 kHz	43	3	43.6 dB-Hz	43.2 dB-Hz	43.1
FM with Companding	A.I. > 0.65	23.0 kHz	53.5	10.0	57.8 dB-Hz	54.8 dB-Hz	54.0
DM/CPSK; 16 kb/s	A.I. = 0.52 = 0.65	22.4 kHz	48	4.5	48.9	48.3	48.1
DM/CPSK; 32 kb/s	A.I. > 0.65 S/N = 32 dB	44.8 kHz	55.4	8.9	58.3	56.4	55.8
DM/FFSK; 16 kb/s	A.I. = 0.52	17.6 kHz	48	5.5	49.1	48.4	48.1
DM/FFSK; 32 kb/s	A.I. > 0.65 S/N = 32 dB	35.2 kHz	55.4	9.9	59.6	56.6	56.0

TABLE 7.5

Summary of Modem System Requirements for Data

REQUIREMENT FOR DATA TRAFFIC			REQUIRED AT DEMODULATOR INPUT			$(C/No)_{Total}$ in dB-Hz REQUIRED AT DEMODULATOR FOR		
MODULATION METHOD	PERFORMANCE	BANDWIDTH	$\frac{E}{No}$ dB	$\frac{C}{No}$ dB	$\frac{C}{N}$ dB	$C/_{IM} = 12$ dB	$C/_{IM} = 16$ dB	$C/_{IM} = 20$ dB
CPSK 75 b/s	$P_e \leqslant 10^{-5}$	105 Hz	9.8 + 3	31.5	11.3	40.2 dB-Hz	33.3 dB-Hz	32.2 dB-Hz
2.4 kb/s	$P_e \leqslant 10^{-5}$	3.36 kHz	9.8 + 3	46.6	11.3	55.3 dB-Hz	48.4 dB-Hz	47.3 dB-Hz
4.8 kb/s	$P_e \leqslant 10^{-5}$	6.72 kHz	9.8 + 3	49.6	11.3	58.3 dB-Hz	51.4 dB-Hz	50.3 dB-Hz
FFSK 75 b/s	$P_e \leqslant 10^{-5}$	82.5 Hz	9.8 + 3.3	31.8	12.6	NP*	34.5	32.7
2.4 kb/s	$P_e \leqslant 10^{-5}$	2.64 kb/s	9.8 + 3.3	46.9	12.6	NP	49.6	47.8
4.8 kb/s	$P_e \leqslant 10^{-5}$	5.28 kb/s	9.8 + 3.3	49.9	12.6	NP	52.6	50.8
FSK 75 b/s	$P_e \leqslant 10^{-5}$	90.0	13.2 + 2.8	34.7	15.2	NP	42.7	36.5

* NP = not possible

(ii) For Good Quality Voice or Encrypted Field Quality Voice - Digital Modem

Adaptive Delta Modulation (ADM)

		Encrypted Field Qual. Voice	Good Quality Voice
Sampling rate		16 kb/s	32 kb/s
Signal to Quantization Noise Ratio (S/Q)		13 dB	30 dB
Idle Circuit noise		42 dBrnCo	37.5 dBrnCo
Dynamic Range		20 dB	30 dB
Frequency response (with respect to response at 1 kHz)	300 Hz:	+1 dB	+1 dB
	3000 Hz:	-6 dB	-6 dB

Binary CPSK Modem

E/No (thermal)	5.3 dB for Pe = 10^{-2} 7.4 dB for Pe = 10^{-3} 9.8 dB for Pe = 10^{-5} (for Data)
Bit Rate	R (variable up to 32 kb/s, plug in or switchable)
RF Bandwidth Required	1.4 R
Inter Symbol Interference Margin	1.5 dB
Implementation Margin	1.5 dB
Source Encoding	Differential
System Frequency Stability	10^{-7}

7.1.3 TASK 3 - POWER BUDGETS, EIRP AND BANDWIDTH REQUIREMENTS

(The Bandwidth requirements are specified in the above Modem Specifications).

The power Budgets and EIRP requirements for the three systems are shown in Table 7.6.

