Telesat

Telesat Canada

LOW RATE DATA TRANSMISSION

TASK 23

Prepared For
Department of Communications
Ottawa, Canada

Submitted by
Telesat Canada, Ottawa, Canada

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SUMMARY

The purpose of this study was to make recommendations concerning the design of a data acquisition and control system (transmit/receive) and a data acquisition service (transmit-only) for the MSAT system. Many different factors were considered so that acceptable performance was achieved without increasing the cost of the data collection units or the cost of the service to the user.

Several simple modulation techniques were considered from the standpoint of capacity, power/bandwidth tradeoff, and ease of implementation. DMSK operating at 2400 kbps was chosen because of its high capacity for use with transmit-only data terminals and FSK operating at 1000 bps was chosen for transmit-receive data terminals because of its simplicity.

Random access is the only channel sharing technique that can be used with transmit-only data units if they have no receiver. To ensure a higher probability of a data packet being received without errors, the data packet is repeated an number of times. It was shown that three transmissions of a packet is sufficient to ensure a high probability of packet reception success. For transmit-receive data units each unit is commanded by the network control centre when it is time to transmit data.

Several coding techniques were considered to increase the probability of successful data transmission. A (15,11) BCH code was chosen for use with the transmit-only data terminals and a parity check code was chosen for use with the transmit-receive terminals.

The capacity using DMSK at 2400 bps with a random access protocol was shown to be 1800 data collection units per channel for a 99% probability of packet success.

Frequency control for data collection units was shown to be difficult to achieve without using an external frequency reference or an ovenized oscillator. The most practical scheme is to use a pilot signal transmitted via MSAT, although this requires a receiver for transmit-only data units and therefore increases the cost.

The system can achieve an uncoded bit error rate of 10^{-5} for fixed terminals, but operation is poorer if L-band is dedicated for fixed and transportable services with less power transmitted into the satellite.

A small market study was performed. Previous market estimates by Woods Gordon were added to estimates of the market by Canadian data collection platform manufacturers. The size of the potential market in Canada was estimated by one manufacturer to be between 3000 and 4000 units.

An estimate of the prices of data collection terminals was made using input from a manufacturer. The cost of UHF transmit only terminals is estimated to be $7425 in quantity 100.

1.0 INTRODUCTION

The purpose of data collection platforms (DCPs) is the unattended collection of data from remote areas. This task can best be performed by satellite. Satellite systems offer low cost for the transmission equipment. Terrestrial radio systems can have a high capital cost if repeater systems are necessary. The cost per user can be low for a satellite system since all DCP users across Canada will share the cost of the service. Also, the cost per DCP is the same for a small user as for a large user. This is in contrast to radio systems whose capital costs would be prohibitive for a user of a small number of DCPs.

There are two main satellite data collection systems currently in operation which can be used by North American customers. They are the GOES system and the ARGOS system.

The GOES system is operated by NASA and the National Earth Satellite Service (NESS) of the National Oceanic and Atmospheric Administration (NOAA) of the U.S. This system consists of two geostationary satellites which serve the eastern and western U.S. There are 200 channels spaced 1.5 kHz apart. Users within a channel have a time slot during which they can transmit, so that more than one user can occupy a channel. In addition, the users are limited to transmissions of either every 3 hours or once per hour. It is claimed that up to 10,000 transmissions of 30 seconds duration can be handled by the system per hour. Data are transmitted using PSK at a rate of 100 bps to a central collection facility and then passed on to the user. The DCPs transmit in the band 401.7-402.1 MHz. Data transmissions are limited to environmental data because of the frequency allocation. Users must be sponsored by a U.S. federal agency in order to use the system. There is no charge to use the system, but the user is responsible for costs incurred in transferring data from the central collection facility.

The ARGOS system is a joint program of Centre National d'Etudes Spatiales (CNES) of France and NASA and NOAA of the U.S. This system consists of two low orbit satellites. Because of their low orbit, the satellites can cover the entire earth. A single 24 kHz channel at 401.65 MHz is used. This frequency is in the same allocation as the GOES system and is likewise limited to the transmissions of environmental data. Users share the channel by random access. Data are transmitted at 400 bps using PSK. Data are transferred by the satellite to a central collection facility and then transferred to the users. There is a charge to use the ARGOS system but the charge is used only to recover operating costs, not capital costs. The ARGOS system is intended to be used by governmental agencies; it is not available for private users.

The MSAT system will offer features similar to the GOES system but with two significant differences. Data collection will not be limited to environmental data, so industrial applications can use the system. The other different feature that the MSAT system could offer is more frequent sampling periods. As long as the user is willing to pay more, he should be allowed to transmit as frequently as he desires, within the limitations of the system. Both of these features should serve to increase the potential market for the MSAT DCP service.

The MSAT system will accommodate both one-way and two-way data collection systems. The one-way DCPs will only be able to transmit their data. They will not be able to receive signals from the control station. This type of data collection platform is useful for data gathering where the user wants to create a data base. It is expected that most DCPs will be of this type. The two-way platforms will have the ability to receive commands as well as transmitting data. This type of DCP can be used when the user wants to control a process or when the user wants data from the remote site at exact times. Because of the receiving ability of this type of DCP, it will probably be considerably more expensive than one-way DCPs.

The purpose of this report is to consider the factors involved in the design of a data collection platform network using MSAT. Section 2 considers the structure of the DCP network. Section 3 looks at different modulation techniques and determines which are most appropriate for a data collection system. Section 4 addresses the bit error rate of the system and chooses a value to be used as a design target. Section 6 examines different access techniques to share channel bandwidth amongst the data collection platforms. Section 7 develops a message format to allow data to be sent from platforms to the user. Synchronization, platform identification, and data length are considered in this section. Section 8 considers what type of MSAT channel the data collection platform service will use. Demand-assigned, dedicated, and share channels are options which are examined. The number of data collection platforms that a channel can support is studied in Section 9. The analysis considers the number of bits transmitted, the frequency of transmission, and bit rate. Section 10 considers the effect of frequency stability of the transmitted signal from the platforms and looks at different methods of ensuring that the signal has the required stability. Section 11 presents link budgets for the data collection service for UHF and L-band operation. Fixed platform locations are considered as well as drifting platforms (buoys or balloons). Reduced power operation is presented when practical as an option of reducing platform power drain. Section 12 considers the items which may require periodic maintenance. Methods of reducing the necessary maintenance are examined. Data collection platform costs are estimated in Section 13. Costs are developed for UHF and L-band platforms for both transmit-only and transmit/receive configurations. Section 14 attempts to estimate the size of the market for MSAT data collection platforms. The estimates of Canadian manufacturers are presented in this section. Conclusions and recommendations appear in Section 15.

2.0 DCP NETWORK

The architecture of the network connecting the data collection platforms to the end-users does not have a large effect on the cost of the DCP, but it can affect the cost of using the system. To transfer data from the DCP to the satellite, there are two links which could be used. The DCP can use the normal remote terminal uplink at UHF (or L-band) to the satellite, or the DCP can transmit to the satellite using the SHF feederlink. The disadvantage of using an SHF uplink and a UHF downlink is that valuable satellite UHF power is used. Another option that could be used is an SHF-SHF link. This is practical because an SHF-SHF cross-strap is expected to be part of the system to allow base stations to communicate with each other. One problem with using an SHF uplink is that it is expected that the transmit chain would be more expensive than a UHF transmit chain. Also, using an SHF-SHF link would not be much different than using Ku-band on one of the ANIK satellites. One of the attractions of using MSAT for a data collection service is the UHF transmission capability. Therefore, this study will only address the situation of transmitting data in the UHF band or L-band.

There are a number of methods which can be used to deliver the DCP data to the user. The data can be transmitted directly to the user by the DCP. This would require a UHF-UHF cross-strap, which is not presently part of the MSAT baseline system [1]. Direct transmission to the user could also be achieved if the user had an SHF base station. In either case, raw data would be transmitted to the user which would require that the user have the processing capability to decode and format the DCP transmission. Therefore, this method would be expensive.

An alternative is for the DCP to transmit the data to a central processing site which decodes the information, and sends it to the appropriate user. This method would be less expensive than the former method since all users share the receiver and processor. This method could also include a number of options for relaying the data from the central processing site to the end-user. The data could be sent via an MSAT Mobile Telephone Service (MTS) or Mobile Radio Service (MRS) channel. This method would cause a certain delay in transferring the data since the station would have to request a channel, and the possibility exists that the call could be blocked. Another method which is similar, is for the data to be transferred via a dial-up modem over the terrestrial telephone system. If the user needs the data with minimal delay, a leased telephone line may be used to transfer the data. The option of using a dedicated MSAT channel to transfer data from the central processing centre to the user would undoubtably be too expensive to consider.

3.0 MODULATION TECHNIQUES

In determining a suitable modulation technique to use to communicate with DCPs, many factors must be considered. These include the bit rate, spectral occupancy, the power required, ease of carrier recovery, the complexity of the modulator/demodulator, and the cost of the implementation.

The bit rate should be chosen so that capacity is maximized while not causing excessive adjacent channel interference. For FSK, a 5 kHz channel will allow a data rate of approximately 1500 bps [5].

Communications to and from a data collection platform are digital. Many digital modulation techniques exist. Typical modulation techniques include: frequency shift keying (FSK), binary phase shift keying (BPSK), quadriphase shift keying (QPSK), offset keyed quadriphase shift keying (OK-QPSK), and minimum shift keying (MSK).

The complexity of the modulator is approximately the same for FSK and BPSK. FSK can be generated by applying a bipolar form of the input binary waveform as the input to a voltage controlled oscillator. BPSK can be generated by applying bipolar input data to a product modulator, where the input data is multiplied by a carrier signal. QPSK is generated by splitting the input data stream and summing the output of two BPSK modulators together. The modulating signals for the modulators are 90° out of phase with each other. Each modulator operates at half the data rate of a normal BPSK modulator, and the output data rate of the QPSK modulator is then the same as the BPSK modulator. An OK-QPSK modulator is the same as a QPSK modulator, except that the data streams to the two BPSK modulators are staggered one-half bit period relative to one another. MSK modulation is the same as QPSK modulation, except that the carrier signal is multiplied by half-sinusoid pulses rather than rectangular non-return-to-zero pulses.

The demodulation of digital signals can be performed either coherently or non-coherently. For coherent demodulation, the receiver tries to estimate the phase of the carrier. For non-coherent demodulation, the signal is passed through filters for FSK or the signal is compared with a delayed version of itself for PSK or MSK. Non-coherent demodulation performs more poorly than coherent demodulation for low SNR, but the performance of non-coherent demodulation approaches that of coherent demodulation for high SNR.

Some coherent demodulation schemes result in a 180° phase ambiguity. This can be overcome by differentially encoding the bit stream. This works as follows: if the last two bits are the same, a binary '0' is sent and if the last two bits are different, a binary '1' is sent (or vice versa). Therefore, inverting the input bit stream does not alter the output differentially encoded bit stream. This technique is required for some non-coherent demodulation schemes as well. The disadvantage of differential encoding is that when noise corrupts a bit, it will affect the next bit as well. Therefore, single bit errors become double bit errors.

The cost of implementing a digital modulation receiver has been traditionally related to the complexity of the receiver through the parts count. If the demodulator is implemented using a digital signal processing chip such as the TMS 32010, the parts count for any modulation technique should be the same. However, the cost of developing the software for the more complex modulation schemes will likely be greater. This development cost is a non-recurring cost which will decrease as more DCPs are manufactured.

The following sections briefly describe each modulation technique.

3.1 FSK

The modulated signal can be written mathematically as:

$$s(t) = A \cos \ (\omega_c \pm \Delta\omega)t \qquad kT \leq t \leq (k + 1)T$$

where A is the amplitude of the carrier, ω_c is the carrier frequency, $\Delta\omega$ is the frequency offset between the carrier and the transmitted tones, and T is the symbol duration.

The transmitted signal consists of tones equally spaced on either side of the carrier. The phase is discontinuous and because of this, the signal can have a fairly wide spectral occupancy. The wider the separation of the tones in frequency, the lower the probability of error, but the wider tone separation increases the bandwidth of the signal.

3.2 BPSK

A BPSK signal can be written as:

$$s(t) = A\, a_k \cos(\omega_c t) \qquad kt \leq t \leq (k + 1)T$$

Where $a_k = \pm 1$, representing the transmitted data, A is the amplitude of the signal, and T is the duration of the signalling interval.

The data causes either a 0° or 180° phase shift in the phase of the carrier. This is equivalent to changing the sign of the signal. The changes in phase are not continuous and this causes the signal to have a large spectrum.

3.3 QPSK

A QPSK signal can be thought of as two BPSK signals in phase quadrature. The transmitted signal can be written as:

$$s(t) = 1/\sqrt{2}\ A[a_k \cos(\omega_c t) + b_k \sin(\omega_c t)] \quad kT \leq t \leq (k+1)T$$

where $a_k = \pm 1$, $b_k = \pm 1$, representing two bits of the transmitted sequence.

The spectrum of QPSK is the same as that for BPSK, but since QPSK transmits two bits for each bit transmitted by a BPSK modulator, thus for the same bit rate, the QPSK spectrum is half that of BPSK.

3.4 OK-QPSK

An OK-QPSK signal is the same as a QPSK signal, except the bits in the phase quadrature channels are delayed by a half bit period. This eliminates 180° phase changes from one bit period to the next. The transmitted signal can be written as:

$$s(t) = 1/\sqrt{2}\ [a_k \cos(\omega_c t) + b_k \sin(\omega_c (t-T/2))] \quad kT \leq t \leq (k+1)T$$

The delay between the two bit streams does not affect the spectrum of OK-QPSK as compared with QPSK, but it does make a difference in the filtered output of the signal in the band-limited case.

3.5 MSK

Minimum shift keying is a special case of continuous phase FSK with modulation index h = 0.5. The transmitted signal can be written as:

$$s(t) = A \cos(\omega_c t + a_k \pi t/(2T) + \theta_k) \quad kT \leq t \leq (k+1)T$$

where $a_k = \pm 1$ and corresponds to the transmitted data. θ_k is the phase of the signal at the start of the baud interval.

The modulation index is calculated as,

$$h = \Delta f T$$

where Δf is the difference in the signalling frequencies, and T is the symbol duration.

The error performance of various modulation techniques in an additive white Gaussian noise (AWGN) channel is shown in Figure 1 (from [2]). The modulations shown are: coherently detected PSK (CPSK), differentially encoded coherently detected PSK (DECPSK), differentially detected PSK (DPSK), fast FSK (FFSK or MSK), orthogonal coherently detected FSK (CFSK), and orthogonal non-coherently detected FSK (NCFSK).

The spectra of various modulation techniques are shown in Figure 2 (from [2]). In (a) the spectra of FFSK (MSK) and QPSK and OK-QPSK are shown. The spectra of QPSK and OK-QPSK are the same since a delay in the two bit streams to the quadrature modulators does not affect the spectrum. Note how FFSK has a wider main lobe than QPSK, but the secondary lobes fall off faster. In (b) the spectra of BPSK and FSK are shown. The BPSK spectrum is twice as wide as the QPSK spectrum in (a). The FSK spectra are for $M = 2$, 4, and 8. M refers to the number of frequencies used for signalling. The frequency separation has been chosen so that $2\Delta f\ T = 1/M$.

3.6 MODULATION: ONE-WAY PLATFORMS

This section will consider the factors that are relevant when choosing a modulation technique for the link from the DCP to the base station.

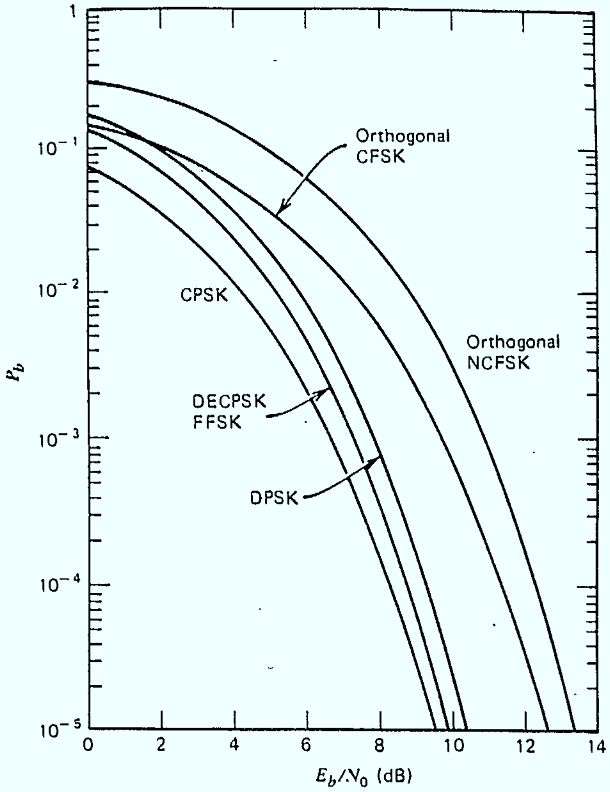


Figure 1 : Probability of a Bit Error for Various Modulation Techniques

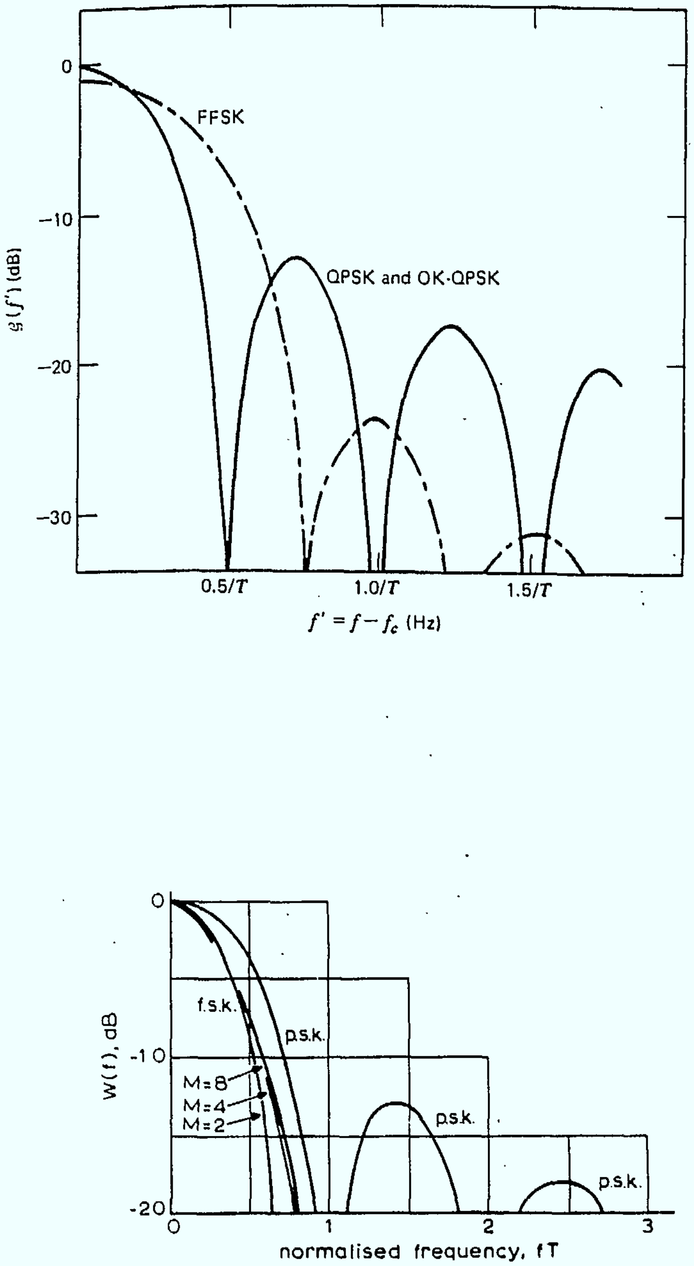


Figure 2 : Spectra of Various Modulation Techniques

The demodulation process can be performed coherently or incoherently. Coherent demodulation is more complex to implement, but since the receiver is at the base station, this is not an important consideration from the standpoint of DCP cost. Coherent demodulation has better performance than incoherent demodulation which means lower transmit power from the DCP can be used.

Communications from the DCP to the base station are bursty and therefore, each burst must include a preamble for acquiring carrier phase and bit timing. Coherent demodulation requires more bits in the preamble to acquire synchronization. Typical values for CPSK, DPSK, DMSK, and FSK are shown in Table 1 [3]. As can be seen from the table, coherent PSK takes more than 10 times as long as DPSK to acquire synchronization. Increased preamble length increases message inefficiency, and therefore reduces the number of DCPs that the MSAT channel can accommodate.

The bit rate should be chosen to be high enough to give sufficient capacity to support as many DCPs as possible. One limit on the bit rate is the bandwidth of the channel. Another limitation is the desire to keep interference into adjacent channels as low as is practical. The adjacent channel interference (ACI) depends on the spectral properties of the modulation as well as the bit rate. For BPSK, adjacent carriers must be spaced 6R (R is the data rate) apart to keep the degradation in E_b/N_o in an adjacent channel below 1 dB [4].

Here, E_b is the energy transmitted per bit in each signalling interval and N_o is twice the double-sided noise density for a Gaussian channel. For a 5 kHz channel bandwidth, this would limit BPSK operation to approximately 800 bps.

TABLE 1

Acquisition Times for Various Modulations

	PULL-IN TIME	
Modulation	400 bps	800 bps
CPSK	2000 ms	2000 ms
DPSK	113 ms	57 ms
DMSK	236 ms	166 ms
FSK	239.5 ms	172 ms

For MSK, the carriers should be spaced 1.5R apart to keep the ACI degradation below 1 dB [4]. Therefore, operation at 2400 bps would not cause significant ACI. For FSK, a 5 kHz channel bandwidth will allow a data rate of approximately 1500 bps [5].

Of the modulation techniques considered, coherent QPSK is the most power efficient. But since coherent modulation is not suitable for DCP use, we will only compare non-coherent performance. DBPSK requires approximately 1 dB less E_b/N_o than DMSK at an error probability of 10^{-5} [2]. However, if a non-redundant error correcting circuit is added to the DMSK demodulator, its performance is improved to within 0.1 dB of DBPSK at an error probability of 10^{-5}. Incoherent FSK requires 3 dB more power than DBPSK at an error probability of 10^{-5} [2].

3.7 MODULATION: TWO-WAY PLATFORMS

Data traffic on the link from the base station to the DCP will be low for two reasons; the number of two-way DCPs will probably be much smaller than the number of one-way DCPs because of the higher cost of a two-way DCP as well as the high channel usage cost (using a two-way link rather than a one-way link), and the number of users that require a two-way service is expected to be small. The command burst from the base station will be shorter than the burst from the DCP because no data is sent to the DCP, only a command. The modulation technique should be chosen to minimize the complexity of the receiver at the DCP. This rules out using coherent demodulation.

In order to keep the DCP receiver as simple as possible, either no coding or a simple code will be used on the base station to DCP link. To compensate for this, a lower data rate will be used which will improve the bit error rate performance for a given received power. The 3 dB power penalty for using FSK can be compensated for by reducing the bit rate. Therefore, FSK at a bit rate of 1200 bps will perform the same as 2400 bps PSK. The implementation of the FSK receiver would be non-coherent in order to minimize the complexity.

From Appendix B of [3], the effect of phase noise on an emergency signalling transmitter has been computed for DBPSK and NCFSK. Emergency signalling is one of the data services considered in [3].

