MULTIPATH MODULATION–ADAPTIVE TECHNIQUES

MARCH 1970

FINAL REPORT for Period
April 1969 – March 1970

Prepared for

GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland 20771

HLI

HEKIMIAN LABORATORIES, INC.

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Final Report

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Multipath/Modulation Study--
Adaptive Techniques

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Contract No. NAS5-10749

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PREFACE

OBJECTIVE. It was the aim of this Study to investigate adaptive modulation techniques for combating the expected high level of multipath anticipated in the NASA Tracking and Data Relay Satellite System (TDRS) and to recommend a modulation design that would at the same time provide the necessary thru-put data rate, RFI protection, and range and range-rate capability. Emphasis was placed on designs leading to small, light weight, reliable and efficient circuitry for the s/c and designs that were conservative of bandwidth and power. It was indicated that a VHF voice capability and simultaneous s/c range-rate measuring capability were highly desirable. Emphasis was placed on the VHF requirements with the objective of handling upwards of thirty (30) VHF users simultaneously. Rapid and reliable acquisition was deemed important.

SCOPE OF WORK. The Study centered around an adaptive burst communication system that became known as the ABC system. Analyses of important aspects of the TDRS environment and of critical ABC performance items were developed to support the signal design philosophy and prove the feasibility of the ABC system. The TDRS medium was analytically characterized (for the first time, it is believed) in its time domain multipath response. This model was used to develop an ultra-conservative signal design that was shown to reject TDRS multipath components by more than 30 dB under all conditions. The signal design was shown to be compatible with present NASA allocations and operational procedures. Two means of providing an ABC-compatible voice capability were shown. The ABC system is not limited by self-jamming, as contrasted to wideband spread spectrum modulations, and hence it can make effective use of increased power to realize improved performance. The ABC system was shown capable of supporting more than sixty (60) simultaneous users through any relay. The system was shown to be workable with any common form of relay, including the hard-limiting repeater. Range and range-rate analysis was developed to show that the system would perform as well as required with a minimum of power and within the allocated bandwidth. It was shown that Doppler rate effects and the effects of s/c oscillator instability did not interfere with the establishment of coherent carrier communications for the ABC system. It was shown that the system offers possibly the best means of combating the RFI that is anticipated. Study of the ECAC data on RFI projections plus numerous discussions with NASA GSFC and Rosman STADAN people indicated the nature and extent of the RFI problem. Such first-hand information was obtained by site visits to the GSFC Network Training and Test Facility (NTTF) and to the Rosman STADAN station as well as by direct and indirect contact with GSFC personnel. These also served to provide direct insight into the operational procedures and, as a result, the ABC system is highly compatible with present procedures, facilities and equipment. A minimum of retrofit is required to implement the ABC system and the personnel training requirements are minimal. Performance calculations, including link calculations, were provided. Implementation was shown via block diagrams of the user and ground station equipments and by a discussion of the required changes in the existing equipment.

CONCLUSIONS. As a result of the Study, it can be stated that the ABC system will meet all of the objectives of the TDRS. Data thru-puts 400% greater than that required can be accommodated in a standard 30 kHz allocation while at the same time providing simultaneous coverage by any relay for more than sixty (60) VHF users. RFI immunity is better than that available from competitive techniques when applied to the TDRS environment. No major problems are anticipated in ABC implementation or use.

SUMMARY OF RECOMMENDATIONS. In view of the results of the Study, the ABC system should be considered as a leading contender for TDRS use. HLI recommends that, irrespective of the choice of the modulation scheme used for TDRS that NASA should (1) seek exclusive allocations for command and telemetry, (2) use the 400 MHz band in lieu of the present VHF bands, and (3) perform an orbiting RFI experiment that would properly characterize the TDRS RFI environment. HLI also recommends that additional research be made into (1) a novel means of essentially doubling the number of ABC channels, (2) a program to demonstrate the compatibility of ABC with GRARR by a sequence of real tests and (3) a program to demonstrate the feasibility of an analog voice modulation scheme for use with ABC.

ACKNOWLEDGMENT

There are many people that contributed time, knowledge, and assistance to this Study in numerous ways. Hekimian Laboratories, Inc., is deeply indebted to those individuals, one and all. Especial thanks are due to Dr. Kenneth Peltzer, formerly of NASA/GSFC and Mr. John J. Schwartz for the valuable and understanding guidance and assistance they have provided during the course of this Study. Special thanks are due also to Mr. John Bryan for his kind assistance in our RFI study on several occasions. Messrs Ralph Taylor, Morton Foxe and John Treimer also provided valuable assistance in the RFI area. Thanks are due also to the staff at the Rosman STADAN station for their valued assistance and kind cooperation. In particular, we would like to thank Mr. B. W. McKendree, Jr., for his time in giving us an excellent overview of the Rosman operations. Messrs Rouse Kessee and Walter Newbauer provided a most thorough and practical input into the range and range-rate operations which has proven of great value in the study. Thanks are also given to the NTTF personnel at Goddard.