TABLE 7.6

Summary of Power Budgets and EIRP Requirements

SATELLITE LINK	SATELLITE SYSTEM			
	SHF/UHF	UHF/SHF	SHF/SHF 12/14 GHz (Commercial)	
			SCPC/FDMA-FM	FDM-FM
UP-LINK	SHF (8 GHz)	UHF (400 MHz)	14 GHz	14 GHz
Earth Station Tx Power	16 dBm/Voice Ch.	52.6 44.4 36.6 dBm		
Earth Station Antenna Gain	60.5 dB (60')	-0.5 7.7 15.5 dB		
Earth Station EIRP	76.5 dBm/VF Ch.	52.1 dBm		
Satellite G/T	-0.9 dB/k	-7.1 dB/k		
Satellite Received signal level		-107 dBm/VF Ch.		
DOWN-LINK	UHF (300 MHz)	SHF (7 GHz)	12 GHz	12 GHz
Satellite Tx Power	29 dBm/V. Ch.	37 dBm single carrier Sat.		
Satellite Output Backoff		5.6 dB	2 dB	0 dB
Satellite Antenna Gain	19 dB	27.3 dB		
Satellite EIRP (per VF Ch.)	48 dBm	38.7 dBm		
Satellite EIRP (per single carrier Sat.)		58.7 dBm	73 dBm	76 dBm
Earth Station G/T	-5.7 to -27.8 dB/k	35.5 dB/k (60' Paramp)	17.2 dB/k (6.5')	28 dB/k (16.4')
Fade Margin			2.3 dB (99.9%)	7.9 dB (99.99%)
Channel Capacity (VF one way)			611 (with TED)	1026 *

* RF Bandwidth is 30 MHz

7.0 SUMMARY AND CONCLUSIONS

7.2 CONCLUSIONS

The major conclusions of this study are as follows:

(a) For field quality voice (and alternative 75 b/s teletype), the adaptive narrow band FM modem is preferred. If encryption is a further requirement, then 16 Kb/s adaptive delta modulation with coherent PSK should be adopted.

(b) For good quality voice with or without encryption (and alternative data transmission), the 32 Kb/s adaptive delta modulation coherent PSK system should be chosen.

(c) The UHF and SHF system margins and power budgets are as presented in the Summary above. The up-links and down-links do not appear to provide any major problem areas except for the following:

  i) A man-pack station is not technically feasible unless a high gain UHF spot beam satellite antenna is used (e.g. 30 feet, unfurlable antenna). The present limitation is the up-link transmit power constraint in the man-pack.

  ii) For air-borne or ship-borne mobile stations, multipath fading at UHF is potentially an area of critical concern. A diversity system with UHF mobile antennas with a gain of 10 dB or more may mitigate against this problem.

  iii) In the UHF up-link the presence of high level man made interference with unpredictable frequency of occurence is potentially another area of major concern.

  iv) In the adaptive narrowband FM system, special attention should be paid in the system design to ensure that the overall link frequency stability and phase jitter noise specifications are met.

8.0 ADDENDUM

The Statement of Work of the Contract calls for evaluation of various factors such as error correction coding and voice activation of the individual RF carriers in the Single Channel Per Carrier (SCPC) systems, and the effect of these on the choice of various modems. In the course of the study, because of the nature of the performance requirements, it turned out that these factors have no influence on the choice of the modems. Discussions on error correction coding, voice activation and other ancillary matters are therefore not included in the main body of this report. Nevertheless, it is considered that these discussions might be useful as general background information and are therefore now presented in this Addendum.

(a) CODING TECHNIQUES

1. Error Correcting Codes

In this section, two types of parity check forward error correcting codes (block and convolutional), are considered. They are judged for their practical use in the present study.

In block coding techniques, each group of k consecutive information bits is encoded into a group of n bits for transmission, thus allowing (n-k) bits for parity check. The blocks are generated from feedback shift registers and are limited in operating speed due to the propagation delay in the feedback path. Decoding algorithms for block codes generally consider the known structural properties of the code; examples are algebraic decoding (Peterson and Chien and Berlckamp).

For convolutional coding, information bits are shifted through a stage shift register and parity check bits are formed as a binary function of a particular subset of the information bits in the shift register. Thus, they are implemented by a feed-forward shift-register and capable of higher speed operation. The code rate 1/r indicates that for each information bit, there are (r-1) parity check bits; the constraint length, k, indicates that the parity check bits depend on a sequence of k information bits. Decoding of convolutional codes is based on efficient probabilistic searching procedures; examples are sequential (Wozencraft), maximum likelihood (Viterbi) and threshold (feedback) decoding. For the sequential and Viterbi decoding algorithms, it is possible to make use of soft-decision demodulator output (i.e. 2 or 3-bit quantization) to enhance error correcting capabilities. An improvement in the order of 2 dB can be obtained compared to the case of hard decision demodulator output.