It has been computed that phase noise is not significant for DBPSK above 50 bps and for NCFSK above 20 bps [3]. Note that the analysis of [3] is pessimistic, as they have assumed a 10 dB higher phase noise spectra than that used in [12] because they assumed low quality oscillators. The oscillator used for the transmit portion (from the DCP) of the two-way DCP is expected to be of better quality than that used for emergency signalling, so the analysis of [3] would be a worst-case scenario as applied to DCP terminals.

4.0 BIT ERROR RATE REQUIREMENT

The bit error rate (BER) requirement is an important issue which most DCP users do not consider. This consideration is not an option on existing DCP systems so the DCP users must accept what is offered. For a user, the bit error rate is not important directly, but rather, the probability of error in a message. Most DCP systems, however, have been designed for a specified BER.

According to the ARGOS designers, data collection needs a BER better than 2 x 10^{-5} [6]. A study of DCP user requirements for the ERTS (Earth Resources Technology Satellite) system concluded a BER of 10^{-5} was required [7].

We will try to achieve a bit error rate of 10^{-5} for the MSAT DCP system. Whether or not this design goal can be achieved depends on the modulation method used, the demodulator implementation margin, as well as the EIRP from the DCP. The probability of error in a message can be reduced to less than 10^{-5} through the use of coding. Coding techniques are considered in the next section.

5.0 CODING

The purpose of coding is to increase the reliability of data while minimizing the expansion of bandwidth required to achieve this increased reliability. The process of coding identifies and corrects errors caused by the transmission channel. There are three types of error control schemes: forward error correction (FEC), automatic repeat request (ARQ), and a combination of FEC and ARQ.

Automatic repeat request is a method whereby the receiving terminal broadcasts back to the transmitter a signal indicating successful reception of a block of data for each block received correctly or it broadcasts back a signal indicating unsuccessful reception of a block of data when it receives data with errors. The system can be designed so that both types of signals are sent. Whenever the sending terminal receives indication that a block of data was not sent correctly, it retransmits the data. In this way, error-free transmission is achieved at the expense of increased traffic on the channel. Note that this method only applies to the case where a two-way link exists.

Forward error correction involves adding redundant bits to the data in order to increase the ability to recognize errors. There are two main types of FEC coding; convolutional codes and block codes. Convolutional codes are applicable when the data arrives serially in a constant stream. Since the block length of the data sent by DCPs is relatively short, convolutional codes are not a good choice.

Block codes format blocks of length k into coded blocks of length n . The code rate r is k/n. Block codes exist to detect and correct random errors and there are block codes that can be used for dealing with burst errors. The choice of which block code to use depends partly on the type of channel that is involved. Since DCPs have a fixed position, the fading at the DCP is constant with time. Errors will be caused by thermal noise. Therefore, random errors rather than burst errors are expected to dominate in a DCP network.

Typical families of block codes include linear block codes, cyclic codes, Golay codes, quasi-cyclic codes, etc. Cyclic codes are of importance due to the ease of the implementation of the encoder. This is an important feature since the encoder is at the DCP.

BCH codes are one of the most important families of codes among the cyclic codes. The data stream to be encoded is divided into blocks of length k for an (n,k) code producing an encoded block of length n bits. Ideally, the value of k should be chosen so that the data block can be divided into an integral number of blocks of length k . Otherwise, the final block will be "padded out" with zeros to form a block of length k.

It is desirable that the code be able to detect as many errors as possible. However, in order to increase the number of errors that a code can detect, more redundant bits must be added to the code. Since an MSAT channel will be very expensive, we want to maximize the number of DCP users per channel, and therefore minimize the length of each burst.

The characteristics of a number of candidate single error correcting BCH codes are shown in Table 2. The value of t is the number of errors the code can correct. The value of d, the minimum distance, is 3 for this code. Therefore, these codes can be used to correct single errors or detect double errors. The codes that encode data in large blocks are

TABLE 2

Characteristics of Single Error Correcting BCH Codes

n	k	t	d	n/k
7	4	1	3	1.75
15	11	1	3	1.36
31	26	1	3	1.19
63	57	1	3	1.11
127	120	1	3	1.06

desirable from the standpoint of minimizing the code data rate, but they are inefficient for small blocks of data, requiring that redundant zeros be added to fill the encoder. It is unlikely that the user would want to send less than 16 bits of data per transmission as this would be a rather inefficient use of the DCP. More efficient communication can be obtained by buffering the data from several sampling intervals and then transmitting them in a single burst.

For an (n, k) BCH code with minimum distance d, the probability of an error occurring which is detected but not corrected is equal to the probability that more than $(d - 1)/2$ but less than d errors occur.

P (detected but not correctable errors occur)

$$= \sum_{i=I}^{d-1} \binom{i}{n} p_b^i (1 - p_b)^{n-i}$$

where $I = (d - 1)/2 + 1$ and p_b is the probability of a bit error.

The probability that an undetected error occurs cannot be computed exactly, but can be upper bounded as the probability that d or more errors occur. The reason why this probability cannot be computed exactly is that although the minimum distance of the code is d, some code words can be more than d bits apart in Hamming distance (Hamming distance is the number of bit positions in which two code words are different), so some errors of distance d are detected. The probability of undetected error is bounded by:

$$P \text{ (undetectable error)} \leq \sum_{i=d}^{n} \binom{i}{n} p_b^i (1-p_b)^{n-i}$$

Examples of this probability are shown in Table 3 for the (15, 11) BCH code.

TABLE 3

ERROR PROBABILITIES FOR THE (15,11) BCH CODE

No. of Message Bits	No. of Blocks	$P_b = 10^{-4}$		$P_b = 10^{-5}$		$P_b = 10^{-6}$	
		P1	P2	P1	P2	P1	P2
16	2	2.1×10^{-6}	9.1×10^{-10}	2.1×10^{-8}	9.1×10^{-13}	2.1×10^{-10}	9.1×10^{-16}
32	3	3.1×10^{-6}	1.4×10^{-9}	3.1×10^{-8}	1.4×10^{-12}	3.1×10^{-10}	1.4×10^{-15}
64	6	6.3×10^{-6}	2.7×10^{-9}	6.3×10^{-8}	2.7×10^{-12}	6.3×10^{-10}	2.7×10^{-15}

P_1 = P (at least 1 block has an error which is detected but not correctable)

P_2 = P (at least 1 block has an error which is not detected)

From Table 3 it can been seen that the error event probabilities are very small for a bit error probability of 10^{-5}. Due to the small probabilities, doubling the message bits effectively results in a doubling of the error probabilities.

Another method of protecting the transmitted data is with single error detecting parity bits. A single parity bit is used to protect a group of bits. The total number of ones in the bits are added together and the parity bit is set so that the group has even or odd parity. This coding method can detect all combinations of an odd number of errors. Any combination of an even number of errors does not alter the parity of the bits and is thus undetectable with this coding scheme.

The probability of an error occurring which is detected is:

P (odd number of errors)

$$= \sum_{i=1}^{N/2} \binom{N}{2i-1} p_b^{2i-1} (1 - p_b)^{N-2i+1}$$

N is the number of data bits and parity bits.

The probability of an error occurring which is not detected is:

P(even number of errors)

$$= \sum_{i=1}^{N/2} \binom{N}{2i-1} p_b^{2i} (1 - p_b)^{N - 2i}$$

For this parity scheme, a valid message can be discarded if an error occurs only in the parity bit. The probability of this occurring is approximately p_b.

The various error events are shown in Table 4 for different single error detecting parity codes. From this table it can be seen that increasing the number of parity bits per block of message bits reduces the probability of an undetected error occurring but the additional parity bits increase the probability that a valid message is rejected because of an error in the parity bits. The addition of parity bits does not appear worthwhile because the probability of rejecting valid data is the dominant error event. Therefore, anything that increases this probability should be avoided.

Comparing the single error detecting parity check codes with the single error correcting, double error detecting BCH code reveals the usefulness of error correction. The single error detecting codes do not alter the probability that data is rejected, and at the same time they introduce the probability that valid data could be rejected. The BCH code reduces the probability of undetected error to an almost negligible value and makes the probability that the data block is rejected a very small value.

5.1 ACKNOWLEDGEMENT SCHEME

An acknowledgement scheme between the DCP and base station is desirable for two-way platforms. The acknowledgement scheme ensures that the user always receives data that is correct (at least to the extent that the coding system can determine that it is correct). The average number of transmissions per platform in this scheme should be less than the fixed number of transmissions used for one-way DCP transmissions. There are three possible acknowledgement schemes which could be implemented.

TABLE 4

Error Probabilities for a Parity-Check Code

CODE	P_1	P_2	P_3
1 parity bit for 4 data bits	5×10^{-5}	1×10^{-9}	1×10^{-5}
1 parity bit for 8 data bits	9×10^{-5}	3.6×10^{-9}	1×10^{-5}
1 parity bit for 16 data bits	1.7×10^{-4}	1.4×10^{-8}	1×10^{-5}
2 parity bits for 8 data bits	1×10^{-4}	2×10^{-9}	2×10^{-5}
2 parity bits for 16 data bits	1.8×10^{-4}	2.8×10^{-8}	2×10^{-5}
4 parity bits for 16 data bits	2×10^{-4}	4×10^{-9}	4×10^{-5}

P_1 = P(at least 1 error occurs and is detected)

P_2 = P(at least 1 error occurs and is not detected)

P_3 = P(valid data is rejected)

The first method is a positive acknowledgement scheme. In this case, for every packet sent by the DCP, the base station returns an acknowledgement packet indicating successful reception of the packet. If the base station does not receive the packet correctly, it sends no signal to the DCP. After waiting some predetermined length of time, if the DCP does not receive an acknowledgement packet, it automatically retransmits its packet.

For the second method, if the base station receives a packet from the DCP correctly, it sends no signal to the DCP. If the base station receives a packet with errors, it sends a negative acknowledgement packet to the DCP requesting retransmission of the packet.

The third acknowledgement method is a combination of the other two methods. The base station sends an acknowledgement packet to the DCP for every packet that it receives correctly and it sends a non-acknowledgement packet for every packet it receives incorrectly. The DCP will retransmit a message after a certain period of time if it has not received an acknowledgement or non-acknowledgement packet.

The advantages and disadvantages of each scheme will now be considered. The advantage of the positive acknowledgement scheme is that there is a very small probability that a packet will be lost.

Even in the event that the base station receives nothing, the DCP will automatically retransmit the packet. The disadvantages of this scheme are increased traffic and unnecessary retransmissions. For a well designed system, the majority of packets will be received without errors. Therefore, the number of acknowledgement packets will approximately equal the number of message packets. Also, in the event that an acknowledgement packet is lost, the DCP will retransmit the message unnecessarily. However, the probability of an acknowledgement packet being lost is small.

The advantage of the negative acknowledgement scheme is that it minimizes the extra traffic associated with an acknowledgement scheme. An acknowledgement packet is sent only when a packet is received incorrectly. The probability of this event should be small. The disadvantage of this scheme is that a packet may get lost and never be received at the base station. Since the base station doesn't know that a packet was sent, it does not send a retransmit packet and in the absence of this packet, the DCP will not retransmit. However, the probability of totally missing the packet at the base station should be very small.

The advantage of the positive and negative acknowledgement scheme is that the probability that a packet will be lost is very small. Also, the base station can be certain that a retransmission will occur if a packet is received incorrectly. As well, the delay associated with waiting for the "time-out" period to expire before retransmitting a packet as used with the positive acknowledgement scheme is eliminated. The disadvantage of this scheme is that it has overhead associated with every packet.

The recommended technique for use with the MSAT system is the positive acknowledgement scheme. One of the desirable features of two-way DCPs is their ability to confirm reception of a command. With a negative acknowledgement scheme, there exists the possibility that the command transmission is lost.

6.0 ACCESS TECHNIQUE

A network of many DCPs requires a method of allowing the DCPs to transmit their data to the base station reliability. There are several methods of sharing the channel. There is a trade-off between reliability of the access method and the complexity of the method. The section examines various methods as applied to DCPs.

6.1 ACCESS TECHNIQUE FOR ONE-WAY PLATFORMS

The possible techniques that can be used to share the DCP channel include FDMA, TDMA, CDMA, and random access.

FDMA is not a practical candidate because the necessary bandwidth would be too costly and assigning a fixed portion of spectrum to a DCP would be wasteful, since each DCP generates a small amount of traffic. Demand-assigned FDMA is not practical since the link is one-way only.

TDMA could be implemented in a smaller bandwidth than FDMA but this access technique requires accurate timing information at the DCP. Without a link from the base station to the DCP it would be very difficult to keep the DCPs synchronized.

For a CDMA system, each DCP would have a unique code with which it would spread its data transmission. At the base station, the receiver would have to try to demodulate the received signal with the codes for all DCPs. This would require processors operating in parallel for each DCP. Since the network could contain several thousand DCPs, the required number of processors at the base station would increase the cost of the base station greatly. For this reason, CDMA is not considered a desirable access method.

Random access is the most practical system to implement for a one-way link. Messages are transmitted at fixed intervals. Because each DCP is unaware of the transmission times of the other DCPs in the network, collisions between packets transmitted by different DCPs can occur. Since a DCP does not know when a packet collision has occurred, in order to increase the probability of successful reception of a packet, a DCP should automatically retransmit a packet a fixed number of times. In order to avoid colliding with the same DCP, the retransmission time is randomized between two fixed limits (e.g. between 5 and 6 minutes after the first transmission). The probability of successful reception of a packet depends on the traffic in the channel and the number of retransmissions per packet.

We can attempt to compute the probability that a packet is received successfully at its destination. To do this, we first assume that the total channel traffic can be modelled as a Poisson process. This is only an approximation since retransmissions are not a Poisson process. The probability that at least one of the identical messages transmitted by a DCP is received successfully at its destination is:

$$P_s = 1 - (1 - P_1)^n$$

where P_1 is the probability that a packet transmitted by a DCP does not collide with a packet from some other DCP, and n is the total number of transmissions of a packet.

The probability that a packet does not collide with another packet is:

$$P_1 = e^{-2Gn}$$

where G is the average channel traffic in a packet duration. The average number of successful packets in a packet duration is:

$$S = G P_S$$

Note that this analysis assumes that the network consists of one-way DCPs. The effect of two-way DCPs on the network should be small since they are expected to be small in number. Another assumption that has been made is that each packet is the same size. This is not expected to be the case; each DCP will transmit a different number of data bits. The probability of successful transmission is plotted versus throughput efficiency for different numbers of packet transmissions for each message in Figure 3 (from Appendix G of [3]). From this figure, it can be seen that for a success rate greater than 90%, 3 packet transmissions per message is close to optimal. Negligible gain in throughput efficiency is achieved by transmitting each packet four times.

6.2 TDM

Time division multiplexing is an efficient access technique. Its drawbacks include the requirement for a receiver at the DCP. Timing information can come from the MSAT control centre, or from some global navigation system such as GPS.

Each DCP would have time slots which would be used to broadcast data. This would eliminate the problem of collisions occurring between the transmissions of different DCPs. The time slots could be of a fixed length or variable length for different number of data bits transmitted. The advantage of a fixed length time slot is the simplicity of timing. Each time slot could be assigned a number and each DCP would be assigned the number of the time slot during which it would transmit. The disadvantage of this method is the

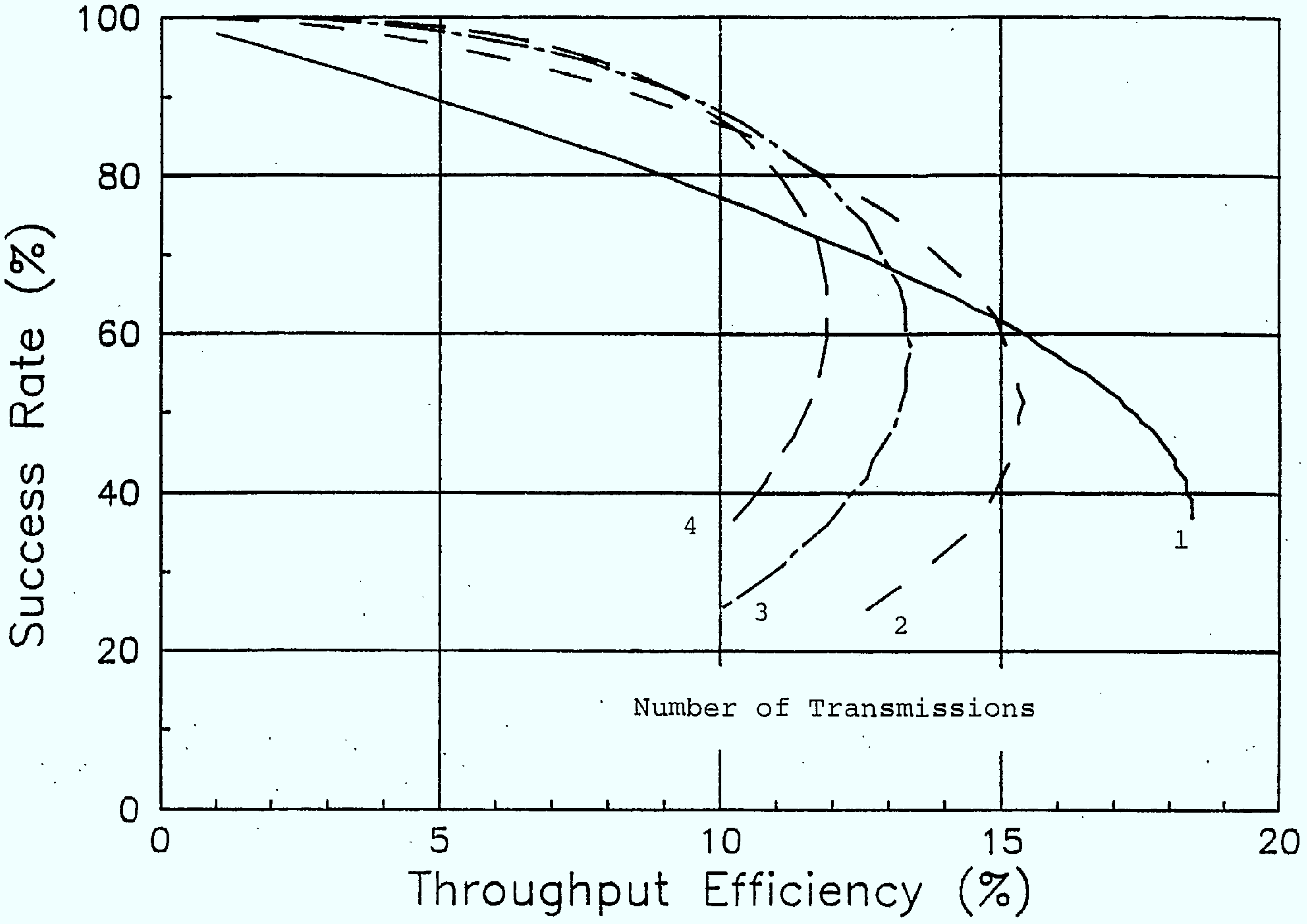


Figure 3 : Packet Success Rate as a Function of Throughput Efficiency for Random Access Channel Sharing

inefficiency involved if a user does not need all of a slot which is allocated to him. However, the effect of this inefficiency should be small and of no concern unless the capacity of the channel was reached.

The advantage of variable length time slots is that the time is used as efficiently as possible. The disadvantage is that the timing procedure is more complex.

In order to allow for timing inaccuracies and propagation delays, a guard band is required between transmission slots. The guard band ensures that no collisions occur between the transmissions of the different DCPs.

Timing information need not be disseminated continuously. The DCP will have an on-board clock which is corrected periodically. The more frequently that the clock is updated, the less accurate the clock on the DCP need be.

The paired transmit channel (from the Base station) could be used to send timing information. The same channel would be used for one-way and two-way DCPs. This would not interfere with the operation of two-way DCPs because the timing information would be sent only a few times a day.

Since each DCP has a fixed time slot, a TDM access scheme has no need for an address code to identify the transmitting DCP.

6.3 ACCESS TECHNIQUE FOR TWO-WAY PLATFORMS

All the candidate access techniques considered for the one-way platforms could be used for two-way platforms. Random access is not a likely technique to be used since the existence of a forward link from the base station allows a more efficient access scheme to be used. FDMA cannot be used for two-way platforms due to the limited bandwidth available. It is also not efficient to dedicate a portion of the bandwidth to each DCP because the traffic generated by each DCP is small.

TDMA is a practical technique to implement with a two-way link but the extra circuitry required to extract timing information makes this technique unattractive economically. The two-way link would not make CDMA any more attractive to use for two-way platforms than for one-way platforms.

A desirable technique to use with two-way platforms is polling. The central control station keeps a list of times when each DCP should be interrogated and, at the proper time, commands the DCP to send data or perform any other task desired by the user. A disadvantage of this technique is that the user would not be able to command his DCPs from his own site because such precise timing between the user and the central control station would be required that a dedicated link between the two would be necessary. This scheme would involve an acknowledgement system between the DCP and central control system so that retransmissions could be requested whenever data is received in error.

7.0 MESSAGE FORMAT

Due to the intermittent nature of communications between DCPs and the base station, messages are sent in bursts. Since the receiver does not have the benefit of a continuous signal from the DCP, synchronization must be acquired with each burst. Therefore, along with the data, the DCP must send information that allows the base station receiver to synchronize, and defines the start of the message. As well, the DCP must send information to identify itself. This section examines the various components required by the DCP message.

7.1 DCP TO BASE STATION LINK

The part of the burst dedicated to acquiring carrier phase and symbol timing is called the preamble. The length of the preamble depends on the type of modulation and the complexity of the demodulator.

Preambles generally consist of a period of unmodulated carrier which is used by the carrier recovery circuitry to estimate the carrier phase. This is followed by a string of ones and zeros which are used to define the bit rate and timing instants.

The following paragraphs describe the preambles used by different DCP systems and modems.

A data collection platform system designed by COMSAT [5] uses FSK at a bit rate of 1 kbps and allocates 100 bits for carrier frequency acquisition and 30 bits for bit timing recovery.

The ARGOS data collection system [6] uses PSK modulation at a bit rate of 400 bps. The preamble consists of 64 bits of unmodulated carrier for carrier frequency acquisition followed by 15 bits for bit timing recovery.

The GOES system [9] transmits data using ±60° PSK at a bit rate of 100 bps. The preamble consists of 500 bits of unmodulated carrier followed by 200 bits of alternating ones and zeros.

The burst format proposed by Miller [3] for their 2400 bps DMSK modem proposes a preamble of 64 bits for carrier acquisition and timing recovery.

After carrier sync and timing recovery have been achieved, the receiver needs a signal to identify the start of the information bits. This is accomplished with a special pattern of bits known as the sync word or unique word (U.W.). The receiver has a correlator of length equal to the unique word length, and each new bit received is shifted into the correlator. The output of the correlator, when it exceeds some threshold, is used as a "start of message" signal. The threshold of the correlator may require an exact match between the unique word and the received bit stream, or it may allow 1, 2, or more errors. Requiring an exact match reduces the number of false alarms (a false alarm occurs when part of the preamble or the data is interpreted as the start of message), but it also increases the probability of missing the unique word because of a bit error. Allowing one or more errors in the unique word decreases the probability of missing the unique word but increases the occurrence of false alarms. False alarms can be reduced by ignoring start of message signals until the end of the current message. In other words, once a start of message signal is received, the output of the correlator is ignored until the end of the message has been reached.

Missing a unique word is more damaging to the system operation than a false alarm because a loss of data is involved. The probability of false alarm is smaller than the probability of a miss, since multiple bit errors are required for a false alarm while a single bit error can cause a miss (if no errors are allowed in the unique word).

The length of the unique word should be long to minimize the probability of false alarm; but as the length is increased, the probability of a miss is increased. Figure 4 is a plot of the probability of a miss versus the unique word length assuming that zero errors, one error, and two errors are allowed for a correlator match to occur. The probability of a bit error, P_b, is assumed to be 10^{-5}. The probability of a miss assuming that n errors are allowed in the unique word is:

$$P_m = \sum_{i=n+1}^{N} \binom{N}{i} P_b^i (1 - P_b)^{N-i}$$

where N is the number of bits in the unique word.

A false alarm is most likely to occur in the data portion of the message, where any bit pattern can occur. The chance of a false alarm occurring can be reduced by using a "time window" with the correlator. This means that the output of the correlator will be ignored during certain portions of the message. After a unique word has been detected, the output of the correlator can be ignored during certain portions of the message. After a unique word has been detected, the output of the correlator can be ignored until the end of the message. Also, at the beginning of the message, the correlator output can be ignored until carrier AFC and BTR is completed.

The bit pattern of the unique word is chosen so that it has a low correlation with the bit timing recovery (BTR) pattern and shifted versions of itself. A good unique word pattern will differ in N/2 places from any possible pattern in the shift register. Note that the only valid patterns occurring during the time window are the BTR pattern and the UW pattern.

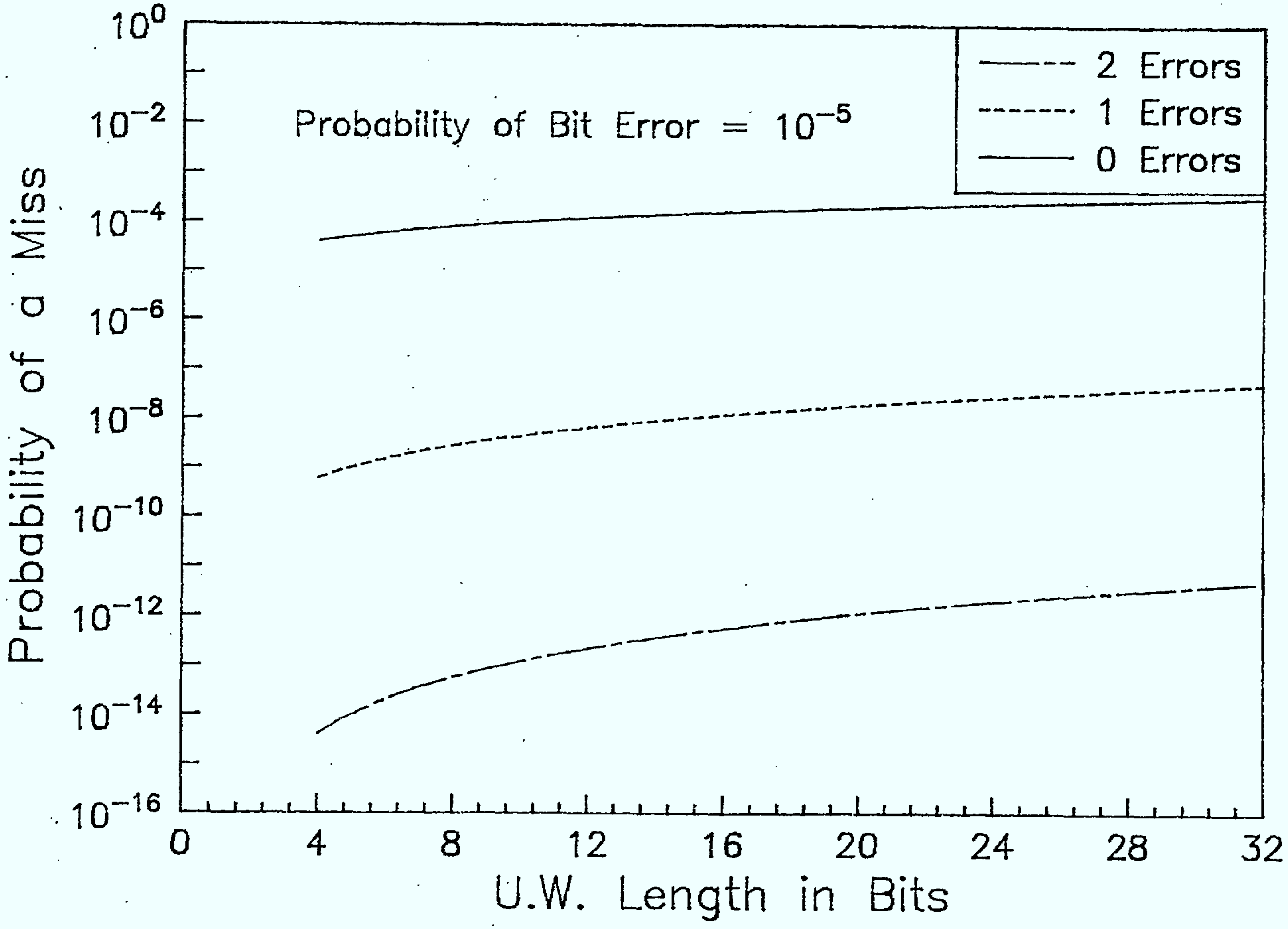


Figure 4 : Probability of Not Detecting the Unique Word as a Function of Unique Word Length

As the pattern moving through the shift register changes from the BTR pattern to the UW pattern, the number of differences between the shift register contents and the UW varies from N/2 - 1 to N/2 + 1 [10].

Computing the probability of false alarm exactly is not possible without knowing the unique word pattern. However, an upper bound to the probability of false alarm can be computed. We will assume for each pattern in the shift register a minimum number of bit errors is required for a false alarm. Also, we will assume that bit timing recovery is completed instantaneously; therefore, 32 bits of BTR pattern exist in the UW time window.

We have chosen to allow 0 or 1 bit position difference between the unique word and the shift register contents for a match to be declared. We will assume for each pattern in the shift register that N/2 + 1 bit positions match with the unique word pattern, i.e. N/2 - 1 errors in the non-matching bits will cause an exact match with the UW.

For a given pattern in the shift register, the probability of false alarm is,

$$P_{FA} = \sum_{i=0}^{E} \binom{N/2-1}{N/2-1-i} p^{N/2-1-i} (1-p)^{N/2+1+i}$$

$$+ \sum_{i=1}^{E} \binom{N/2+1}{i} \binom{N/2-1}{N/2-1-E+i} p^{N/2-1-E+2i} (1-p)^{N/2+1+E-2i}$$

where p is the probability of a bit error, and E is the number of differences allowed between the UW and the received data.

P_{FA} is the probability of a false alarm during the first baud interval of the time window. The probability of a false alarm in the second baud interval is the probability that a false alarm did not occur during the first baud interval multiplied by the probability P_{FA}.

$P(\text{false alarm in second time slot}) = (1 - P_{FA})P_{FA}$

Therefore, over the time window, the probability of false alarm is,

$$P_{FA\ Total} = P_{FA} + (1 - P_{FA})\ P_{FA} + (1 - P_{FA})^2\ P_{FA} + \ldots$$

Since $P_{FA} << 1$, $P_{FA} \simeq WP_{FA}$, where W is the length of the time window in baud intervals.

A graph of the probability of false alarm versus the length of the unique word in bits is shown in Figure 5. The pattern in the correlator shift register can differ from the unique word pattern in 0 or 1 position for a match. The probability of a bit error has been assumed to be 10^{-5}.

The choice of a length for the unique word is made by considering both the probability of a miss and the probability of a false alarm. From Figure 4, it can be seen that allowing 2 mismatches in the correlator reduces the probability of a miss to the less than 10^{-12} for unique word lengths of less than 32. Allowing no errors causes the probability of a miss to increase to 10^{-4} or less. Since we want the probability of a miss to be small compared with the bit error probability, we will allow one or more mismatches. Allowing exactly one mismatch produces a probability of a miss in the region of 10^{-7} or less for bit lengths of 32 or less. This is sufficient for our needs.

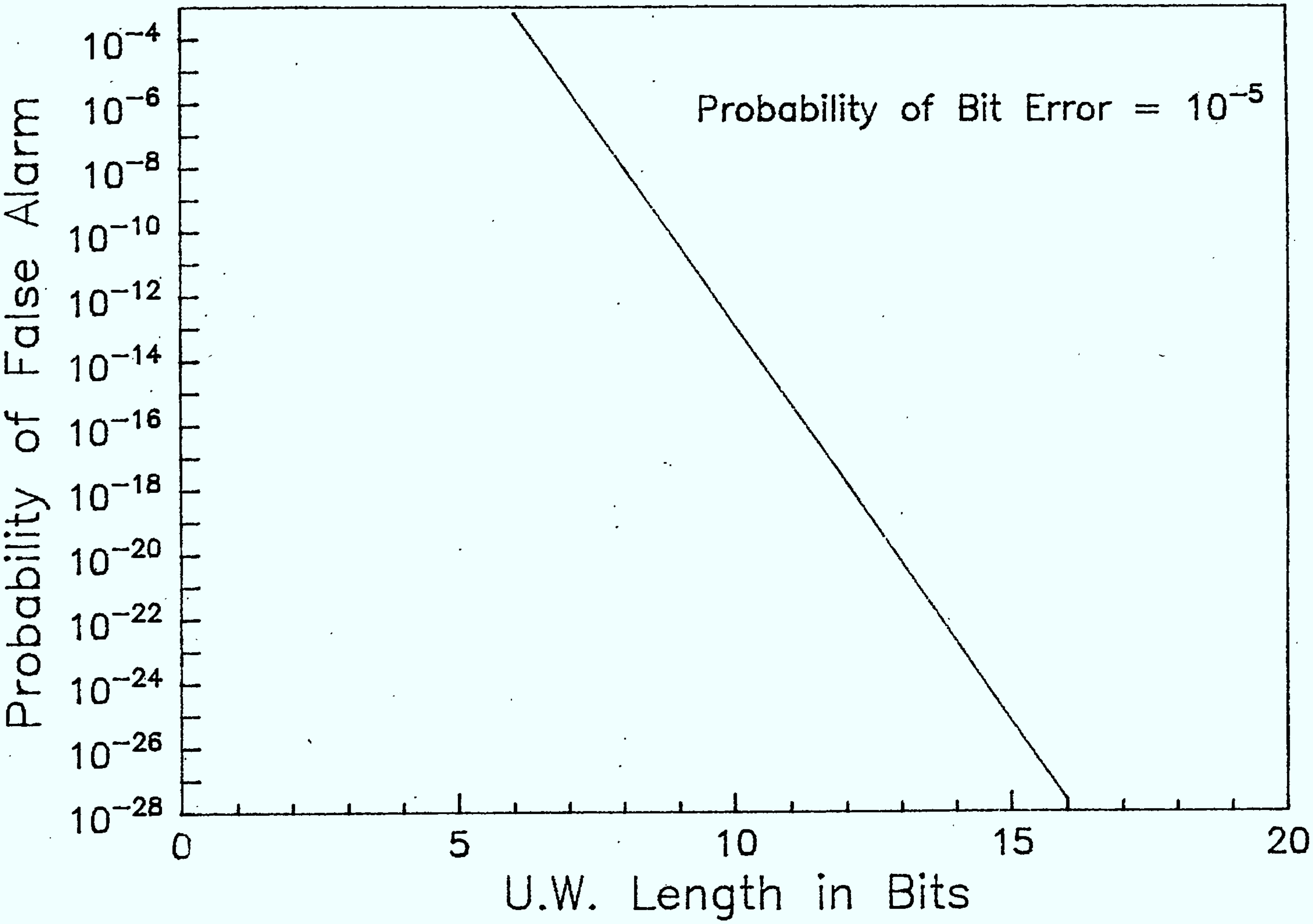


Figure 5 : Probability of Falsely Detecting the Unique Word as a Function of Unique Word Length

From Figure 5, we can see that the probability of false alarms decreases rapidly with increasing unique word length. For a unique word length of 8 bits, the probability of a miss is approximately 10^{-9} for the same length. Since this produces sufficiently small miss and false alarm probabilities, we recommend using a unique word length of 8 bits.

7.2 BASE STATION TO DCP LINK

The format of the command signal from the base station to the DCP is similar to the format of the message from the DCP. The structure of the preamble depends on the type of transmission to the DCP. Continuous or burst transmission can be used. Continuous transmission simplifies demodulation at the receiver. No part of the preamble needs to be reserved for carrier phase recovery since the receiver locks to the signal soon after transmission commences from the DCP. Since transmission is continuous, the demodulator remains locked to the signal, losing lock only when the signal fades severely. The disadvantage of this method is that it is power inefficient as power is transmitted even when there is no message. Another disadvantage of this method is that the channel cannot be shared. Channel sharing would reduce the cost charged to the user for using the channel.

The other method of transmission is burst transmission. This method requires that part of the preamble be used for carrier recovery. However, burst transmission allows the channel to be shared. If the number of two-way DCPs is small, then most of the channel capacity will be available for some other data service.

For either type of transmission, a unique word will be required to mark the start of the information part of the packet. We recommend using the same format for the unique word as is used for one-way DCPs.

8.0 CHANNEL ASSIGNMENT

Channels in MSAT for MTS and MRS are assigned to the user on a demand requested basis. This is the most practical method given the narrow spectrum and bursty nature of the traffic. Several channels are set aside for the user to request a channel and the central controller assigns to the user the transmit and receive frequencies when a channel is available. It is not practical for data collection platforms to participate in this scheme as it requires a two-way link to the base station, as well as a frequency synthesizer at the DCP. This would result in a more costly DCP. In addition, since DCP transmissions are short, the overhead required to request and wait for a channel would require more time than the data transmission.

The most practical scheme appears to be a dedicated channel for data collection platforms. The number of channels required would depend on the number of users as well as the message length, data rate, and the efficiency of the multiple access scheme.

Two-way DCPs and one-way DCPs can share a transmit channel. The presence of the one-way DCPs should have a small effect on the two-way DCP performance since the two-way DCPs will retransmit a packet in the event of a collision until error free transmission is achieved. The presence of the one-way DCPs will increase the probability of undetected error for the two-way DCPs due to packet collisions. The one-way DCPs also increase the average number of retransmissions required by the two-way DCPs for successful packet reception. The presence of the two-way DCPs will decrease the probability of successful packet transmission for the one-way DCPs. However, the decrease is expected to be small because the number of two-way DCPs is expected to be small relative to the one-way DCPs.

The two-way DCPs need a return link from the base station to the DCPs. Using a dedicated channel is undesirable, as this would double the channel usage fee charged to the user. Since MSAT channels are expected to be expensive, a dedicated return channel will greatly reduce the economic viability of two-way DCPs. An inexpensive solution from the user's standpoint would be to have the base station transmit at the same frequency that it receives the DCP data. Only one MSAT channel would be needed. A special frequency translator would be required at the satellite. Another disadvantage of this method is that the number of channels which could offer a two-way DCP service would be fixed at the time of the manufacture of the satellite, so expansion would not be available if needed.

Another low-cost alternative to using a fully dedicated channel for the transmit link to the DCP is to use an unused DAMA assignment channel. Since MSAT channels are assigned in pairs - one transmit, one receive - each DAMA signalling channel will have a corresponding assignment channel. The traffic of the signalling channel will have contention, so the signalling traffic will exceed the assignment traffic. Therefore, it is expected that the DAMA system will not use all of the assignment channels reserved for that purpose. For the first generation system, the number of assignment channels are expected to be fixed at five, so they cannot be placed in the MTS or MRS voice channel pool. Since their frequency is fixed, rather than dynamically assigned, the DCP would not require a frequency synthesizer to make use of this service. Also, since these channels would otherwise be idle, the charge to the user would likely be less than that for a voice channel. Also, this channel can be shared by other data users such as wide-area paging to further reduce the cost for the DCP user.

Whether or not the DAMA assignment channels would be useful for use as DCP channels depends on how they would be used. The easiest method of choosing an assignment channel for a user is to have the user select one of the five request channels and then use the paired channel as the assignment channel the channel paired with the request channel. The drawback of this method is that the assignment channel traffic, which is less than the request channel traffic, could be spread across all five channels. Therefore, each channel would be under-utilized. The unused capacity could be used to transmit commands to two-way DCPs. The drawback of this method is that the DCP would use only one of these channels. If many users were using this channel to request a channel, there would be no capacity left for the DCPs. This condition, however, would not likely occur often and the time of the unavailability would likely be short.

Another scheme which would allow some of the assignment channels to be empty would involve the DAMA system assigning the user a request channel and an assignment channel at log-on. The assignment channel would not necessarily be the paired channel of the request channel. Therefore, the assignment channels would be filled consecutively rather than at random. Since the assignment channel traffic is expected to fill three channels [11], two channels would be left unused and one of them could be used by the DCP service.

9.0 CAPACITY

In this section, we will estimate the capacity of the various modulation techniques using a random access protocol. The capacity depends, in part, on the length of the preamble of each burst. We will use preamble lengths the same size as used on existing systems. For DMSK, we will assume a preamble length of 64 bits, as used in [3]. For FSK, we will assume a 130 bit preamble as used in [14]. For BPSK and QPSK there are no known burst transmission systems based on an incoherent detector. The detection of differential MSK is similar to the detection of differential PSK, so we will assume a preamble of 64 bits for BPSK.

The unique word length chosen in section 7.1 was 8 bits. This is the length which will be used in the following calculations. The address code will be 13 bits, which can identify 8192 DCPs.

Four bits of the packet before the data portion are reserved to identify the number of data words to be transmitted. A (15,11) BCH code will be applied to all parts of the packet following the unique word.

As mentioned in Appendix C, a survey of DCP manufacturers indicates that an average DCP uses between 3 and 5 sensors. We will compute the capacity assuming 48, 64, and 80 bits of data are sent, corresponding to 3, 4, and 5 sensors, respectively.

As indicated in Appendix C, most current users of the GOES system are limited to transmissions every 3 hours. A few users are permitted to broadcast data every hour. In our calculations, we will compute the capacity for transmission periods of once every 3 hours, 1 hour, and 10 minutes. The latter period will show the effect of users who wish to transmit more frequently than is permitted by the GOES operators.

The multiple access efficiency decreases as the probability of successful packet transmission is increased. We will compute the channel capacity for probabilities of successful packet transmission of 90%, 95%, 97%, and 99%.

The channel capacity is shown in Table 5 for DMSK at 2400 bps, FSK at 1500 bps, and BPSK at 800 bps for packet success rates of 99%, 97%, 95%, and 90%, assuming 64 bits of data are sent once per hour.

The effect of average data transmission size on the channel capacity is shown in Table 6 for DMSK at 2400 bps, at 99% packet success rate, and for a transmission period of once per hour. The capacity is shown for a transmission of 48 bits, 64 bits and 80 bits.

The effect of the average transmission period on the channel capacity is linear. As an example, for DMSK at 2400 bps with a packet success rate of 99%, 64 data bits transmitted, and a transmission period of once per hour, the channel capacity is 1800 DCPs, as shown in Table 5. For a transmission period of once every 3 hours, the capacity would be tripled, i.e. 5400 DCPs. For a transmission period of once every 10 minutes, the capacity would be reduced to 300 DCPs.

The numbers shown in Table 5 are the number of DCPs that can be supported in the channel without reducing the probability of success below a certain value. This maximum capacity will

TABLE 5

Channel Capacity For Different Modulation Techniques

Modulation	Packet Size
DMSK at 2400 bps	64 + 8 + (13 + 4 + 64) x 15/11 = 192 bits
FSK at 1500 bps	130 + 8 + (13 + 4 + 64) x 15/11 = 258 bits
BPSK at 800 bps	64 + 8 + (13 + 4 + 64) x 15/11 = 192 bits

Modulation	Packet Success Rate	Channel Efficiency	# of DCPs Per Channel
DMSK at 2400 bps	99%	4.0%	1800
	97%	6.2%	2790
	95%	7.6%	3420
	90%	9.5%	4275
FSK at 1500 bps	99%	4.0%	837
	97%	6.2%	1297
	95%	7.6%	1590
	90%	9.5%	1988
BPSK at 800 bps	99%	4.0%	600
	97%	6.2%	930
	95%	7.6%	1140
	90%	9.5%	1425

TABLE 6

Channel Capacity For DMSK Using Random Access And Different Data Lengths

Data Length	Packet Size
48 bits	64 + 8 + (13 + 4 + 48) x 15/11 = 162 bits
64 bits	64 + 8 + (13 + 4 + 64) x 15/11 = 192 bits
80 bits	64 + 8 + (13 + 4 + 80) x 15/11 = 207 bits

Data Length	Capacity
48 bits	2400 bps x 0.04/162 bits x 3600 s/hr = 2133 DCPs
64 bits	2400 bps x 0.04/192 bits x 3600 s/hr = 1800 DCPs
80 bits	2400 bps x 0.04/207 bits x 3600 s/hr = 1670 DCPs

not likely be attained immediately. The number of DCPs will probably start at a smaller number and grow as time passes. Therefore, at least for the initial part of the life of the system, the packet success rate will be larger than that indicated in Table 5. The packet success rate when the number of DCPs is half what the channel can support is shown in Table 7. As can be seen, the success rate is substantially larger at half capacity.

9.1 TDM Capacity

The capacity of an MSAT channel using a TDM access scheme depends on the packet size of the data, the data rate, the overhead of the packet, and the guard times required to account for timing uncertainties. The guard times required by the TDM access scheme depends on the accuracy of the timing signal plus an allowance for uncertainty in the position of the DCP. As computed in [3], a guard time of ±13.96 ms is required to account for variations in the distance from the DCP to the satellite. The guard time required for timing error would depend on the accuracy of the timing system. We will assume that the timing error is negligible compared to the guard time required for position uncertainty.

We will assume that a DCP is assigned a slot size large enough to accommodate the number of bits of data that it has to transmit. Examples of the slot sizes required for 2400 bps (DMSK) transmissions are shown in Table 8. A preamble of 64 bits is assumed for AFC and BTR, and 8 bits is the size of the U.W. and a (15,11) BCH code is used. For a transmission of 16 data bits, a 71 ms slot size is required. A 102 ms slot size is needed to transmit 64 data bits and for a transmission of 256 data bits, a 208 ms slot is required.

TABLE 7

Full Capacity and Half Capacity Success Rates

FULL CAPACITY SUCCESS RATE	HALF CAPACITY SUCCESS RATE
99%	99.9%
97%	99.5%
95%	99.2%
90%	98.0%

TABLE 8

Packet Time Calculations For DMSK Using TDM

Preamble:	64 bits for BTR and AFC
U.W.:	8 bits
Data:	16-256 bits + coding
Data Number:	4 bits + coding
Coding:	(15,11) BCH coding

Minimum Data Transmission: 16 bits

Packet Length = 64 + 8 + (16 + 4) x 15/11 = 102 bits
102 bits/2400 bps = 43 ms + 28 ms guard time
= 71 ms

Data Transmission: 64 bits

Packet Length = 64 + 8 + (64 + 4) x 15/11 = 177 bits
177 bits/2400 bps = 74 ms + 28 ms guard time
= 102 ms

Maximum Data Transmission: 256 bits

Packet Length = 64 + 8 + (256 + 4) x 15/11 = 432 bits
432 bits/2400 bps = 180 ms + 28 ms guard time
= 208 ms

The number of DCPs which could be accommodated by this scheme would depend on the distribution of the data transmission sizes and transmission periods among the DCPs. If we assume that on average, a DCP transmits 64 bits every hour, the channel capacity is:

3600 s per hour/102 ms per transmission
= 35,294 DCPs

All of this capacity would not be realizable since the placement of DCP time slots initially would be far apart which could cause unusable gaps as more DCPs use the service.