Some decoding methods, e.g. sequential decoding, cannot tolerate bursts of errors, because of input buffer overflow and cannot be directly used in a burst error environment such as that caused by signal fading and interference. Interleaving which reduces the burst error effect by distributing the errors over more than one code word or message may be implemented in a circulating register and provides an improvement in error probability of approximately two orders of magnitude.

2. Effect of Coding on Performance

Forward error correcting codes rely on the addition of redundant bits to the input information to provide parity checking and error correcting capability. They reduce the E/No requirement at the expense of the transmission bandwidth. In general, the coder performance can be measured by the coding gain (the effective reduction of E/No in an additive white Gaussian noise) and the code rate (the inverse of the bandwidth expansion, and is a measure of code efficiency). Another effect of coding is the extra time delay caused by the encoding and decoding processes. Long delay may cause undesirable subjective degradation to the voice communication.

Table A.1 gives the relative performance of some of the error correcting codes. Costs tabulated are approximate and given only as an indication of equipment complexity. Fig. A1 plots the coding gain and bandwidth expansion factor, and Fig. A2 shows the improved error probability performance by using codes.

From Table A.1, it is evident that error correcting codes are more effective at low error probabilities; e.g. the coding gain is invariably higher at error probability of 10^{-5} than that at 10^{-3} for all the codes considered. For block codes, the (273, 191, 8) code gives a relatively economical means of providing close to 3 dB power reduction at the expense of 1.4 bandwidth expansion. In general, longer block lengths and fewer check bits would increase the code efficiency in terms of bandwidth expansion. The code gain depends on the error correcting capability for similar block length and code rate. The cost of block coders depends on the type of decoding algorithm and increases greatly as the block length and error correcting capability

TABLE A1

Summary of Error Correcting Codes

CODE TYPES	REF	DESCRIPTION	BANDWIDTH EXPANSION	CODING GAIN dB		APPROXIMATE COST
				$P_e = 10^{-3}$	$P_e = 10^{-5}$	
(273, 191, 8)	A.3	Block code with threshold decoder	1.43	1.2	2.9	$ 700
(255, 131, 18)	A.3	Block code with Burlekamp-Chien decoder	1.95	-	3.8	10,000
Rate $\frac{1}{2}$, K = 7	Link-a-bit Corp. Model LV 7015(8.4)	Convolutional code with Viterbi decoder with 3 bit Quantization	2.0	3.7	5.1	4,000
Rate $\frac{1}{2}$, K = 10	LF 1011-256	Convolutional code with feedback decoder and hard quantization	2.0	0.9	2.2	3,000

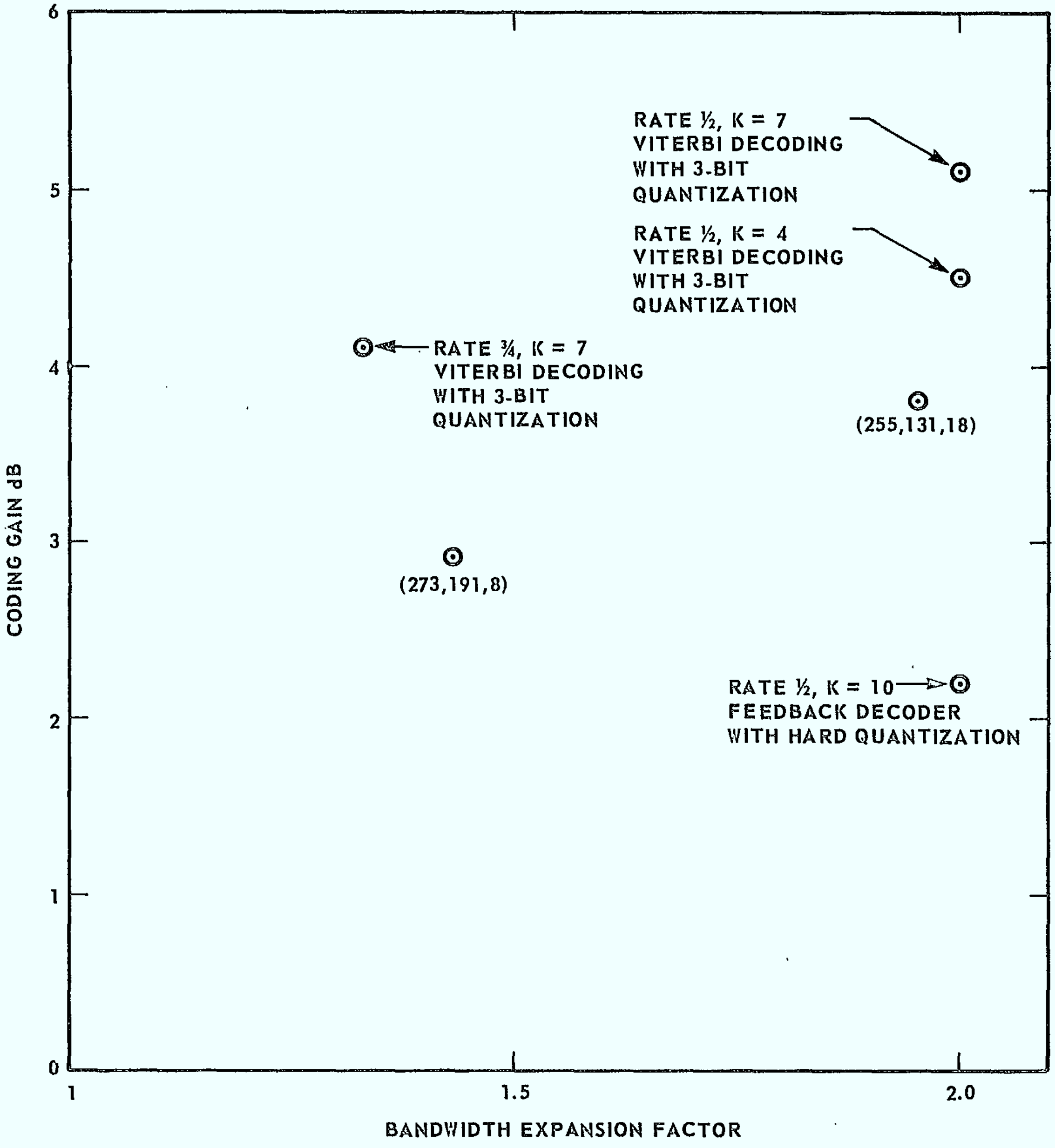

FIGURE A.1

Coding Gain vs Bandwidth Expansion Factor
($P_e = 10^{-5}$)