Table 9 shows calculations for a TDM scheme using 1000 bps FSK. A preamble of 130 bits is required for AFC and BTR, 8 bits is used for the unique word, and a (15, 11) BCH code is used. Assuming an average transmission of 64 bits every hour, the channel can support:

3600 s per hour/271 ms per transmission = 13,284 DCPs

9.2 TWO-WAY CAPACITY

The capacity of the two-way DCPs can be computed approximately if some assumptions are made. We assume a positive acknowledgement scheme. We assume that the command word is received correctly at the DCP. It is also assumed that the network controller completes the interrogation of one DCP before interrogating the next. In other words, the network controller will wait for the acknowledgement from a DCP before interrogating the next one. Although it is more efficient to interrogate the DCPs without waiting for the acknowledgements, the complexity of the interrogation algorithm would be greatly increased because of the need to ensure that the interrogation

TABLE 9

Packet Time Calculations For FSK Using TDM

Preamble: 130 bits for BTR and AFC
U.W.: 8 bits
Data: 16-256 bits + coding
Data Number: 4 bits + coding
Coding: (15,11) BCH coding

Minimum Data Transmission: 16 bits
Packet Length = 130 + 8 + (16 + 4) x 15/11 = 168 bits
168 bits/1000 bps = 168 ms + 28 ms guard time
= 196 ms

Data Transmission: 64 bits
Packet Length = 130 + 8 + (64 x 4) x 15/11 = 243 bits
243 bits/1000 bps = 243 ms + 28 ms guard time
= 271 ms

Maximum Data Transmission: 256 bits
Packet Length = 130 + 8 + (256 + 4) x 15/11 = 498 bits
498 bits/1000 bps = 498 ms + 28 ms guard time
= 526 ms

commands do not interfere with the previous DCP's acknowledgements and because of the complexity of re-interrogating a platform if no acknowledgement is received.

We assume that the modulation is FSK at a bit rate of 1000 bps. The command word is 8 bits plus a parity bit. The acknowledgement word is 4 bits long.

We assume that it takes a signal 135 ms to travel from the earth to the satellite. We assume that the time required to process the signal at the data collection platform is negligible compared with the propagation delays.

The time taken to interrogate a DCP is:

Time to transmit command word from base station:

151 bits preamble
<u>9 bits data</u>
160 bits @ 1000 bps = 0.160s

Time to propagate from base station to satellite to DCP:

2 x 0.135s = 0.27s

Time for DCP transmission:

151 bits preamble
<u>90 bits coded data</u>
241 bits @ 2400 bps = 0.1s

Time for message to travel from DCP to base station:

2 x 0.135s = 0.27s

Time for base station to acknowledge:

151 bits preamble

4 bits acknowledgement word

155 bits @ 1000 bps = 0.155s

Total Time = 0.160s + 0.27s + 0.1s + 0.27s + 0.155s = 0.955s

The total capacity depends on the frequency of data transmission. If we assume that DCPs transmit once per hour, on average, the channel can support 3769 DCPs.

The above analysis assumed that no channel errors occurred. If the message from the DCP was received in error, then the base station would not acknowledge, and the DCP would wait until the end of the time-out period before retransmitting the message. This would, therefore, reduce the channel capacity.

For comparison purposes, we will compute the capacity of a two-way system assuming that the base station interrogates the next DCP immediately rather than waiting until the first DCP has sent its message. Therefore, the base station can interrogate other DCPs during the period in which its command message to the first DCP is travelling to the DCP, the DCP transmits its message and the message travels to the base station.

The amount of time that the base station spends on a DCP is the time taken to transmit the interrogation message and the time to transmit the acknowledgement packet. The time is:

0.16 s + 0.155 s = 0.315 s

The capacity of the channel is approximately 11,400 DCPs if we assume that each DCP transmits once per hour on average. The capacity was computed assuming that there are no channel errors which would require the DCP to transmit its message more than once.

10.0 LONG TERM FREQUENCY CONTROL

The accuracy of the transmitter frequency of the DCP must be maintained over long intervals of time to ensure that the probability of error in a message remains low and to avoid adjacent channel interference caused by the DCP frequency drifting. The stability of the oscillator should be maintained over a long interval of time so that the DCP user does not have to make a trip to the field to adjust the oscillator.

Drifting in the oscillator frequency causes degradation due to two effects. The first is degradation from the quadrature term in the demodulator when f_c/T is not an integer [16]. The second effect is an attenuation in the signal amplitude caused by the receiver bandpass filter.

There are three methods which can be used to generate a stable DCP transmitter frequency:

1) Use a highly stable oscillator
2) Use a pilot signal sent over one of the MSAT channels
3) Use a reference signal from some other system

Each of these methods will be discussed in the following sections.

10.1 STABLE OSCILLATOR

The required frequency stability for the DMSK modem is ±440 Hz [12]. For operation in the UHF band, ≈800 MHz, this represents a stability of 5.5×10^{-7}.

There are two factors which affect the stability of a crystal oscillator, temperature range and aging. The angle at which a crystal is cut determines its accuracy. A stability performance of $\pm 5 \times 10^{-6}$ can be achieved with accurate cutting. Temperature compensation is used to further reduce the crystal's frequency variation with temperature. Temperature compensation is achieved with the use of an analog or digital circuit with temperature characteristics equal and opposite to that of the crystal. Using this technique, stabilities of 1.5×10^{-7} over the range -30° to 60°C can be achieved.

The frequency variation due to aging is caused by the loss of impurities and quartz from the crystal which affects the mass of the crystal and therefore, the frequency. Temperature variation causes the crystal to "age" faster. Frequency variation due to crystal aging for a non-temperature stabilized crystal is of the order of one part in 10^{6} per year.

In order to achieve a frequency stability of 5.5×10^{-7}, both temperature and aging stability must be considered. To reduce the variation due to aging to a low enough value, an ovenized oscillator would have to be used. The oven protects the oscillator from external temperature variations and thus improves the long term frequency characteristics of the crystal. The disadvantages of ovenized oscillators include increased cost and larger power drain on the DCP battery.

10.2 PILOT SYSTEM VIA MSAT

Another method to achieve frequency stability is to make use of a pilot signal transmitted via one of the MSAT channels, and to use this signal either to correct a local oscillator on-board the DCP or to drive an oscillator. This method requires the DCP to have a receiver.

Using an AFC loop to reduce the range of frequency inaccuracy in a local oscillator reduces the frequency stability requirement by a factor of 2 [12]. This is an insufficient reduction to avoid using an ovenized oscillator, so the usefulness of this method is limited.

Two methods of direct generation of a frequency reference from an MSAT transmitted signal were examined in [12]. The least expensive method was designed for a total frequency variation of 2×10^{-6} per year. The frequency range of the UHF signal then can vary at most 1.6 kHz. Assuming that the signal is transmitted in an MSAT channel, this allows a guard band of 1700 Hz on the signal. The disadvantage of this method is that a channel must be dedicated to transmitting the pilot.

Rather than transmitting a pilot tone in a separate channel, the frequency reference may be derived from the signal transmitted in the DAMA assignment channel assuming that the assignment channels are fixed. The acquisition of an unmodulated carrier is easier and the resulting frequency error is less than with a DMSK modulated carrier.

10.3 FREQUENCY REFERENCE FROM AN EXTERNAL SYSTEM

The use of an external radio signal to provide frequency stability is an alternative possibility. Highly accurate signals can be obtained from radio navigation systems or time broadcast systems. Generally, a frequency reference from one of these signals is relatively easy to obtain, since the carrier frequency is usually very accurate. The accuracy of the signal usually increases the longer that it is averaged. Timing information (for TDM use) from navigation systems is generally more complex to derive. A description of the most common navigation systems follows.

10.3.1 GLOBAL NAVIGATION SYSTEMS

There are several systems which exist today that can provide navigation functions on a global basis. They are divided into two types: terrestrial-based and satellite-based. Terrestrial-based systems typically use a low-frequency signal to achieve a wide coverage area. Satellite-based systems use low-orbit satellites that cover a large portion of the earth's surface. The following sections will describe some of the popular systems.

10.3.2 LORAN-C

LORAN-C is a terrestrial-based low-frequency (100 kHz) system. It was originally designed to provide navigation for boats. As a result, LORAN-C stations exist near coastal regions. A group of LORAN-C stations form a chain and timing differences between stations in the chain are used for position determination. Receivers use only the groundwave signal from a LORAN-C station for the highest accuracy. Regular LORAN-C stations provide groundwave coverage up to 1200 nautical miles from the transmitter. Many DCPs would be located in areas for out of the range of any LORAN-C station groundwave. Due to the low frequency of the LORAN-C signal, it will propagate large distances by reflecting off the ionosphere. All of Canada is covered by the skywave signal [13].

The accuracy of LORAN-C is limited by the ability to predict propagation effects. A conventional receiver employed in shipping uses data published daily by the U.S. Coast Guard to correct for propagation effects. DCPs deployed in remote areas would not have access to these daily publications. The DCPs would have to use average values, averaged over the year. Since some propagation effects vary over the year, high accuracy would not be a achievable.

The user also needs to know the position of the DCP fairly accurately in order to compute the delay from the satellite. This requirement reduces the flexibility of the DCPs. In order to use the DCP in different locations, the delay value must be changed each time the DCP is moved.

LORAN-C does not provide time-of-day information. The LORAN-C stations transmit pulses which are used by a receiver to correct an internal clock. The receiver must know the time-of-day initially. This requires that the clock be set prior to deploying a DCP. In the event of a power failure, the clock would have to be reset. This makes the maintenance procedure more complicated.

10.3.3 OMEGA

The OMEGA system is a VLF terrestrial-based navigation system. There are 8 stations which provide global coverage. Both marine and aeronautical users employ this system. The frequency of the signals is between 10 kHz and 14 kHz, depending on the station. An OMEGA receiver compares the phase of two stations which is used to determine the user's position. The receiver makes use of propagation predictions much like LORAN-C does. The predictions are published by the U.S. Defence Mapping Agency.

OMEGA does not provide time-of-day information. The user's clock must initially be set to the correct time and drifts in the timer can be corrected using OMEGA signals.

10.3.4 GPS

The global positioning system will consist of 18 low orbit satellites when it reaches full operation. The satellites provide coverage to the entire earth. A receiver must be able to use the signals from four satellites at once to get an accurate position determination via GPS. Most places on earth are in view of at least 4 of the satellites for 100% of the time. The system operates at L-band. Two signals are broadcast from each satellite: L_1 at 1575.45 MHz and L_2 at 1227.6 MHz. The L_1 carrier is modulated by a 10.23 MHz clock rate "P-code" and a 1.023 MHz "C/A code". The P-code has a repetition rate of 267 days. This code provides the fundamental accuracy of the system. Due to its large period it is difficult for a receiver to synchronize to it. The C/A code has a period of 1 ms and is easier to synchronize to. Part of the C/A code includes a "Hand-over Word" which assists the user in synchronizing to the P-code. Additional information transmitted from the satellites include: satellite clock correction and ephemeris parameters, and parameters for correcting propagation delays through the ionosphere. Transmitting propagation correction factors via the system is an advantage over other systems where the information is published separately. This is useful for DCPs which cannot change propagation information daily. The coordinated Universal Time (UTC) can be computed from the information transmitted in the navigation message.

10.3.5 NRC TIME SIGNALS

The National Research Council Canada broadcasts standard time signals via radio station CHU. Three frequencies are broadcast: 3.33 MHz, 7.335 MHz, and 14.67 MHz. The transmission mode is upper single sideband with carrier re-inserted. Because the carrier is transmitted, a frequency reference can be easily obtained. The frequencies are derived from cesium clocks. The emission times are normally within 100 μs of the NRC primary cesium clocks. The transmitted frequencies are within 5 x 10^{-12} of the values given by the primary clocks. There is only one broadcast location in Canada, that being near Ottawa.

The time broadcasts consists of two parts: a voice announcement of the time and a data transmission of the time. The broadcast signal normally consists of pulses of 300 periods of 1000 Hz to mark each second. The start of each minute consists of 500 periods of 1000 Hz and the first minute of each hour commences with a 1 second pulse of 1000 Hz followed by 9 seconds of silence. The pulse at 29 seconds of each minute is always omitted. Following the normal pulse at 30 seconds of each minute, for a 9 second period, shorter pulses of 0.01 second duration occur and the NRC FSK digital time code is inserted between each. The FSK time code identifies the day (number of days from the start of the year), the hour, the minute, and the second of the current time. The time code is repeated twice each second for reliability. The last 10 seconds of each minute contain a bilingual station identification and time announcement. The time given is Eastern Standard Time.

10.3.6 SUMMARY

The LORAN-C and OMEGA systems are similar in principle. Both are fairly simple systems and both require information about propagation conditions which are not available from the system itself. These systems also do not allow the user to compute the time-of-day independently. They require initiation from an external clock. The GPS system is a more complex and more accurate system. Propagation errors can be corrected using information transmitted by the system. Time-of-day can be computed with this system. The NRC system is quite simple. The time transmissions can be received with a simple radio. Time-of-day information is directly broadcast.

10.4 ALTERNATIVE METHOD TO ACHIEVE FREQUENCY STABILITY

The use of a different modulation technique is an alternative to solving the oscillator frequency stability requirement. The problem with differential detectors as used with MSK or PSK is the degradation caused when f_c/T is not an integer value. Decreasing the bit rate increases the degradation. Increasing the bit rate is not practical as it will cause adjacent channel interference.

The use of FSK solves this problem since there is no requirement that f_c/T be an integer value. The use of an incoherent receiver is desired for reasons mentioned earlier. An FSK receiver designed for DCP use is described in [14]. The demodulator uses frequencies of 512 kHz and 513.5 kHz. The system was designed to operate at a bit rate of 1000 bps and to allow for a frequency uncertainty of ±10 kHz. The frequency uncertainty will be less for an MSAT system since the channel bandwidth is only 5 kHz. The receiver described in [14] uses a phase-locked loop to remove frequency errors.

The bandwidth of the FSK signal at 1000 bps is approximately 3000 Hz [5]. The minimum frequency drift in a non-temperature stabilized crystal oscillator is 1 part in 10^6 per year. This corresponds to 800 Hz for a 800 MHz system. For an L-band system, the variation due to aging would be 1.6 kHz. The bandwidth of the signal would then be 1.6 kHz x 2 + 3 kHz = 6.2 kHz. An L-band system would have to be operated at a lower bit rate. A bandwidth of 3.2 kHz is required for frequency uncertainty. Therefore, 1800 Hz is left for signal bandwidth. This would allow a bit rate of 600 bps.

One disadvantage of FSK modulation is the increased power requirement. For an error probability of 10^{-5}, an E_b/N_o of 15 dB is required [14].

Since this scheme uses a lower bit rate, the number of DCPs per channel will be less than for 2400 bps DMSK. For a random access scheme, at a packet success rate of 99%, only 558 DCPs could be accommodated assuming 64 bits transmitted once per hour. This number is probably too small for the DCP service to be economically viable. In order for the service to be viable, a more efficient access technique would have to be used. TDMA is a practical access technique, but it has the disadvantage of the necessity of a receiver to access timing information. This extra cost must be weighed against the cost savings associated with being able to use a non-ovenized crystal oscillator.

10.5 OSCILLATOR SHORT TERM STABILITY

As mentioned in Section 3.7, the effect of phase noise is negligible for DBPSK at bit rates above 50 bps and for FSK at bit rates above 20 bps. The effect of phase noise on DMSK is similar to that of DBPSK.

The short term frequency stability requirement for data collection platforms is derived in Appendix A. Since DCPs will not use a frequency synthesizer, the phase noise is small and the short term frequency stability requirement should be easy to meet. As shown in Appendix A, the phase noise specification is -90 dBc/Hz at 1 kHz for the UHF oscillator and the same for an L-band oscillator.

Short term frequency stability is not expected to be as much of a problem for the MSAT system as compared to the COMSAT system [5, 14], since the MSAT system will likely employ differentially detected MSK, whereas the studies at COMSAT, which indicated that phase noise would be a problem, were based on coherently detected PSK systems which used the data signal to create a reference signal. Differentially detected receivers are more robust to the effect of phase noise.

10.6 LONG TERM FREQUENCY CONTROL FOR TWO-WAY PLATFORMS

A two-way platform has a requirement for frequency stability on both links. The frequency stability in the link from base station to DCP is not a factor in the DCP design since high frequency stability of the signal is easier to obtain because the transmitter is at a base station, and therefore, an ovenized oscillator can be used.

The frequency stability requirement of the link from the DCP to the base station is the same as for one-way DCPs. One difference that should be considered is that the two-way DCP has an MSAT receiver which means a frequency control system using an MSAT-generated pilot would be more economical to use.

11.0 LINK BUDGETS

Most of the parameters of the link budgets are fixed by the overall system design. The MSAT system is designed for MTS and MRS service and the DCP service must be fitted to this design. It is desirable to keep the DCP transmitter power as low as possible. Design factors which we have control over include the modulation technique (and, therefore, the power requirement for a given bit error rate which also defines the noise bandwidth and the service availability), the antenna gain, and the transmit power. The DCP service will involve fixed terminals, so fading due to blockage need not be considered. For 99% availability, a 4 dB fade margin is adequate for both UHF and L-band [8]. Since the DCP is fixed, this availability corresponds to 99% of the locations. It is worth noting that for DCPs located at high latitudes, scintillation effects due to ionospheric disturbances in the region would cause signal fluctuations. It is expected that a required margin to account for this phenomenon for DCPs located in high latitudes would be in the order of 1 dB for UHF. No margin would be required at L-band [18].

11.1 E_b/N_o REQUIREMENTS

The power required to produce a given bit error rate depends on the modulation and the implementation of the modulator/demodulator. For DMSK, the modem considered in [3] requires a 2 dB implementation margin. Therefore, an E_b/N_o of approximately 12 dB is required to produce a bit error rate of 10^{-5}. The effect of frequency offset causes a degradation of approximately 0.2 dB [3]. Therefore, to account for this effect, an E_b/N_o of 12.2 dB is required to produce a bit error rate of 10^{-5} or less. For the FSK modem of [5,14], allowing for a frequency offset of 20% requires an E_b/N_o of 15.5 dB to produce a bit error rate of 10^{-5}. The increased signal power required by FSK is partially offset by the lower bandwidth of the signal.

11.2 UHF

The link budget for UHF DCP service using DMSK at 2400 bps is shown in column 1 of Table 10. Using the UHF baseline parameters, a C/N_o of 48.7 dB-Hz is achieved. The resulting E_b/N_o is 14.8 dB. For a bit error rate of 10^{-5}, an E_b/N_o of 12.2 dB is needed. The resulting system margin is 2.6 dB. Since we should allow a margin for implementation losses, it is not practical to reduce the DCP transmitted power, as this would leave insufficient margin. The transmitted EIRP is 11 dBW. Assuming a 12 dBi antenna gain, the DCP transmitted power is -1 dBW or 0.79 W. If an omni-directional antenna with a gain of 4 dBi was used, the DCP transmitted power would be 7 dBW or 5.0 W.

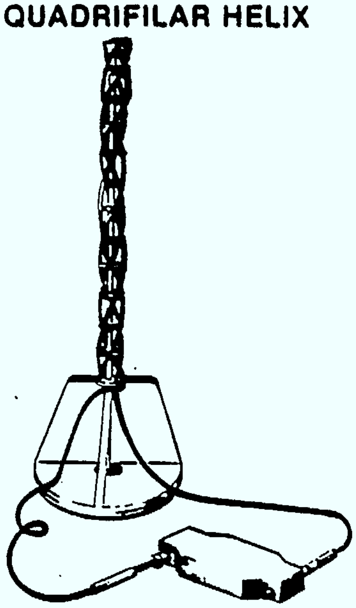
The link budget for UHF DCP service using FSK at 1000 bps is shown in column 2 of Table 10. The resulting C/N_o is 48.6 dB-Hz. This produces an E_b/N_o of 18.6 dB. The required E_b/N_o for FSK to produce a bit error rate of 10^{-5} is 15.5 dB. Therefore, the margin is 3.1 dB. The magnitude of this margin is such that it would be unwise to reduce the transmitted EIRP from the DCP. Therefore, as for 2400 bps DMSK, the DCP transmit power is -1 dBW or 0.79 W for a 12 dBi antenna, and 5.0 W for a 4 dBi omni-directional antenna.

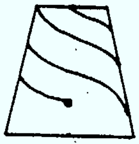
A typical antenna which could be used for UHF or L-band fixed service is shown in Figure 6. Examples of low-gain antennas used for moving platforms are also shown in Figure 6.

TABLE 10

DCP to Base Station UHF Link Budget

Uplink	DMSK at 2400 bps	FSK at 1000 bps	
Satellite G/T	-2	-2	dB/K
EIRP/Carrier	11	11	dBW
Path Loss	183.3	183.3	dB
Fade Margin	4	4	dB
C/N_o	50.3	50.3	dB-Hz
Downlink			
EIRP/Carrier	8.6	8.6	dBW
Path Loss	206.3	206.3	dB
G/T	25.9	25.9	dB/K
C/N_o	56.8	56.8	dB-Hz
Interference (C/I)			
Intermod and Energy Spread			
Uplink	22.8	25.0	dB
Downlink	22.8	25.0	dB
Other Sources			
Downlink	26.8	29.0	dB
Bandwidth	5	3	kHz
C/N_o Total	48.6	48.6	dB-Hz
E_b/N_o Resulting	14.8	18.6	dB
E_b/N_o Required	12.2	15.5	dB
Margin	2.6	3.1	dB





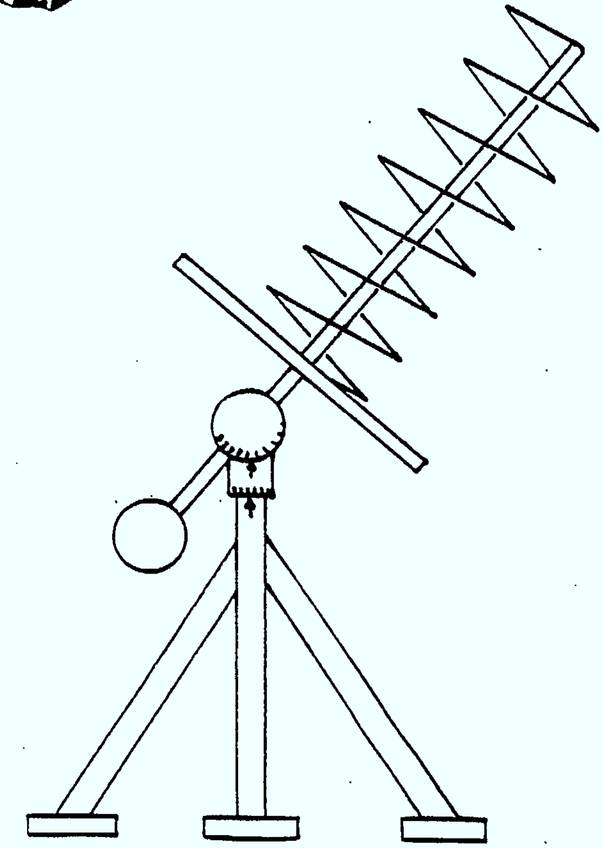


Figure 6 : Examples of Low-Gain Antennas
The Quadrifilar Helix
The Conical Log-Spiral (Right Top)
Example of a High-Gain Antenna
The Helix (Bottom)

11.3 L-BAND

The fade margin for a fixed terminal at L-band is also assumed to be 4 dB. The transmit EIRP from the DCP is higher at L-band by 9.7 dB as compared with the UHF link budget.

The link budget for DMSK at 2400 bps is shown in Table 11. Column 1 is the baseline L-band link budget [15]. The resulting C/N_o is 51.6 dB-Hz. This produces an E_b/N_o of 17.8 dB. The required E_b/N_o is 12.2 dB, so the system margin is 5.6 dB. A system margin of 3 dB should be sufficient, so we can try reducing the DCP transmitted EIRP by 2.4 dB. This reduction affects both the uplink and the downlink. Since the carrier power is reduced by 2.4 dB, the intermod and energy spread C/I is reduced by 2.4 dB. The link budget with reduced EIRP is shown in column 2 of Table 11. The resulting C/N_o is 49.0 dB-Hz which gives the required 15.2 dB E_b/N_o. The DCP transmitted EIRP is 18.3 dB. Assuming an antenna gain of 17 dBi, the required DCP transmit power is 3.1 dBW or 1.3 W.

A different L-band scenario could be implemented: the UHF band would be used for mobile service and L-band would be used for fixed and transportable service. Each terminal would require less power from the satellite, since no margin is needed to overcome fading due to foliage blockage. Therefore, the satellite could support more terminals if spectrum is available. The link budget for this case is shown in column 3 of Table 11. The DCP transmitted EIRP is 8.9 dBW. Note that this is more EIRP than used in the link budgets of [15]. The increased power is necessary to produce a C/N_o of 48 dB-Hz on the uplink and downlink which was shown in the BNR voice quality tests to be necessary for a mean opinion score of 3.

The resulting C/N_o is 42.9 dB-Hz. This produces an E_b/N_o of 9.1 dB. This is less than the required 12.2 dB. The resulting bit error rate would be 3 x 10^{-3}, assuming a 2 dB implementation margin.

The L-band link budget for FSK at 1000 bps is shown in Table 12. The baseline link budget is shown in column 1. The resulting C/N_o is 51.6 dB-Hz. This produces an E_b/N_o of 21.6 dB. The required E_b/N_o is 15.5 dB, so the system margin is 6.1 dB. This allows the DCP transmitter power to be reduced, since we don't need such a large margin. The link budget with reduced power appears in column 2 of Table 12. The total C/N_o is 48.5 dB-Hz which produces the required 18.5 dB E_b/N_o. The DCP transmitted EIRP is 17.8 dBW. Assuming an antenna gain of 17 dBi, the DCP transmitter power is 0.8 dBW or 1.2 W. For an omni-directional antenna with a gain of 9 dBi, the DCP transmitter power would be 8.8 dBW or 7.6 W. The link budget for the case when L-band is used only for fixed and transportable terminals is shown in column 3 of Table 12. The resulting C/N_o is 44.0 dB-Hz and the E_b/N_o is 14.0 dB. This is less than the required 15.5 dB. For an E_b/N_o of 14.0 dB, the bit error rate is 1 x 10^{-4}.

11.4 COMMAND LINK BUDGETS

The link budget for the base station to DCP UHF link for FSK at 1000 bps is shown in Table 13. The total C/N_o is 51.3 dB-Hz which yields an E_b/N_o of 21.3 dB. An error probability of 10^{-5} requires an E_b/N_o of 15.5 dB, so the margin is 5.8 dB. For this link, there is no advantage to the DCP in reducing the power levels.

TABLE 11

DCP to Base Station L-Band Link Budget
DMSK at 2400 bps

Uplink				
Satellite G/T	0.3	0.3	0.3	dB/K
EIRP/Carrier	20.7	18.3	8.9	dBW
Path Loss	189.3	189.3	189.3	dB
Fade Margin	4	4	4	dB
C/N_o	56.3	53.9	44.5	dB-Hz
Downlink				
EIRP/Carrier	8.6	5.7	8.6	dBW
Path Loss	206.3	206.3	206.3	dB
G/T	25.9	25.9	25.9	dB/K
C/N_o	56.8	53.9	56.8	dB-Hz
Interference (C/I)				
Intermod and Energy Spread				
Uplink	22.8	20.4	22.8	dB
Downlink	22.8	20.4	22.8	dB
Other Sources				
Downlink	26.8	24.4	26.8	dB
Bandwidth	5	5	5	kHz
C/N_o Total	51.6	49.0	44.0	dB-Hz
E_b/N_o Resulting	17.8	15.2	10.2	dB
E_b/N_o Required	12.2	12.2	12.2	dB
Margin	5.6	3.0	-2.0	dB

TABLE 12

DCP to Base Station L-Band Link Budget
FSK at 1000 bps

Uplink

Satellite G/T	0.3	0.3	0.3	dB/K
EIRP/Carrier	20.7	17.8	8.9	dBW
Path Loss	189.3	189.3	189.3	dB
Fade Margin	4	4	4	dB
C/N_o	56.3	53.4	44.5	dB-Hz

Downlink

EIRP/Carrier	8.6	5.2	8.6	dBW
Path Loss	206.3	206.3	206.3	dB
G/T	25.9	25.9	25.9	dB/K
C/N_o	56.8	53.4	56.8	dB-Hz

Interference (C/I)

Intermod and Energy Spread				
Uplink	25	22.1	25	dB
Downlink	25	22.1	25	dB
Other Sources				
Downlink	29	26.1	29	dB
Bandwidth	3	3	3	kHz
C/N_o Total	51.6	48.5	44.0	dB-Hz
E_b/N_o Resulting	21.6	18.5	14.0	dB
E_b/N_o Required	15.5	15.5	15.5	dB
Margin	6.1	3.0	-1.5	dB

The L-band command link budget appears in Table 14. Column 1 is the link budget assuming that L-band provides service for mobiles and fixed terminals. The total C/N_o is 53.2 dB-Hz which corresponds to an E_b/N_o of 23.2 dB. For an error probability of 10^{-5}, an E_b/N_o of 15.5 dB is required. Therefore, the system margin is 7.7 dB.

Column 2 of Table 14 is the link budget assuming that L-band provides service only to fixed terminals. Note that the downlink EIRP is increased by 5 dB over the value used in [15]. This is necessary for a link C/N_o of 48 dB-Hz for voice service. In this case, the resulting C/N_o is 45.9 dB-Hz. This produces an E_b/N_o of 15.9 dB, which produces a margin of 0.4 dB. To increase the performance of this link, the power transmitted by the base station into the satellite could be increased. This would also increase the EIRP of the downlink. This method would be more expensive for the DCP user because more satellite UHF power would be used, so the charge for the service would be more. It is not practical to reduce the power required by using a higher gain antenna without significantly increasing the cost of the antenna.

TABLE 13

Base Station to DCP UHF Link Budget
FSK at 1000 bps

Uplink	
Satellite G/T	-3.0 dB/K
EIRP/Carrier	40.1 dBW
Path Loss	206.8 dB
C/N_o	58.9 dB-Hz
Downlink	
EIRP/Carrier	26.5 dBW
Path Loss	183.2 dB
Receiver G/T	-13.4 dB/K
Fade Margin	4 dB
C/N_o	54.5 dB-Hz
Interference (C/I)	
Intermod and Energy Spread	
Uplink	33.8 dB
Downlink	23.8 dB
Other Sources	
Downlink	33.8 dB
Bandwidth	56 kHz
C/N_o Total	51.3 dB-Hz
E_b/N_o Resulting	21.3 dB
E_b/N_o Required	15.5 dB
Margin	5.8 dB

TABLE 14

Base Station to DCP L-Band Link Budget
FSK at 1000 bps

Uplink

Satellite G/T	-3.0	-3.0	dB/K
EIRP/Carrier	40.1	40.1	dBW
Path Loss	206.8	206.8	dB
C/N_o	58.9	58.9	dB-Hz

Downlink

EIRP/Carrier	32.3	18.6	dBW
Path Loss	188.2	188.2	dB
G/T	-8.4	-8.4	dB/K
Fade Margin	4	4	dB
C/N_o	60.3	46.6	dB-Hz

Interference (C/I)

Intermod and Energy Spread			
Uplink	32	32	dB
Downlink	22	22	dB
Other Sources			
Downlink	32	56.0	dB
Bandwidth	3	3	kHz
C/N_o Total	53.2	45.9	dB-Hz
E_b/N_o Resulting	23.2	15.9	dB
E_b/N_o Required	15.5	15.5	dB
Margin	7.7	0.4	dB

12.0 MAINTENANCE

Many DCPs are located in areas which are not easily accessible. Therefore, it is desirable that the data collection platforms never or seldom require maintenance. However, if a DCP remains in the field long enough, it will eventually require maintenance. The design of the DCP system should aim to increase the maintenance internal as much as is practical. There are three items which are most likely to require maintenance:

1) replacement of the battery
2) retuning the transmitter oscillator
3) repairing malfunctioning electronic components

The frequency of battery replacement depends on the transmitter power, the stand-by power (power drain between transmissions), the recharging system, and the battery size. The transmitted power should be made as low as possible in the system design. The use of as high a gain antenna as possible will keep the required transmitter power to a minimum.

The life of the battery can be prolonged by using a recharging system. The energy for recharging must come from the elements, such as wind or solar power. The recharging system also must be able to supply more than the average power requirement of the DCP. Any recharging system is vulnerable to energy shortages, e.g. extended cloudy periods or periods when there is little wind.

The life of a battery system can be extended by using a larger battery or using batteries in parallel. Use of this method depends on any size limitation of the particular application or the user's budget constraints.

The drifting of the transmitter oscillator causes two problems. First, the frequency error causes poorer performance at the receiver, resulting in more errors in the data. The use of coding will allow a larger frequency variation before the effect becomes noticeable, but the increase in the tolerable frequency drift will be small since the degradation in performance is exponential (see Figure 7 [16]). We will attempt to design the system so that it is not necessary to correct for frequency drift more frequently than once a year.

Electronic failures cannot entirely be eliminated in the DCP. One method of increasing reliability is to use redundancy. This method is too expensive for use with DCPs. Reliability can best be increased by using high quality components. The mean time between failures of DCPs should be designed to be greater than the maintenance (for adjustment purposes) interval.

The maintenance program need not be rigorously adhered to. The most important maintenance items are oscillator drift and battery voltage. The oscillator drift can be monitored at the base station so that retuning is not performed until necessary. The battery voltage can be monitored by the DCP and transmitted occasionally, e.g. weekly. These techniques can ensure that the DCP does not receive attention unnecessarily. Microprocessor control of the DCP electronics makes available processing power which is not totally used in the normal DCP activities. This extra processing power could be used to occasionally perform self-diagnostic tests in order to detect impending malfunctions.

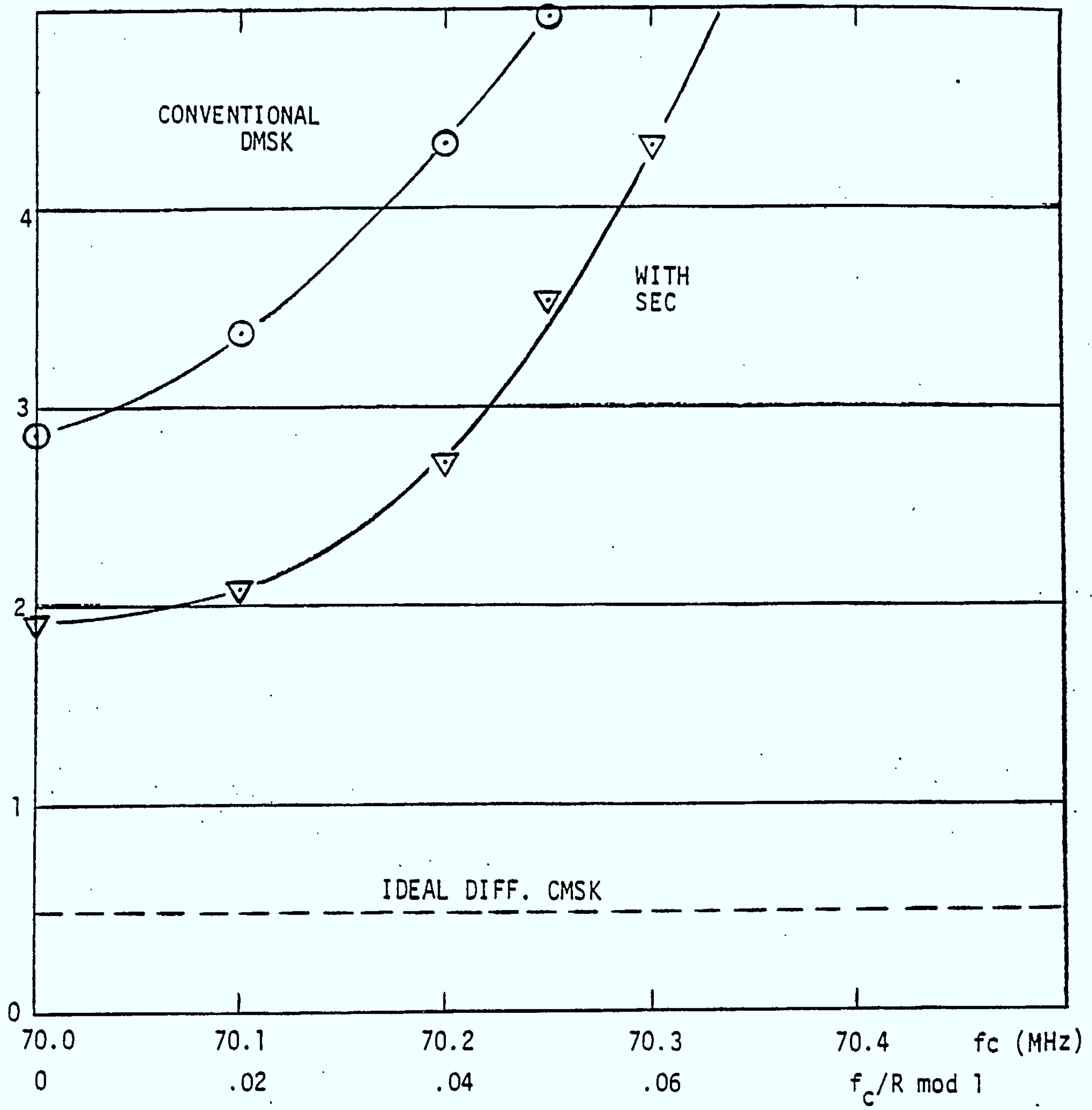


Figure 7 : The Effect of Carrier Frequency Offset on Bit Error Rate Degradation

Data collection platforms used with the GOES system must have an automatic shut down feature that prevents the transmitting from operating continuously [9]. This feature is desirable for the MSAT DCP system as well, since a single channel will be shared by all users which means that a continuously operating transmitter would destroy the other DCP transmissions.

13.0 DCP COSTS

The cost of the data collection platforms will be a factor in determining how successful the MSAT DCP service is. The cost is particularly important for MSAT as compared with the GOES or ARGOS services since the MSAT service is intended to be profitable. A low cost data collection platform should stimulate the market and decrease the overall cost of the service to each user. This section contains estimates of the costs of DCPs.

13.1 UHF DCP COSTS

The cost of a DCP can be broken down into two parts: non-recurring costs and recurring costs. Non-recurring costs refer to one-time costs such as engineering design and equipment costs. Recurring costs are involved every time a DCP is manufactured. Included are material costs, assembly costs, labour costs, overhead costs, etc. A large production run is important to reduce the non-recurring cost per DCP and the material costs. The size of the production run is dependent upon the MSAT DCP market size and the number of DCP manufacturers in the MSAT market.

The non-recurring costs for an MSAT two-way interactive data service terminal were estimated as $200,000 in [3] for a production run of 1,000 units. This cost includes pre-production engineering and capital equipment. The total non-recurring costs for a two-way interactive data terminal was estimated to be $400,000 for quantity 10,000. The increased cost is due to extra equipment needed to make the larger production run. The quantity of DCPs produced for MSAT service is expected to be much less than 10,000. The price increase applied to each DCP produced to offset non-recurring costs would be chosen by the manufacturer depending on the number of DCPs the manufacturer expected to sell over the amortization period.

The non-recurring costs for quantity 1000 production was estimated to be $200,000. The cost per DCP would be $200.

The material costs for quantity 1000 estimated in [3] are shown in Table 15. These costs are for a transmit-only DCP using an MSAT-transmitted pilot for frequency control. Material costs include scrap rate factor, duty, exchange, transportation, and material handling. For quantity 1000, the material costs are estimated at $1,800. A larger production run decreases the material cost. The material cost for quantity 1000 is scaled for different quantities. The scaling factors are assumed to be 1.6, 1.5, and 0.8 for runs of 10, 100, and 10,000.

Labour costs are estimated to be 33% of the material costs. Labour costs include fabrication, assembly, and testing. Wholesale costs are estimated to be 15% above factory costs (material and labour) and retail cost is estimated to be 30% above wholesale cost. The retail price of DCPs is estimated to be $5668 in quantity 100 and $3878 in quantity 1000.

The cost of a receiver is extra for a two-way DCP. All the other parts are the same as for the one-way DCP. The receiver for a DCP service would essentially be the same as for an MSAT data terminal. In [3], the material cost of the receiver is estimated as $734 in quantity 500. Scaled for a 100 terminal quantity, the cost becomes $1101. Adding labour, wholesale, and retail costs increases the two-way cost $2140 above the cost of a one-way DCP. The cost would, therefore, be $7808 per DCP in quantity 100.

P. Williams of Bristol Aerospace of Winnipeg considers the DCP cost of [3] to be incomplete. The costs presented would be for a data logger. Omitted were the costs of electronics for gathering the data and passing it to the

TABLE 15

Material Costs For An MSAT UHF DCP

Transmitter	$500
Antenna*	$400
Modulator	$300
Logic Unit	$50
Control Unit	$100
Pilot Reference	$350
Enclosure	$100
	$1800

* The antenna has a 4 dBi gain. The $400 material cost assumed for such a low gain antenna seems unreasonable. A more likely cost is $50.

data logger. He estimates the additional cost of the electronics to be $2500 to the retail cost.

The material cost of the DCP antenna was estimated to be $400 in [3]. Scaling the cost to the retail level produces a cost of $1244 in quantity 10. According to P. Williams, the cost of an antenna for a GOES DCP adds approximately $450 to the price of a unit. We assume that the cost of an MSAT UHF or L-band antenna will be approximately the same.

After adding the cost of the electronics, and decreasing the cost of the antenna, the retail price of a transmit-only UHF DCP with a frequency control receiver would be $7425 in quantity 100.

The cost of a transmit-only UHF DCP with a frequency control receiver and an omni-directional antenna of material cost $50 would be $7124 in quantity 100.

Adding the $2500 extra cost to the cost of a UHF two-way DCP and reducing the antenna price to $450 (retail) yields a retail cost of $9614 for a two-way DCP in quantity 100.

13.2 L-Band DCP Costs

The components of an L-band DCP will cost approximately the same as those of a UHF DCP with the exception of the HPA. The cost of this component is estimated to be 50% higher than its UHF counterpart [17]. The material cost of the transmitter is estimated to be $1125 in quantity 100. Therefore, the cost of an L-band transmit-only DCP is $8170 in quantity 100. The cost of a transmit-only L-band DCP with an omni-directional antenna would be $7869 in quantity 100.

The cost of an L-band two-way DCP is estimated to be $10,360 in quantity 100.

13.3 COST OF TIME AND FREQUENCY REFERENCES

To estimate the cost of a circuit that derives a frequency reference from an external source such as GPS or LORAN C is difficult since low-cost circuits of this kind have never been produced in large quantity.

A timing receiver marketed by Accutron that uses LORAN-C as a reference costs $11,000 (U.S.). This timing receiver is intended to be the core of an accurate timing reference. The high cost is due to the complex circuitry required to maintain the accuracy of the LORAN-C system and due to the low volume production. This indicates that there is some development work that must be performed before it would be practical to use LORAN-C as a time or frequency reference.

Currently, LORAN-C receivers can be brought for less than $1,000. Future reductions in the price of LORAN-C receivers should be relatively small since the market is limited in size. GPS receivers have a much larger market since GPS is not limited to navigation for ships as LORAN-C is. The cost of a LORAN-C timing receiver would not include the cost of the display or the enclosure (since the DCP enclosure would be used). The internal circuitry would be essentially the same since a standard LORAN-C receiver uses the signals from 3 stations to determine longitude, latitude, and time.

The cost of a GPS receiver manufactured by Accutron is approximately $23,000 (U.S.). This cost is very high because the receivers have been developed recently, so development costs have to be recovered, and because the GPS system is not yet fully operational, so the demand for receivers is low. By the year 2,000, the price for a receiver is expected to be below $500 (U.S.).

The NRC signals transmitted via radio station CHU can be received by a standard shortwave radio. The cost of a receiver then, would be very low. The major portion of a timing reference receiver using station CHU transmissions would be the electronics necessary to extract the timing information from the received signal.

Since a pure carrier signal is sent in the CHU transmissions, a frequency reference would also be inexpensive to obtain. One concern about operating a frequency reference circuit which is tuned to one of the CHU transmission frequencies is that the tuning circuit will drift with time. This is easily compensated for by using the frequency reference signal obtained from the CHU transmission to correct the tuner. As long as the receiver is initially tuned to one of the CHU frequencies, the circuit is self-correcting.

The cost of a timing reference circuit which uses radio station CHU transmissions should be less than the cost of a circuit which derives a frequency reference from an MSAT-transmitted signal. The major cost component of the circuit is likely to be the crystal oscillator which is corrected by the radio signals. The price of a 10 MHz CMOS clock oscillator with an accuracy of ±50 ppm over a temperature range of -55°C to +85°C and an aging rate of 5 ppm was quoted by Vectron to be $97 U.S. in quantity 1 and $38 U.S. in quantity 100. The circuitry to demodulate the CHU radio signal will be very low in cost, since shortwave radios are mass produced. We will conservatively estimate the total cost of the reference circuitry including oscillator to be twice the cost of the oscillator or $76 (U.S.). We multiply this value by 1.4 to get Canadian dollars, so the price of the reference circuit would be $106. Deleting the cost of the pilot reference circuit and adding the cost of the NRC reference circuit yields a transmit-only UHF DCP cost of $6,487 in quantity 100.

14.0 MARKET DATA

Woods Gordon, in 1984, surveyed the market for data collection platforms. The majority of the major users were Federal Government Departments. Their estimate of the number of fixed DCPs operating on MSAT in 1988 was 50 to 100 and 1100 to 1700 in the year 2001. Woods Gordon also surveyed potential users of MSAT for remote control and sensing. They concluded that the size of this market in Canada is relatively small.

The market for data collection platforms in Canada was estimated by one manufacturer as 800 in the year 1990, 100 in the year 1995. and 1300 in the year 2000, (see Appendix C). Another Canadian manufacturer estimated the potential Canadian market for DCPs at between 3025 and 4010. This potential would not likely be fully realized since other competing technologies would capture some of the market, as well as other DCP networks using existing satellites which could be set-up before MSAT is operational.

This market estimate shows that the potential number of data collection platforms in Canada is expected to be between 1300 and 4000. All of the needs of Canadian DCP users should be adequately served using a single dedicated random access channel for the first generation MSAT system.

15.0 CONCLUSIONS

It is difficult to achieve both high capacity in a DCP network and low cost. The two most promising network configurations are: 1) the DCPs transmit using DMSK modulation at 2400 bps and a random access scheme, and 2) FSK transmission at 1000 bps using a TDM access scheme. The disadvantage of a random access scheme is low capacity and a lower probability of successful packet transmission. The disadvantage of the TDM access scheme is the need to use timing signals and the associated cost of a receiver. Although a timing receiver based on radio station CHU signals would be inexpensive, the accuracy of the signal would be degraded due to propagation uncertainties. A timing reference based on GPS signals would not have this problem since GPS transmits propagation correction information with its signals. A GPS receiver, however, is likely to cost more than one based on CHU transmissions. A disadvantage common to both these methods would be the dependency of the MSAT DCP system on signals controlled by an independent agency.