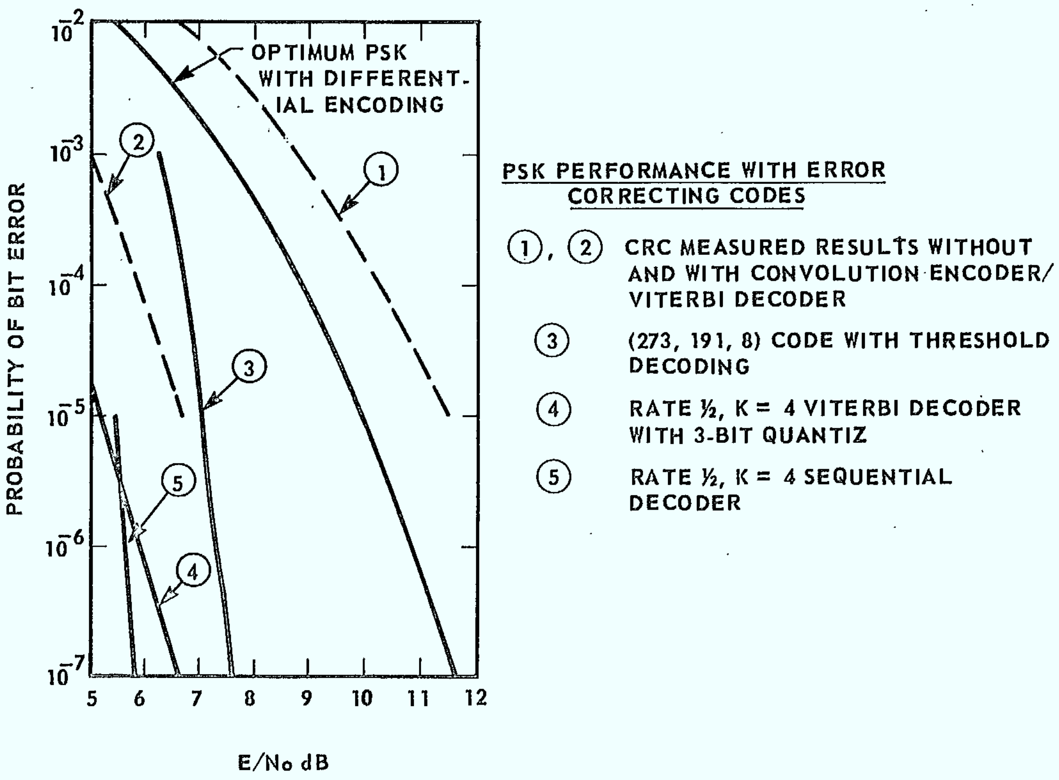

FIGURE A.2

PSK Performance with Error Correcting Codes

A

are increased. For convolutional codes, threshold (feedback) decoders are less expensive than Viterbi decoders, but have a lower coding gain. The bandwidth expansion factor may be reduced by increasing the code rate, for example from 1/2 to 3/4, with a corresponding reduction in the coding gain. Convolutional coders with multi-rate capability are available commercially.

3. Conclusion

Without venturing further into the vast field of forward error correcting codes, the following remarks may be made concerning their application in the present study:

(a) They are not recommended for digitized voice transmission for the following reasons:

- the bandwidth expansion factors increase the r.f. transmission bandwidth beyond that allowed in a 25 kHz channel spacing
- the digitized voice transmission using delta modulation can generally tolerate error probabilities higher than 10^{-2} around which the coding gain is not as effective as for lower error probabilities. Thus, from the viewpoint of cost effectiveness versus performance improvement, the use of coding is not justified.
- the additional time delay through the coder and decoder may cause some subjective degradation to voice communications. This may not be a major factor in satellite communications since the propagation delay is already long in the up and down link paths.

(b) Forward error correcting codes may be applied to the control and supervisory data channels or other high priority data channels. The choice of a particular code depends on the tradeoff of cost and performance and on its capability of operating in the presence of burst errors.

(c) In general, the application of error correcting codes to data channels may be considered in cases where a certain data rate cannot be supported by the power limited satellite link, or in cases where fading or man-made interference is preventing data transmission. However, the following cautions are necessary:

- the use of coding is not cost effective because of the relative low data rates (less than 4.8 kb/s) considered in this study. (Most of the coders considered are capable of operating at rates in excess of 100 kb/s).
- coding is more sensitive to noise in the phase-lock circuit than the r.f. modulation process.
- the maximum error burst length with which the code can cope must be considered in conjunction with the fading or interference statistics.

(b) VOICE ACTIVATION

The satellite capacity may be improved by using a voice-activated switch to gate the channel carrier ON/OFF during idle time of the speech signal. For a channel occupancy factor of 0.4, approximately 3 dB of intermodulation noise advantage can be obtained(8.1). There is also an additional 4 dB advantage in satellite power. The sensitivity of the speech detector which gives the ON/OFF command can affect the transmission quality through selection of the triggering threshold. A digital detector which detects the instantaneous voice signal may be designed to be more sensitive for voice and less sensitive for noise(8.2). This is recommended for both ANBFM and DM/PSK. In the analog voice system, a simple and inexpensive integrated PCM codec can be used to digitize the voice signal before it is applied to the voice detector. The response time is effectively zero (1 to 3 msec) and the hang-over time (time in which the device remains 'on' after the speech power drops below the threshold) is approximately 160 msec, which appears to be about the correct value for human speech.

(c) RF STABILITY

Frequency drift in the satellite link due to the stability of oscillators (long term frequency drift and short term phase noise) or doppler shift may be troublesome. Normally, the rate of drift is small and any rate effect could be neglected. In the FDMA system, each user is assigned with a portion of the frequency band of the transponder. To prevent interference between adjacent RF channels and signal distortion due to equivalent filter de-tuning caused by the frequency drift, sufficient guard bands and frequency control are required. Crystal-controlled oscillators may be used to reduce the phase noise substantially. For the narrow RF bandwidth and channel separation considered in the UHF/SHF satellite link, the frequency drift is governed by the stability of the SHF local oscillators used in the transponder. The total frequency drift for the analog field quality voice should not exceed 1 kHz, and the SHF local oscillator stability must be in the order of 10^{-7} or better. Thus, it appears that the frequency variation can be tracked by an automatic frequency control (AFC) loop with a long time constant.

(d) REFERENCES

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