If DMSK at 2400 bps is used as the transmission modulation by DCPs, then the capacity of a random access system should be sufficient to meet the needs of Canadian users.

The recommended DCP system uses DMSK at 2400 bps for the transmit-only DCPs and FSK at 1000 bps for the command link of the two-way DCPs. The transmit-only DCPs use random access to share a single, dedicated channel.

The message format for a data transmission consists of:

1) a 64 bit preamble for automatic frequency control and bit timing recovery for DMSK and a 130 bit preamble for FSK

2) an 8 bit unique word
3) a 13 bit address code
4) a 4 bit word indicating the number of 16 bit data words to be transmitted
5) a 16 bit to 256 bit block of data
6) a (15,11) BCH code is applied to items (3) to (5), above, to provide error detection and correction.

The message format for transmission from a base station to a DCP for two-way operation consists of items (1) to (3), above, plus an 8 bit command word. A single parity bit is used for error detection. A positive acknowledgement scheme is used between DCP and base station to ensure message reception.

The message frequency used by DCPs should be as frequently as desired by the user with a correspondingly higher cost for more frequent transmissions.

The price of a transmit-only DCP is expected to be $7425 in quantity 100 and the price of a two-way DCP is expected to be $9614 in quantity 100.

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APPENDIX A

SHORT TERM FREQUENCY STABILITY FOR DMSK

This appendix contains a summary of the analysis of [A.1] which computes the oscillator short term frequency stability specification for DMSK.

The oscillator model of a gateway-to-mobile terminal link is shown in Figure A.1. The short term frequency stability is calculated for this link because it is the worst case. Note that this analysis is for a mobile remote terminal rather than a DCP. The mobile terminal results will be interpreted for a DCP.

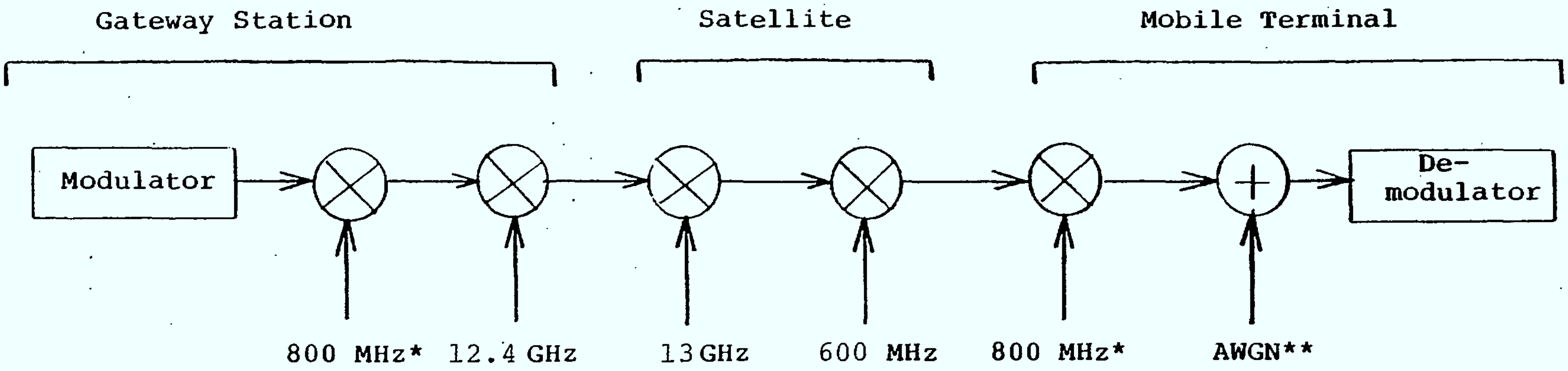
The model of Figure A.1 has been altered slightly from that of [A.1]. The intermediate frequency at the satellite is approximately 200 MHz [A.2], so the second local oscillator at the satellite is approximately 600 MHz. Also, the SHF local oscillator frequencies are more exact than those of [A.1].

It is assumed that all local oscillators are derived from a 10 MHz crystal oscillator and frequency multipliers are assumed to be ideal, i.e. single sideband phase noise is enhanced by 20 log N dB where N is the multiplication factor.

The model of Figure A.1 can be simplified to a single frequency multiplication. This is shown in Figure A.2. The value of N is:

$$\sqrt{(800/10)^2 + (12400/10)^2 + (13000/10)^2 + (600/10)^2) + (800/10)^2}$$
$$= 1801$$

We assume that the effects of thermal noise and oscillator noise are additive prior to the threshold detector in the DMSK demodulator. The probability of error is then:



* Synthesized Signal Source

** AWGN = Additive White Gaussian Noise (Front End Thermal Noise)

⊗ Frequency Translator (mixer)

⊕ Adder

Figure A.1 Gateway Station to Mobile Terminal Link

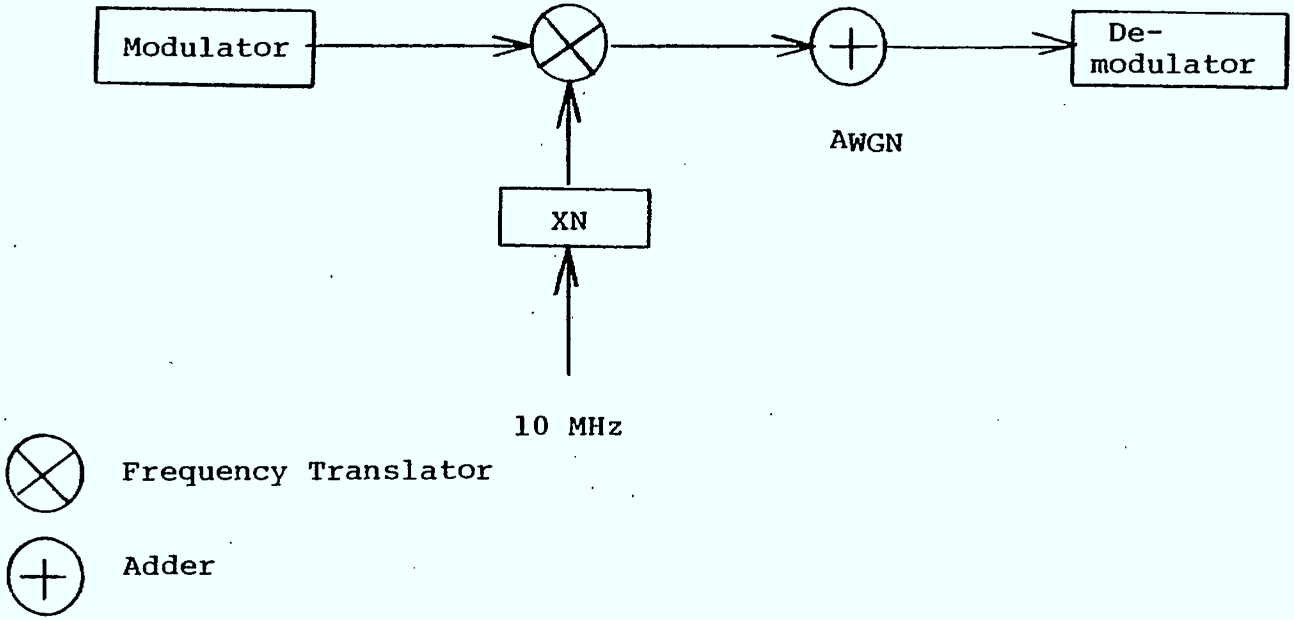


Figure A.2 Simplified System Model

$$P(e) = 1/2 \exp\left[-1/(K\Delta\phi_T^2 + K\Delta\phi_{LO}^2)\right]$$

where $\Delta\phi_{LO}^2$ is the mean square phase deviation (rad^2) resulting from local oscillator phase noise after weighting

$\Delta\phi_T^2$ is the mean square phase deviation due to additive thermal noise. It is equivalent to N_o/E_b if the bandwidth of the received carrier after IF filtering is equal to the bit rate.

K is the numerical value of an implementation margin.

An approximation to the transfer function for the DMSK demodulator is shown in Figure A.3. The transfer function is given in [A.3].

The effect of $\Delta\phi_{LO}^2$ on the bit error rate of DMSK is shown in Figure A.4 for different values of K. With a K of 2 dB, a mean square phase deviation of 0.002 rad^2 on the carrier due to local oscillator noise causes a degradation of 0.2 dB at a P_e of 10^{-6}.

We will assume that a 0.2 dB degradation is the most that we will allow at a P_e of 10^{-6}, i.e. $\Delta\phi^2 \leq 0.002$ rad^2. We can compute the single sideband phase noise.

$$\Delta\phi_{LO}^2 = 2\,\eta_o^2\,(F_2 - F_1) \leq 0.002 \text{ rad}^2$$

where η_o is the single sideband phase noise density

F_2 is the highest frequency on the straight line of interest

F_1 is the lowest frequency on the straight line of interest

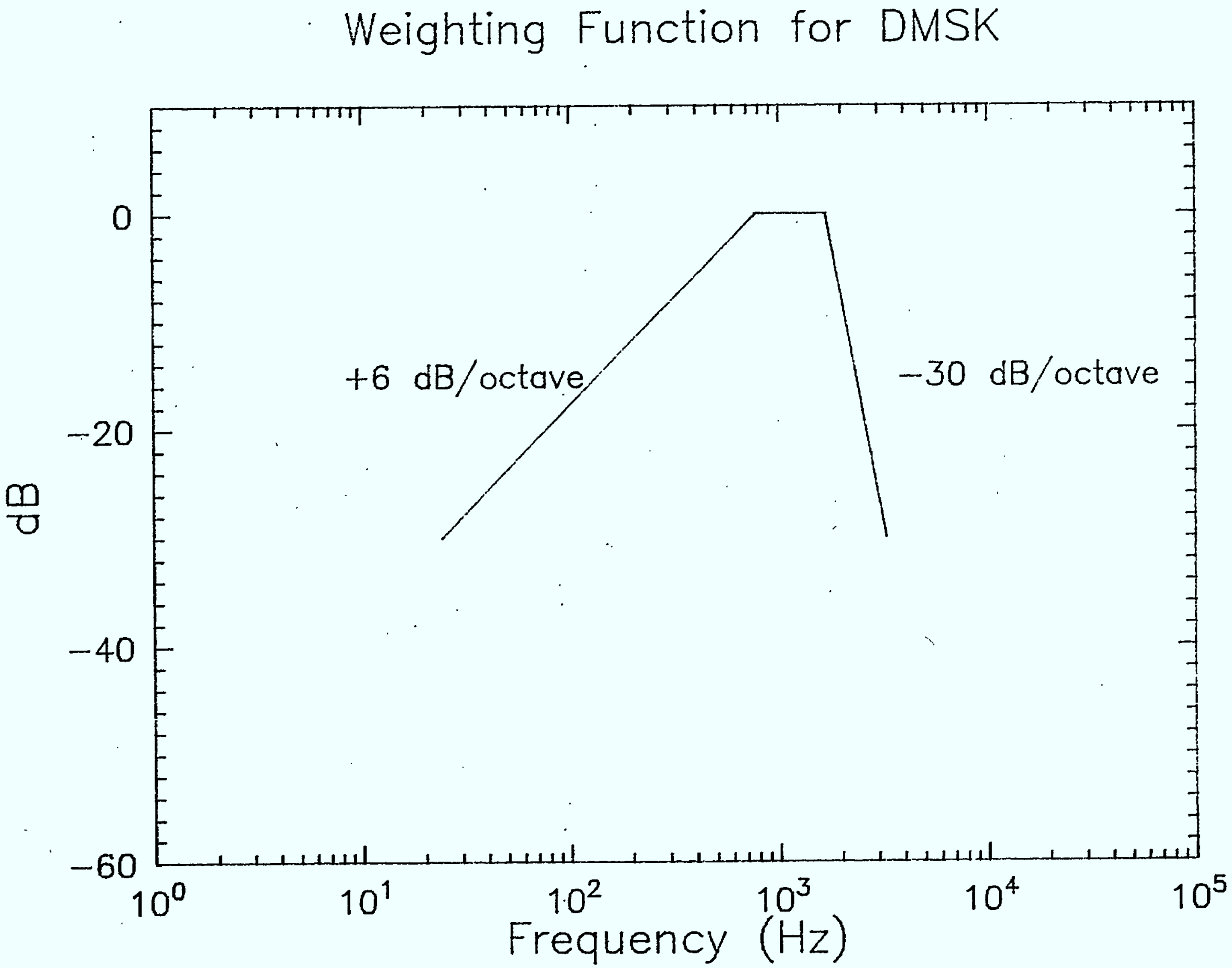

Weighting Function for DMSK
dB
0
−20
−40
−60
+6 dB/octave
−30 dB/octave
10^0
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)

Figure A.3

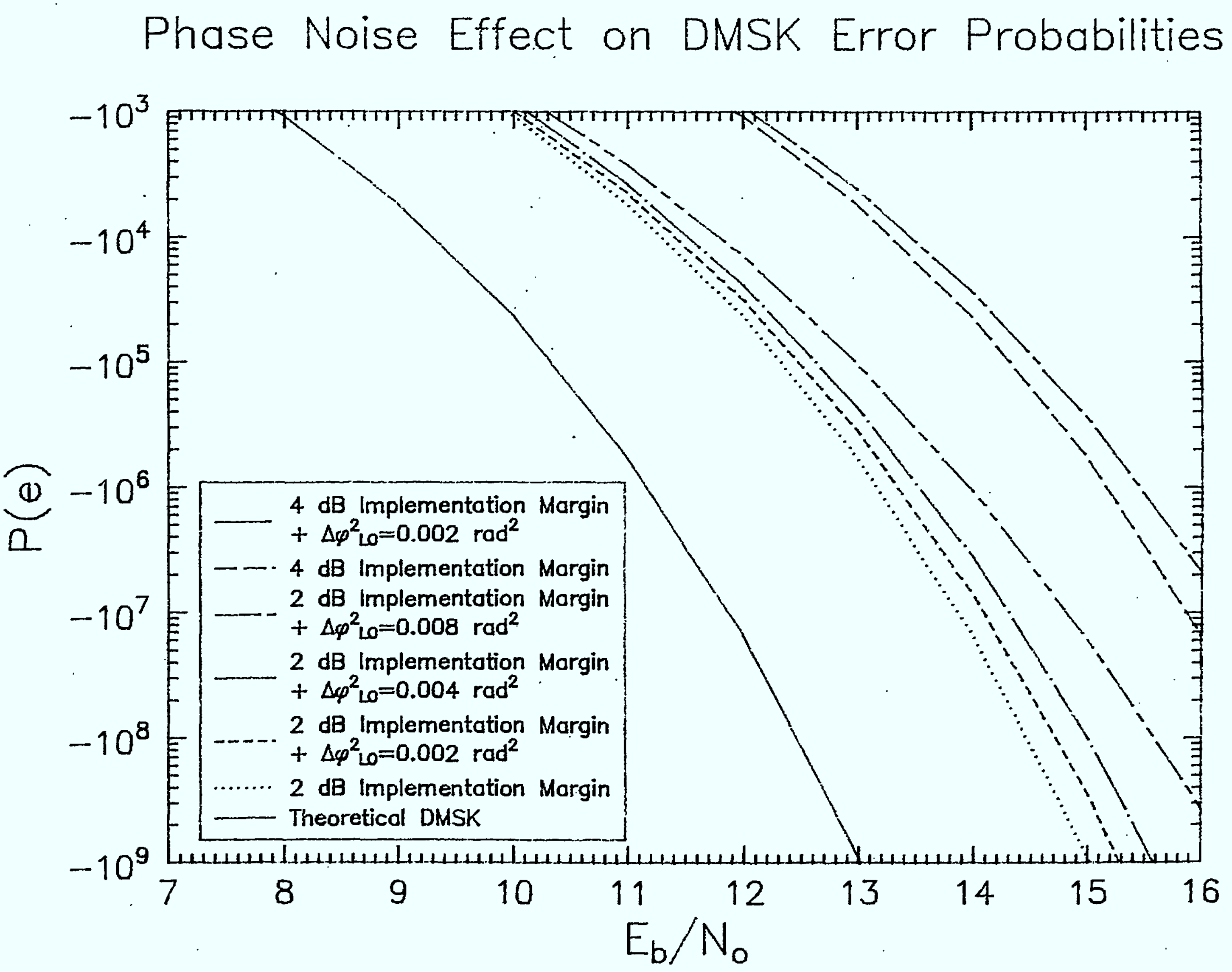

Phase Noise Effect on DMSK Error Probabilities
P(e)
-10^3
-10^4
-10^5
-10^6
-10^7
-10^8
-10^9
7
8
9
10
11
12
13
14
15
16
E_b/N_o
4 dB Implementation Margin + $\Delta\varphi^2_{LO}$=0.002 rad^2
4 dB Implementation Margin
2 dB Implementation Margin + $\Delta\varphi^2_{LO}$=0.008 rad^2
2 dB Implementation Margin + $\Delta\varphi^2_{LO}$=0.004 rad^2
2 dB Implementation Margin + $\Delta\varphi^2_{LO}$=0.002 rad^2
2 dB Implementation Margin
Theoretical DMSK

Figure A.4

$F_2 = 1680$ Hz
$F_1 = 10$ Hz

At a frequency offset of 768 Hz,

$$\eta_o^2(768) \leq 0.002/[2(1680-10)] = 5.98 \times 10^{-7}$$

Therefore, the single sideband phase noise should be less than -62.2 dBc/Hz at UHF.

A 10 MHz reference oscillator is used for calculation purposes. The single sideband phase noise density of the oscillator is shown in Figure A.5. When the phase noise is weighted by the DMSK transfer function, the resulting phase noise density is as shown in Figure A.6. Because this plot is almost flat with frequency, it is assumed to be constant with frequency. The resulting approximation is shown in Figure A.7. The resulting error caused by using this approximation has been calculated to be 2 dB.

At 10 MHz the single sideband phase noise must be 63 dB better when we consider the 65 dB conversion factor and the -2 dB correction factor from flattening the spectrum of Figure A.6.

The requirement for the 10 MHz reference oscillator becomes: SSB phase noise density $\leq$-125 dBc/Hz at 768 Hz offset.

This phase noise specification is the total phase noise for all the oscillators in Figure A.1. The phase noise must now be allocated amongst the oscillators. The allocation of phase noise must be done in accordance with the degree of difficulty in achieving the required specification. SHF fixed oscillators will have the noise sidebands enhanced due to the high frequency. The noise increase due to frequency for UHF synthesizers will not be

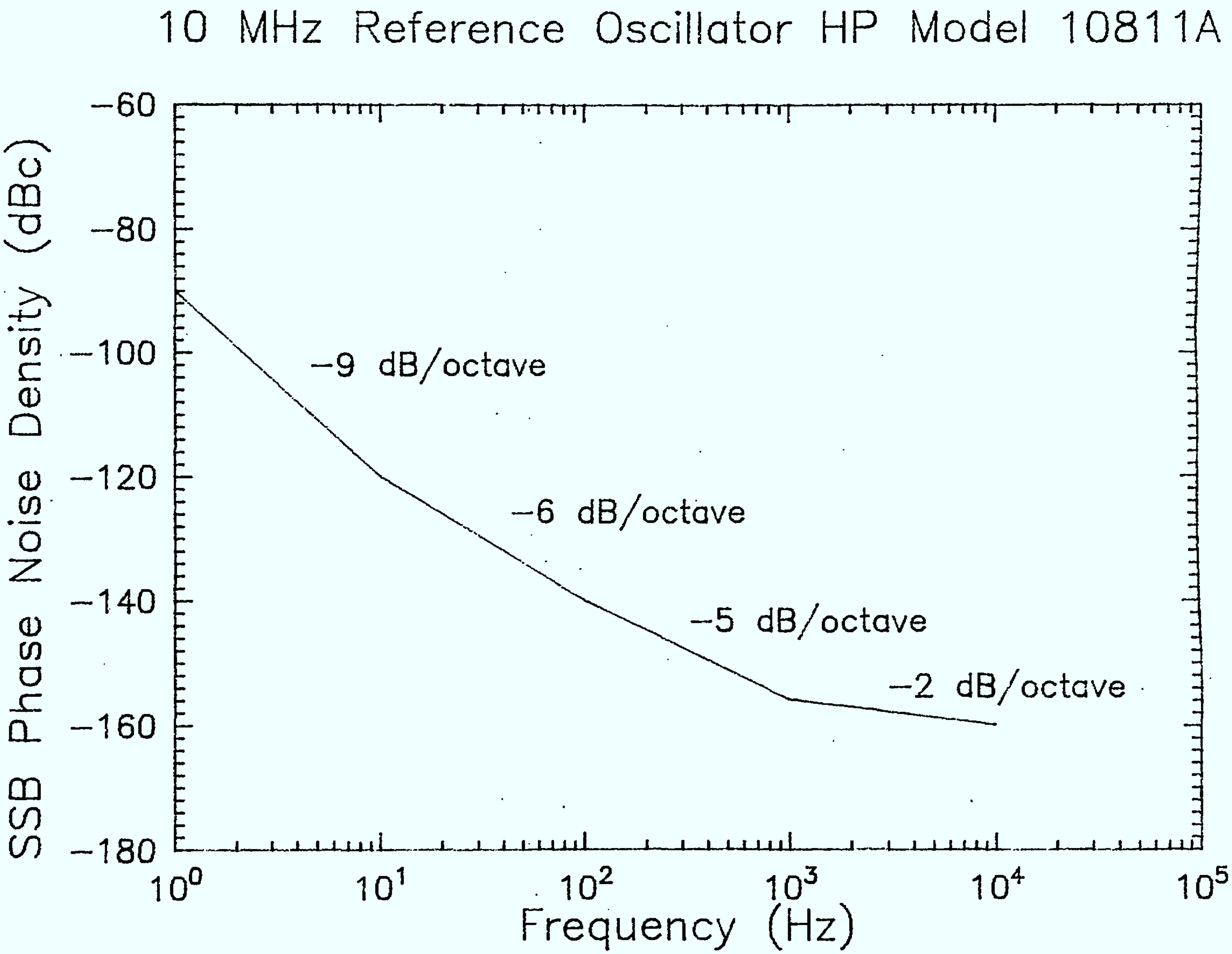

10 MHz Reference Oscillator HP Model 10811A
SSB Phase Noise Density (dBc)
−60
−80
−100
−120
−140
−160
−180
10^0
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)
−9 dB/octave
−6 dB/octave
−5 dB/octave
−2 dB/octave

Figure A.5

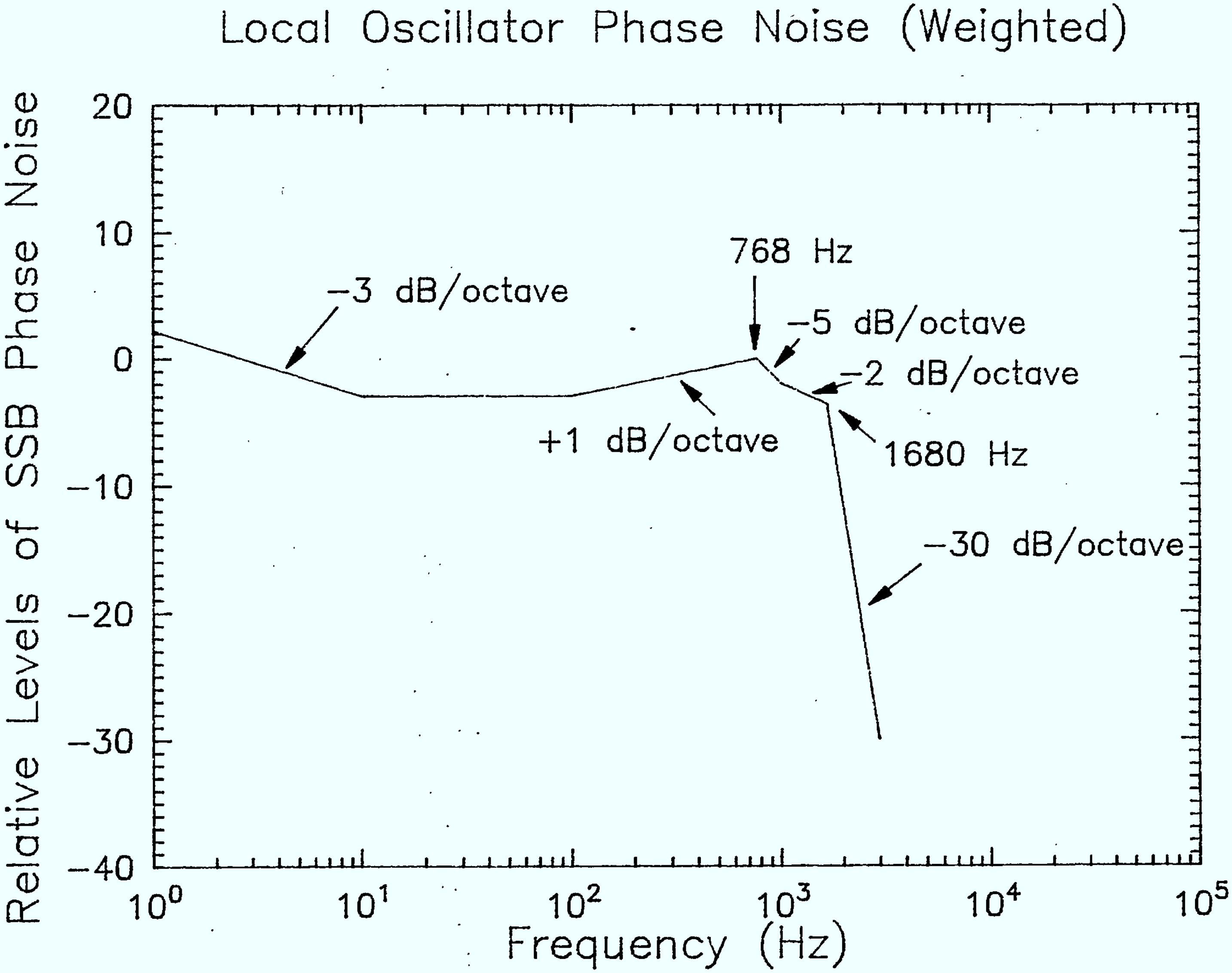

Local Oscillator Phase Noise (Weighted)
Relative Levels of SSB Phase Noise
Frequency (Hz)
20
10
0
−10
−20
−30
−40
10^0
10^1
10^2
10^3
10^4
10^5
−3 dB/octave
+1 dB/octave
768 Hz
−5 dB/octave
−2 dB/octave
1680 Hz
−30 dB/octave

Figure A.6

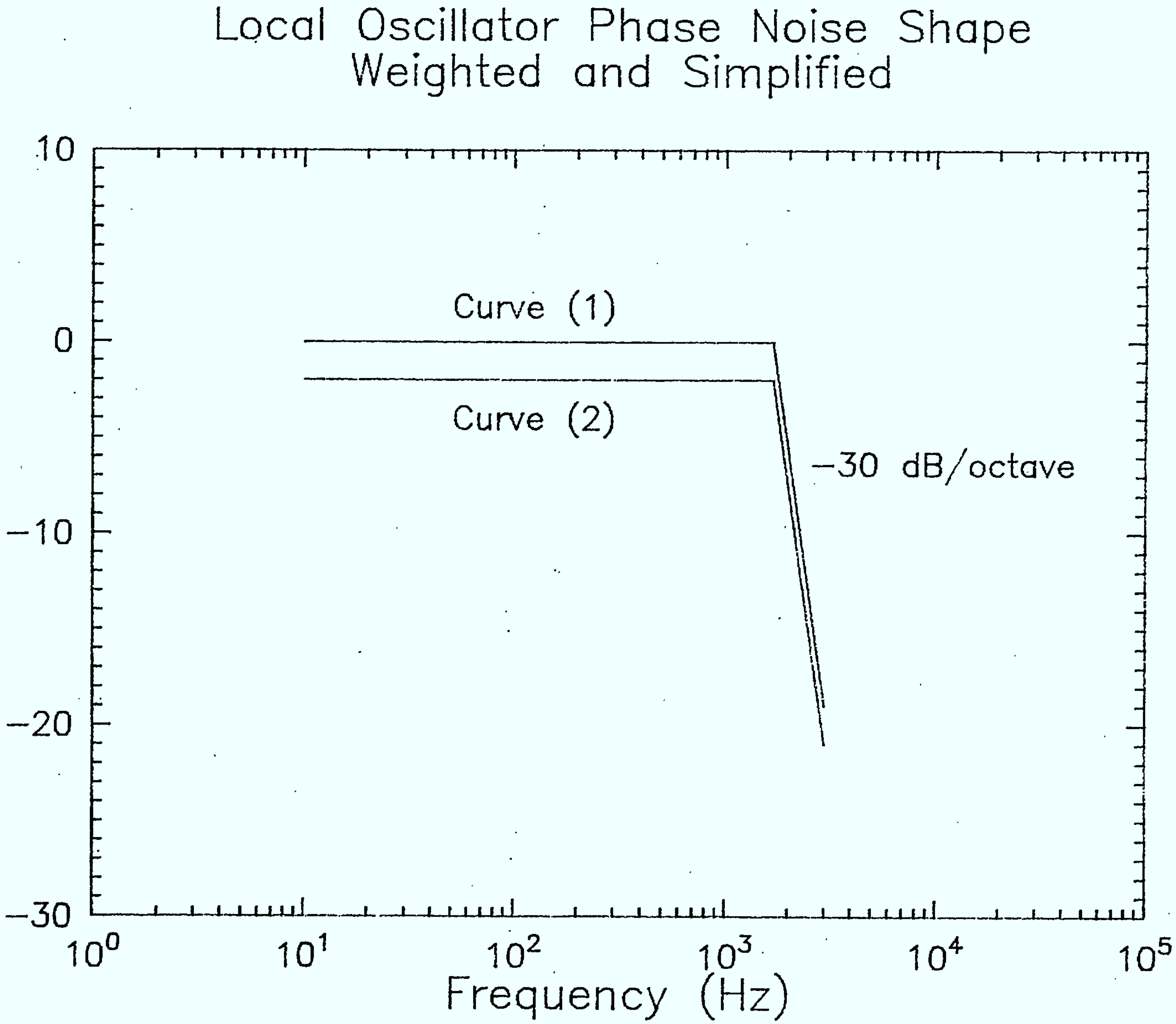

Local Oscillator Phase Noise Shape
Weighted and Simplified
10
0
−10
−20
−30
dB
Curve (1)
Curve (2)
−30 dB/octave
10^0
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)

Figure A.7

as great as that for SHF oscillators, but the noise will be enhanced due to the electronic circuits of the synthesizer. A tentative allocation is to divide the noise equally among the SHF oscillators and UHF synthesizers.

The analysis of [A.1] assumed that MTS would use NBFM for compatibility with the terrestrial system. The short term requirement for NBFM defined the SHF local oscillatory short term specification. Since it is now assumed that MTS will use ACSSB, the SHF requirement of [A.1] does not apply.

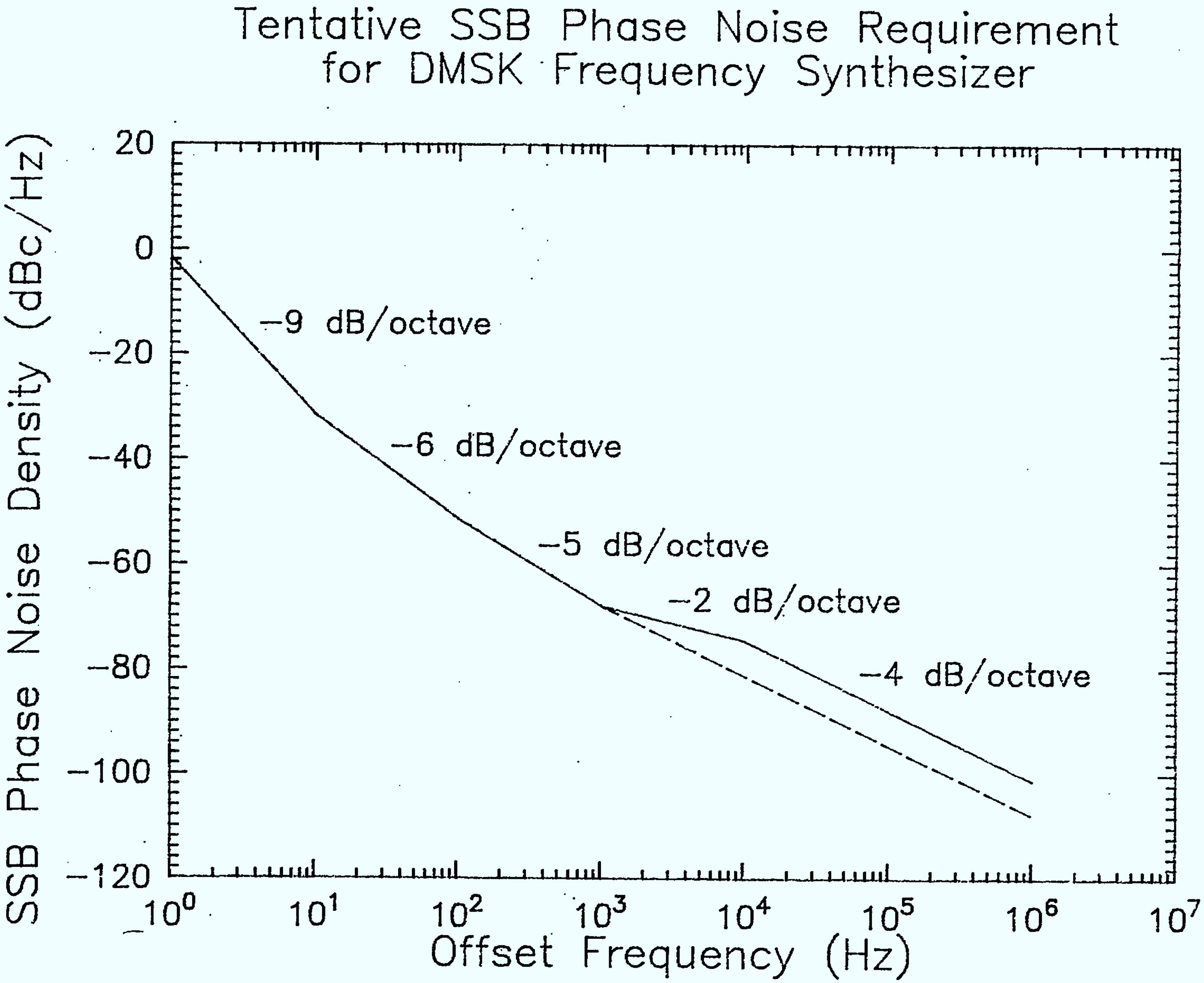
The total phase noise for DMSK was computed to be -62 dBc/Hz at 768 Hz to give a 0.2 dB degradation at $P_e = 10^{-6}$. We allocate the phase noise in the system as:

UHF synthesizer	-68 dBc/Hz at 1 kHz
SHF oscillator	-68 dBc/Hz at 1 kHz

The phase noise density at 1 kHz will be almost the same as at 768 Hz.

The remaining oscillator in the system is the fixed UHF oscillator. The phase noise of this oscillator will be negligible compared with the other oscillators in the system. The oscillator tentatively assigned a phase noise density of -90 dBc/Hz at 1 kHz.

The slope of the single sideband phase noise requirement across the frequency band is taken from the 10 MHz reference oscillator (Figure A.5). The resulting specification is shown in Figure A.8. The portion of the curve from 10 kHz to 1.5 MHz has been given a falling slope of -4 dB/octave to minimize the additive effects of local oscillator noise in a multicarrier environment. To further reduce this effect, the slope of the curve from 1 kHz to 10 kHz will be increased from -2 dB/octave to -4 dB/octave.



Tentative SSB Phase Noise Requirement
for DMSK Frequency Synthesizer
SSB Phase Noise Density (dBc/Hz)
20
0
−20
−40
−60
−80
−100
−120
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
Offset Frequency (Hz)
−9 dB/octave
−6 dB/octave
−5 dB/octave
−2 dB/octave
−4 dB/octave

Figure A.8

Calculation of the increase in the phase noise density at 1 kHz in a 100 carrier system was done for the carrier in the centre (worst case). The results showed that it was necessary to decrease the phase noise density by 3 dB. This was done for all frequencies.

Figure A.8 shows the final recommended practical phase noise specifications (dotted line).

L-Band

The model of the mobile to gateway link for L-band is shown in Figure A.9. It is assumed that the satellite I.F. is 200 MHz, as for UHF. The simplified model, as shown in Figure A.2, uses a value of N of:

$$\sqrt{(1600/10)^2 + (11600/10)^2 + (13000/10)^2 + (1400/10)^2 + (1600/10)^2}$$
$$= 1762$$

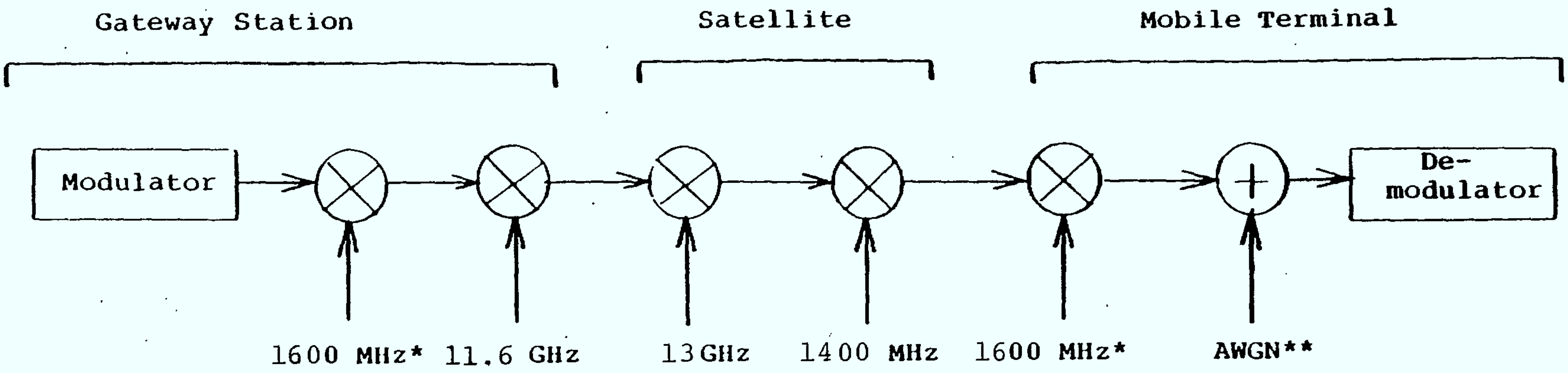
The difference between this number, and the UHF number, 1801, is so small that it can be considered negligible. Therefore, the UHF analysis applies exactly to the L-band case.

References

A.1 "Study of a Frequency Control System and Prototype Development of Frequency Sources and Synthesizers for the Mobile Satellite (MSAT) System Mobile Terminals Phase I Report", Spar Aerospace Limited, Communications Systems Division, Ste. Anne de Bellevue, Quebec.

A.2 Technical memo No. TM-14, Frequency Plan, Spar Aerospace Ltd., Ste-Anne-de-Bellevue, Quebec.

A.3 "Study of Digital Modulation and Multiplexing Techniques Appropriate to the Distribution of Radio Programs by Satellite", Miller Communications Systems Limited, January 3, 1983.



* Synthesized Signal Source

** AWGN = Additive White Gaussian Noise
(Front End Thermal Noise)

⊗ Frequency Translator (mixer)

⊕ Adder

Figure A.9 Gateway Station to Mobile Terminal Link

APPENDIX B

DATA COLLECTION PLATFORM MANUFACTURER SURVEY

In order to determine the requirements of data collection platform users, a questionnaire was sent to manufacturers. The questionnaire included technical and market-oriented questions. The questionnaire was sent to Canadian and American DCP manufacturers.

The results of the questionnaire appear in Tables B.1 and B.2. Table B.1 presents the answers to the technical questions and Table B.2 presents the answers to the market questions.

The companies that responded to the questionnaire are listed below. The companies are not identified in Tables B.1 and B.2 in order to preserve their confidentiality.

Companies

1. Bristol Aerospace Limited
   Winnipeg, Manitoba, 204-775-8331

2. Hermes Electronics Limited
   Dartmouth, Nova Scotia, 902-466-7491

3. Geneq, Inc.
   Montreal, Quebec, 514-354-2511
   (Canadian distribution for Handar of Sunnyvale, California)

4. The Sutron Corporation
   Herndon, Virginia, 703-759-2094

5. Synergetics International Inc.
   Fairfax, Virginia, 703-591-4022

The order in which the companies are listed above is not necessarily the same order in which the responses are given in Tables B.1 and B.2.

A market estimate was solicited from Steel Electronics of Sudbury before the survey of Tables B.1 and B.2 was sent out. The market estimate consists of the potential platforms users would eventually place on a DCP network if it was available now. This estimate is for Canada only and contains non-environmental applications as well as environmental applications. The estimates appear in Table B.3. The total demand is estimated to be between 3025 and 4010 DCPs.

TABLE B.1

Manufacturer Survey
Technical Data

		Co. #1	Co. #2	Co. #3	Co. #4	Co. #5
1.	Satellite system used with DCPs	GOES	ARGOS	GOES ARGOS	GOES	GOES ARGOS
2.	Maximum number of sensors used on DCP (for different models)	35 50 80	16	16 16	16 48	32 8
3.	Average number of sensors used by customer on a DCP	8	3-4	3-4	5	2-8
4.	Maximum number of transmissions per hour by DCP	20	60	1	60	15 60
5.	Average number of transmissions per hour used by customer	1/3 hr	5/day	1/3 hr.	1/3 hr.	1/3 hr.
6.	Manufacture Two-Way DCPs	No	No	Yes	No	Yes
7.	A/D converter precision in bits	8/8/2	12	12	12	8,12,18 8,12
8.	Power Transmission	45 W 45 W 45 W	2 W	8 W -	-	10 mA 505 mA
9.	Power In Standby Mode	0.75 W 0.75 W 0.75 W	0.16 W	0.28 W -	-	3-7 mA 1.3 mA

10. Maintenance required by DCP

Co. #1:	Check sensors with moving parts once per year Battery will last 5 years with solar panel
Co. #2:	Replace battery every 6 months to 1 year
Co. #3:	Recalibrate frequency once per year Batteries last 2 to 3 years with solar panel
Co. #4:	Replace battery every 6 months
Co. #5:	Replace battery every 1-2 years. Calibrate DCP clock annually

Note:

Entries consisting of a dash indicate that the respondent did not answer the question. Questions with more than one answer per company indicate that the company has more than one model of DCP and the answer correspond to different models.

TABLE B.2

Manufacturer Survey
Market Data

	Co. #1	Co. #2	Co. #3	Co. #4	Co. #5
1. Current cost of a DCP (quantity 1)	$7000 9000 10000	$3980	$6000 6000	$3440(US) 2330(US)	$3500-6000(US) $2000-3000(US)
(quantity 100)	5900 7800 8500	-	5500 5500	2752 1864	
2. Projected cost increase by 1990	+15%	-5%	-25%	+15%	+10-40%
by 1995	+15	-	-40%	+25%	+50-100%
3. What percentage of DCP sales involve two-way DCPs	N/A	N/A	5%	N/A	25%*
4. Has market been analyzed	Yes	No	No	Yes	Yes
5. Estimate of the number of DCPs in use in 1990	800			5000(U.S.)	10,000(US)
1995	1000			7000(U.S.)	20,000(US)
2000	1300			10,000(U.S.)	50,000(US)
6. What percentage of DCP demand will be for:					
transmit-only	80%			99.9%	40%
transmit-receive	20%			0.1%	60%

7. What market applications exist for DCPs (transmit-only)

Co. #1: Power utilities, meteorology, hydrology, seismic applications, lightning detection, forest fire detection, dam surveys

Co. #2: Ocean weather stations, Ice beacons, location determination, tracking boats, expeditions, etc, scientific ocean studies

Co. #3: Weather stations, hydrometric stations, forestry, agricultural, oceanographic, industrial monitoring

Co. #4: No answer

Co. #5: Environmental-related

What market applications exist for DCPs (transmit-receive)

Co. #1: Same as answer to question 7

Co. #2: No answer

Co. #3: Weather stations, SCADA (supervisory control and data acquisition)

Co. #4: No answer

Co. #5: Transportation, Utility, Petroleum

*25% of terrestrial-based DCPs sold are two-way

TABLE B.2 (CONTINUED)

Manufacturer Survey
Market Data

	Co. #1	Co. #2	Co. #3	Co. #4	Co. #5

9. Key factors which will influence DCP market:
   Co. #1: Availability of channels for transmission allowing more frequent and longer data transmissions
   Co. #2: No answer
   Co. #3: Cost, lower power, reliability
   Co. #4: Cost
   Co. #5: Cost

TABLE B.3

ESTIMATE OF DCP DEMAND

USERS AND APPLICATIONS		POTENTIAL PLATFORMS
Federal Government		
AES	- remote weather monitoring	250-300
Inland Waters	- lake, stream, river monitoring	200-250
Acid Rain	- So2, NOX remote monitoring	200-250
Coast Guard	- beacons, buoys, lightstations	100-150
Forestry	- aerial spraying, fire control	150-175
Transport	- airport monitoring (generators, etc.)	100-150
External Affairs	- remote border crossings, etc.	10-20
Security	- site monitoring	15-20
C.B.C.	- remote relay site monitoring	25-30
Provincial Governments		
	- flood forecasting, water management	200-250
	- forestry management	100-120
	- seismic monitoring	50-75
	- pollution monitoring	50-75
	- highway management (traffic)	75-100
	- security at remote sites	30-50
Seaway Authority		
	- lock management, beacons, security	25-30
Utilities, Electrical and Communications		
	- remote communication sites, towers, repeaters	250-300
	- telephone relays, exchanges	50-75
	- substations, generating stations	150-200
Mining Industry		
	- remote exploration sites	50-75
	- unmanned sites (security)	50-75
	- bulk storage	10-20
	- pollution monitoring	10-20

TABLE B.3 (CONTINUED)

ESTIMATE OF DCP DEMAND

USERS AND APPLICATIONS		POTENTIAL PLATFORMS
Petroleum, Gas		
	- pumping stations	50-75
	- seismic monitoring	100-150
	- pipeline monitoring	125-150
	- offshore rigs	50-75
	- bulk storage	25-50
	- security	100-125
Forestry		
	- fire control	20-30
	- forest management	20-30
	- remote process control	10-20
	- security at remote sites	25-50
Transportation		
	- signal and switch monitoring	300-350
	- bulk storage	10-20
	- security	25-50
	- "hot box" detection	15-25

APPENDIX C

USER SURVEY

This appendix contains a summary of the results of a survey performed by Operations Research Inc., of Silver Spring MD in 1973 for NASA. The survey was performed in order to determine potential user's requirements for a data collection platform.

A questionnaire was sent to 838 potential data collection users. Of these users, 259 answered the questionnaire. A total of 179 respondents indicated a willingness to answer a more detailed questionnaire. The second questionnaire was answered by 62 organizations.

The U.S. government is a large user of the data collection platforms. The U.S. Army Atmospheric Sciences Lab uses 5000 DCPs and the Civil Works Directorate, Remote Sensing Research employs 3000 DCPs.

The following sections describe the survey results pertaining to platform requirements which are useful for the MSAT DCP network system design.

NUMBER OF DATA COLLECTION PLATFORMS PER USER

The number of platforms owned by each user is shown in Table C.1. Of the 52 respondees, 2 together indicated 8,000 platforms, leaving 3,260 other platforms distributed among 50 users.

TABLE C.1

Platform Distribution Among Respondees

Number of Platforms (N_p)	Number of Respondees With N_p Platforms
0	10
1	1
2	2
3	3
4	2
5	5
6	3
7	1
8	2
9	1
10	5
12	2
15	1
16	1
18	1
20	1
25	2
30	3
31	1
35	1
50	1
80	1
90	1
95	1
100	1
144	1
210	1
245	1
300	3
900	1
3,000	1
5,000	1

Total Number of Platforms = 11,260

NUMBER OF SENSORS PER PLATFORM

The users' requirement for sensors is shown in Figure C.1. As shown, 17.7% of the users indicated 4 sensors or less. 51.6% of the users indicated 8 sensors or less. 30.6% of the users indicated 16 sensors or less.

DECIMAL PRECISION OF DATA

The accuracy required by the user in the number of decimal digits of the measurement are shown in Figure C.2. As can be seen, 32.3% of the users indicated 2 digits, 38.7% indicated 3 digits, and 24.2% indicated 4 digits. 8% of the users did not answer the question.

ANALOG SENSOR VOLTAGE RANGE

Not all sensor transducers connected to a DCP will have identical voltage ranges. Therefore, the users were asked what their requirements were. The results are shown in Figure C.3. As can be seen, 38% of the users require a voltage range from 0 to 5 volts. 27% of the users need a range of -10 to +10 volts. 16% of the users indicated some other voltage ranges. The remaining 19% of the users did not answer the question.

DIGITAL SENSOR BITS PER MEASUREMENTS

The users' requirement for the number of bits of accuracy in the A/D converter is shown in Table C.3. 51.5% of the users did not answer the question.

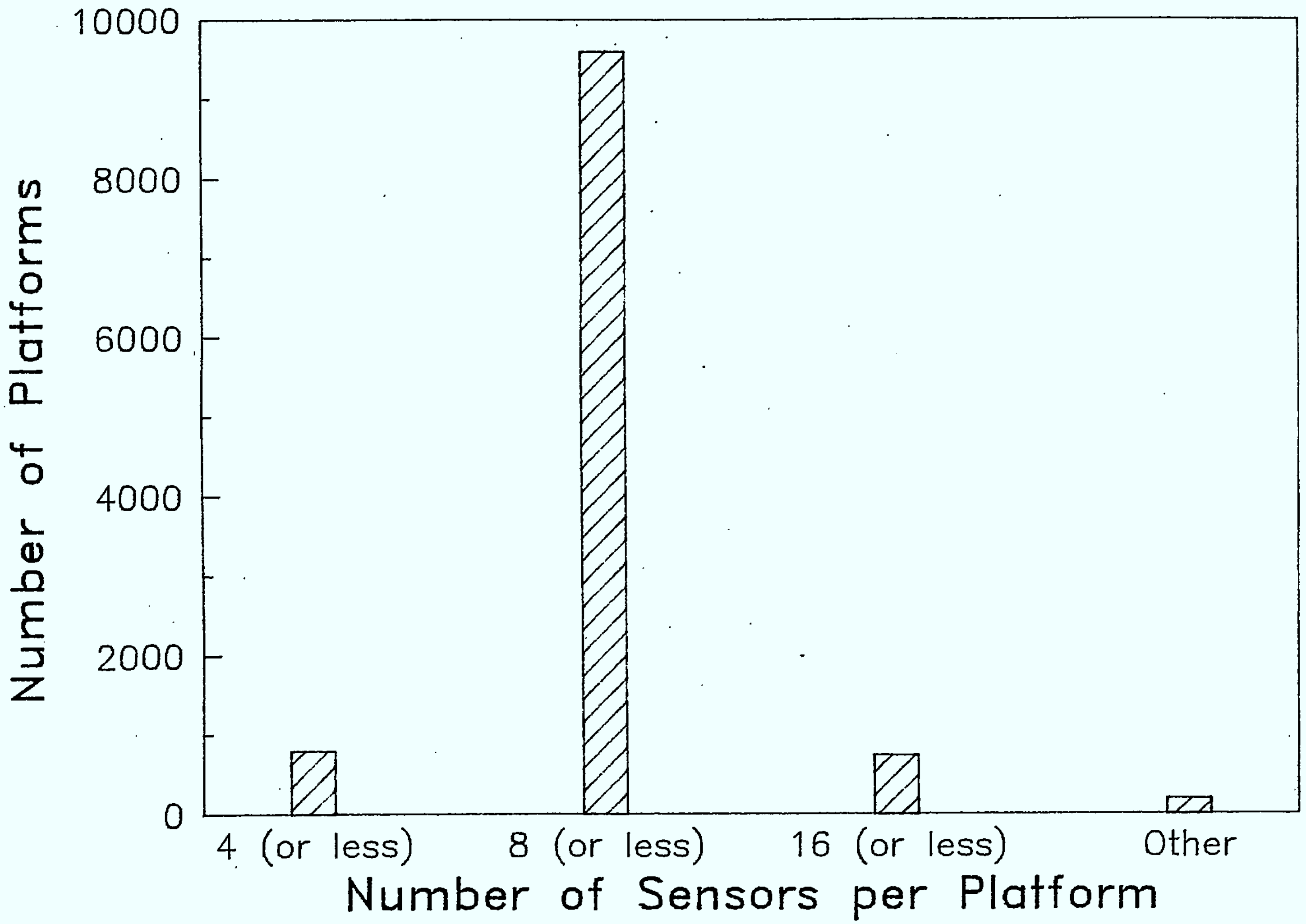


Figure C.1 : Number of Platforms vs. Number of Sensors per Platform

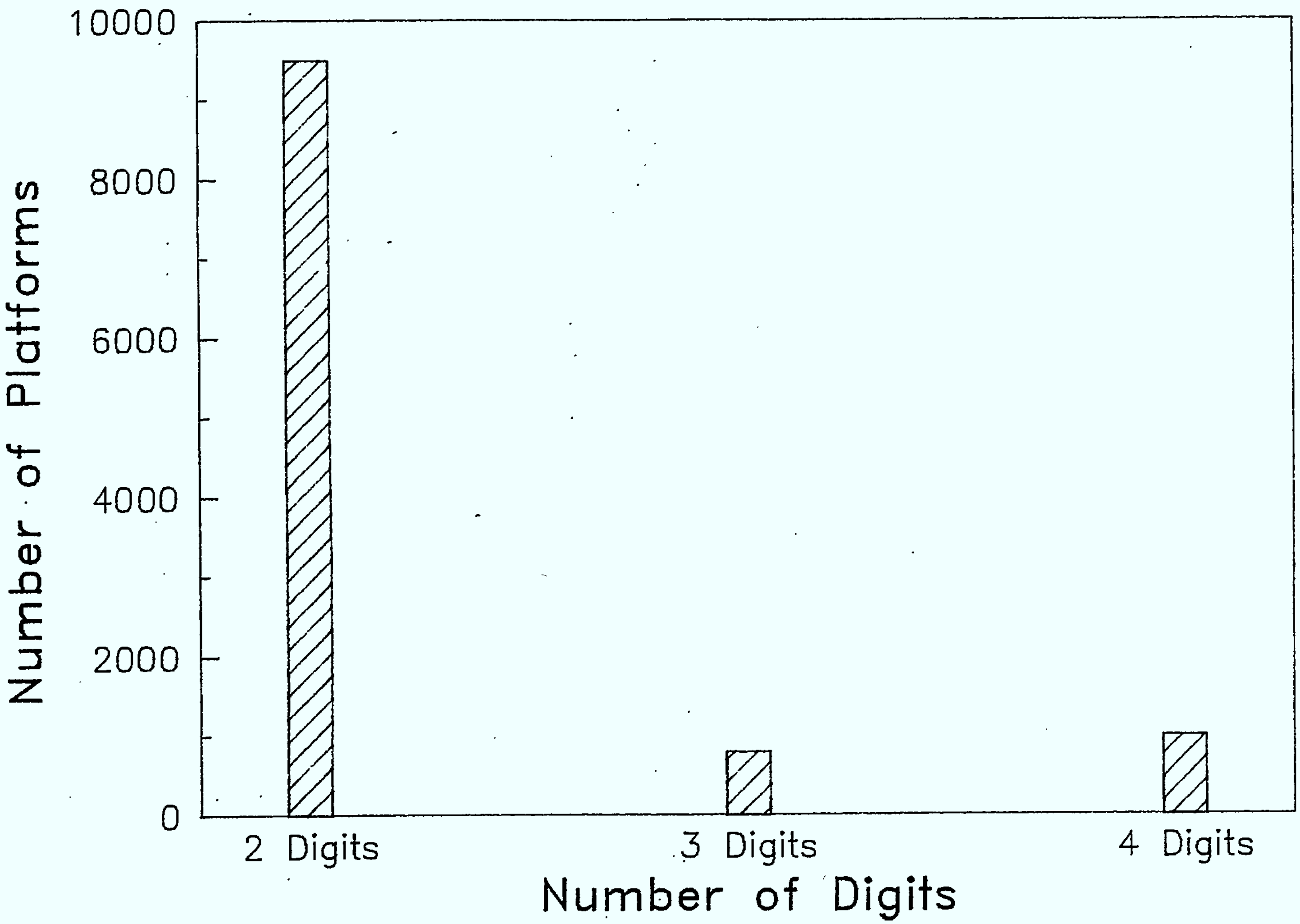


Figure C.2 : Number of Platforms vs. Highest Required Decimal Precision of Sensor Output

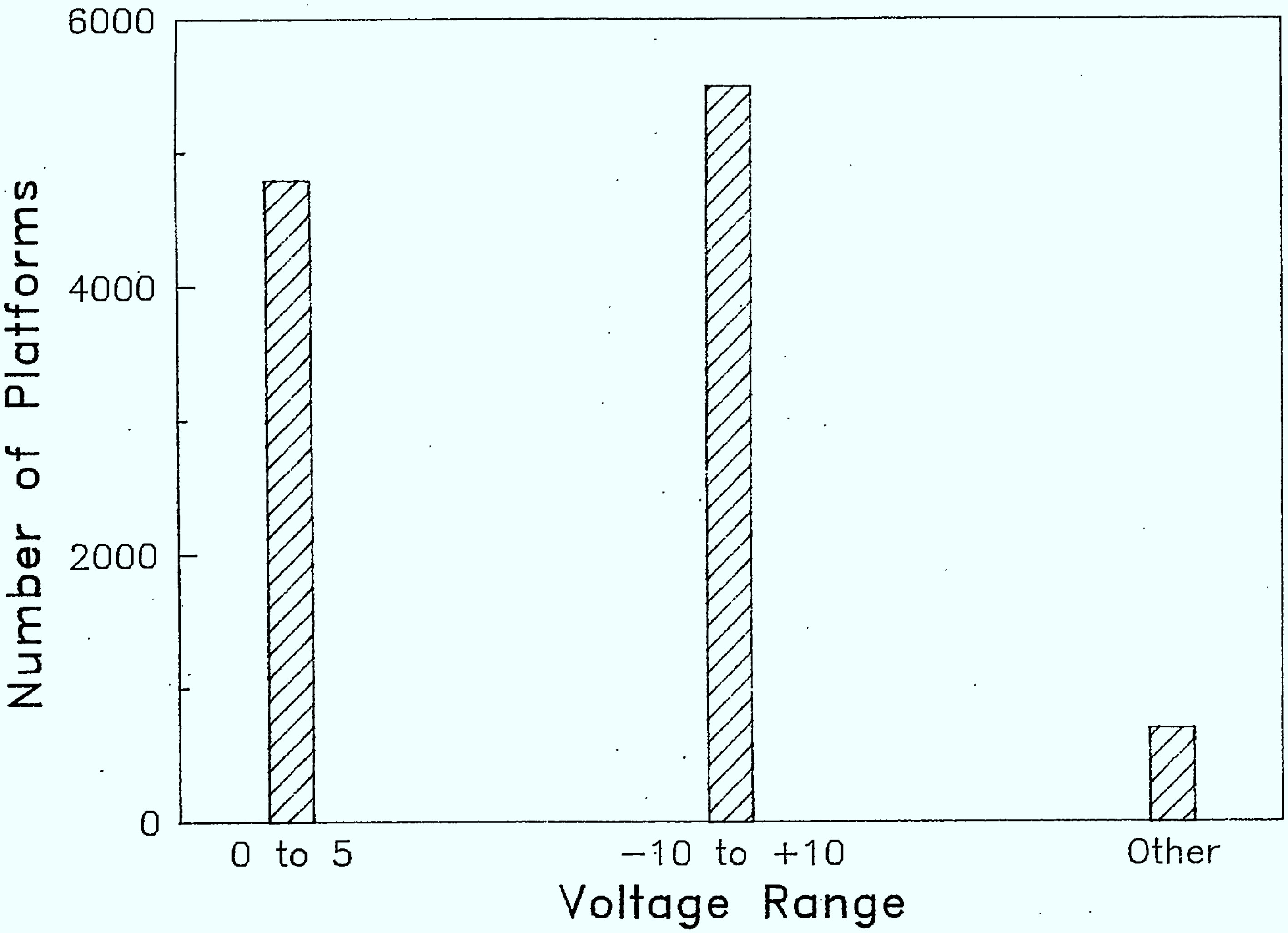


Figure C.3 : Number of Platforms vs. Voltage Range of Analog Sensors

TABLE C.3

Bits Per Measurement Distribution

Number of Bits	Percent of Users	Percent of Platforms
4	6.45	48.14
5	3.22	0.25
6	1.61	0.00
7	1.61	0.16
8	4.83	5.14
10	6.45	7.26
11	1.61	0.31
12	1.61	1.43
14	3.22	0.17
15	3.22	0.11
16	6.45	5.19
18	1.61	14.30
20	1.61	0.07
31	1.61	0.24
32	1.61	0.09
48	1.61	1.43

SYNOPTIC PERIOD

An important parameter in the design of a DCP is the sampling period which the user desires. The survey results are shown in Table C.4.

COMMANDABLE/INTERROGATEABLE PLATFORMS

DCP users may require the ability to send commands to their platforms. The requirements of the users are shown in Figure C.4. As shown, 32.25% of the users said such a capability was unnecessary. 53.22% of the users said that such a capability was desirable. 4.84% of the users said that such a capability was mandatory. The remaining 10% of the users did not answer the question.

ENVIRONMENTAL TEMPERATURE RANGE

An important factor in the design of a DCP is the environmental temperature range that the unit will be subjected to. The DCP users were asked in the questionnaire to indicate the range of temperatures which they expected that their DCPs would be subjected to. Their responses are shown in Table C.5.

TABLE C.4

Synoptic Period Distribution

Synoptic Period	Percent of Users	Percent of Platforms
continuous	6.54	3.37
0.5 hr.	8.06	48.56
1.0 hr.	29.03	5.16
2.0 hr.	8.06	5.43
6.0 hr.	14.51	3.81
12.0 hr.	16.13	19.66
24.0 hr.	22.58	12.71
Other	9.67	1.26

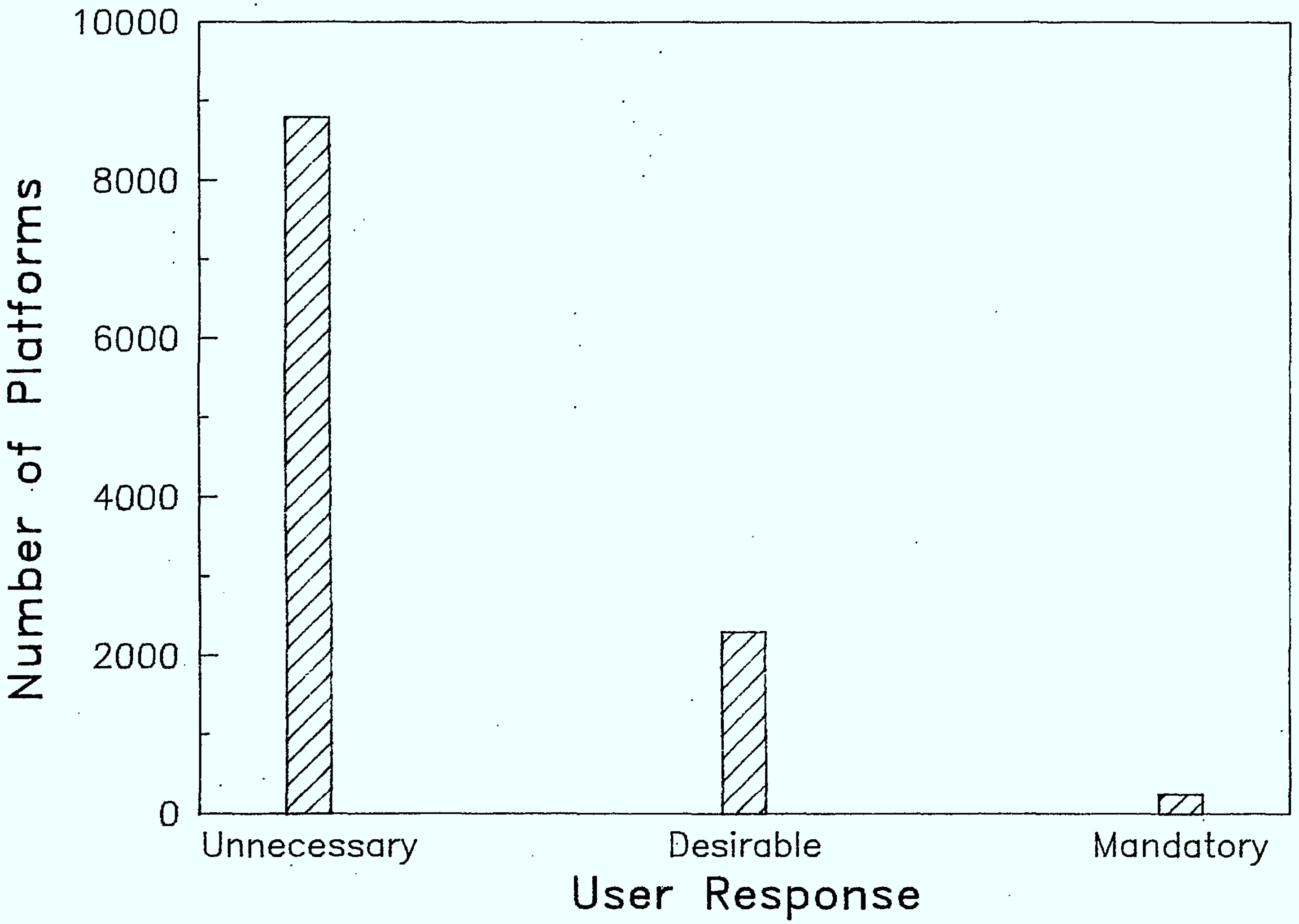


Figure C.4 : Number of Platforms vs. Commandable Interrogatable Platform Responses

TABLE C.5

Environmental Temperature Distribution

Temperature Range (°F)	Percent of Users	Percent of Platforms
-100/+150	1.61	0.00
-75/+100	1.61	0.48
-50/+125	1.61	0.48
-50/+150	1.61	0.16
-20/+100	1.61	0.01
0/120	1.61	1.43
+50/+100	3.22	0.25
-100/+50	1.61	4.80
-100/+100	9.67	52.28
-50/+50	4.84	2.47
-50/+100	37.1	8.58
-50/+120	1.61	14.37
0/+50	3.22	5.03
0/+100	25.80	11.40

EXPECTED PLATFORM LIFE

In order to assess the reliability requirements of DCPs, the users were asked to indicate the duration of their experiments which would coincide with the minimum expected life of their platforms. The distribution of platform life expectancies is shown in Table C.6.

USER COST ESTIMATE

In the questionnaire, the users were asked to indicate what they considered to be a reasonable cost for a data collection platform. The results of this question are shown in Table C.7. 14% of the users did not answer the question.

DATA DELAY

A significant parameter is the tolerable delay between the time that a measurement is made at a DCP and the time that the data reaches the user. In the questionnaire, the users were asked to indicate the delays that they considered to be tolerable. Table C.8 summarizes the results.

TABLE C.6

Data Collection Platform Expected Life Distribution

Expected Life	Percent of Users	Percent of Platforms
1 month	0.0	0.00
3 months	4.84	2.71
6 months	4.84	4.79
1 year	19.35	9.18
2 years	22.58	1.99
5 years	12.90	1.70
indefinite	40.32	79.58

TABLE C.7

Data Collection Platform Cost Distribution

Cost	Percent of Users	Percent of Platforms
≤$100	9.67	4.21
≤$500	16.13	2.02
≤$1,000	24.19	71.74
≤$2,000	17.74	7.04
≤$5,000	12.90	12.76
Other	6.45	0.76

TABLE C.8

Distribution of DCP Data Delay

Delay	Percent of Users	Percent of Platforms
1/2 hour	8.06	53.43
1 hour	11.29	20.60
12 hours	30.64	15.06
1 week	32.25	7.69
1 month	12.90	2.46
Other	9.67	0.72

APPENDIX D

DCP RECEIVER NOISE TEMPERATURE

Two-way DCPs will have a receiver which will have a noise temperature consisting of antenna noise, LNA noise and transmission path noise. This section computes the receiver noise.

The antenna noise temperature consists of noise from the atmosphere, solar noise, cosmic noise, and man-made noise. The noise temperature is estimated using the results of [D.1]. DCPs will typically be used in remote areas, so the measurements of [D.1] made in rural areas will be used to estimate the antenna noise.

From the plotted results, an antenna noise of 152 K is estimated for the frequency 800 MHz. For 1600 MHz, the given values are extrapolated to yield a value of 142 K.

The loss from the antenna terminals is estimated to be 1 dB for both UHF and L-band. This is due to duplexer and cable loss. The noise figure of the receiver is assumed to be the same as the value used in normal MSAT receivers. This value is 2 dB for both UHF and L-band.

The receiver noise temperature at the input of the LNA is computed as:

$$T_R = T_{LNA} + T_o(L - 1)/L + T_A/L$$

where T_{LNA} is the noise temperature of the LNA, T_o is the temperature of the transmission path from antenna to LNA (290 K), T_A is the antenna noise temperature, and L is the loss from the antenna to the LNA.

Using the above formula, the receiver noise temperature is computed to be 350 K for UHF and 343 K for L-band. The gain of a fixed antenna is assumed to be 12 dBi at UHF and 17 dBi at L-band. Therefore, the receiver G/T is -13.4 dB/K for UHF and -8.4 dB/K for L-band.

REFERENCES

D.1 W.R. Lauber and J.M. Bertrand, "Man-Made Noise Level Measurements of the UHF Radio Environment", IEEE National Symposium on Electromagnetic Compatibility, San Antonio, Texas, April 24-26, 1984.