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1. INTRODUCTION. This is the final report prepared by Hekimian Laboratories, Inc. (HLI) for the Advanced Plans and Techniques Branch, Manned Flight Planning and Analysis Division, Goddard Space Flight Center, under Contract No. NAS-10749. The Technical Officer is Mr. John J. Schwartz. The work has involved a study concerning the application of adaptive modulation techniques to combat the anticipated multipath in the TDRS environment. The result of this study is the development of the Adaptive Burst Communication (ABC) system, and it is shown herein that the ABC system offers:

(a) Immunity to multipath interference from earth-reflected energy

(b) Performance to within about 1.4 dB of the theoretically optimum multipath receiver for user altitudes of 100 to 1000 nm.

(c) Potentially greater immunity to RFI than any other modern modulation technique

(d) Compatibility with all types of relays

(e) Ability to utilize coherent carrier techniques for communication and range rate determination

(f) Compatibility with present frequency allocations

(g) Voice channel capability

(h) Compatibility with presently-existing transmitting and receiving equipment

(i) No-cost reversion to non-TDRS mode.

In addition, an overall system block diagram (including user) is presented to demonstrate the ease with which the ABC system can be implemented. A summary of parameters for the Study is presented in Table 1-1.

Table 1-1. Summary of Parameters for the Multipath/Modulation Study

	Unmanned Spacecraft	Manned Spacecraft
Nominal Carrier Frequency	136 MHz to satellite 148 MHz from satellite	2300 MHz to satellite 1800 MHz from satellite
Coherent Bandwidth	1.0 kHz	15 kHz
Fading Bandwidth	150 Hz to 2 kHz	2 kHz to 25 kHz
Differential Doppler	0 to 2 kHz	0 to 25 kHz
Differential Time Delay	200 us to 10 ms	200 us to 10 ms
Number of Spacecraft	10	2
Channel	PCM telemetry, 100 b/s to 1 kb/s	1. Voice (300 Hz to 3 kHz) 2. PCM telemetry, 1 to 50 kb/s
Channel	To Spacecraft: PCM Commands, less than 100 b/s From Spacecraft: PCM telemetry, less than 1 kb/s	To Spacecraft: Voice and PCM, less than 1 kb/s From Spacecraft: Voice and PCM telemetry, 51.2 kb/s
Voice Quality	- - -	20 dB SNR
Data Quality	10^{-5} BER	10^{-5} BER
Spacecraft Altitude	100 to 1000 nautical miles	100 to 1000 nautical miles
Ratio of total reflected power to direct received power	1.0 or less	1.0 or less
Antenna Polarization	Circular	Circular

These parameter differ from those postulated at the start of the Study in a reduced bit error rate (BER) requirement of 10^{-5} instead of the initial objective of 10^{-6} and in the reduction of the emphasis placed on the UHF requirements. The latter change is attributable to the inherent antenna directivity found at the higher frequencies and to the assumption that UHF users will have stabilized and oriented antennas as a matter of necessity. Additional emphasis on VHF performance arose as a result of a desire to provide emergency backup, especially for voice communications, in the event that orientation and/or stabilization were lost. In view of the shift of emphasis, this Study was directed mainly to the VHF considerations. UHF considerations were to be included where appropriate and without affecting the mainstream of the Study.

Emphasis was placed on expanding the target capacity of 10 unmanned spacecraft by a factor of 3 or more. HLI has been able to show a potential capacity of over 60 users for the ABC system in consonance with the directed objectives.

Considerations of operating in a real environment were stressed by the cognizant Technical Director of the Study. To this end, HLI has been able to show that the ABC system is highly compatible with present methods of operation, is simple to use, and through alternate channel utilization offers a high potential for fighting RFI. HLI recognized the threat posed by RFI even in the original porposal wherein it was proposed that ECAC data be examined. Such studies were done and served to guide the development of the operational procedures and ABC system design.

Although no stipulations were made initially concerning the relay satellite deployment, it was found to be necessary to postulate some sort of model to permit certain computations relevant to the ABC system. The 120° equatorial deployment model chosen is one that has been proposed on several occasions and, for all practical purposes, fits the three and four relay satellite configurations presented in the GSFC Phase A Study. The fourth relay would be interposed between the two 120° separated relays, providing coverage for the continental United States (CONUS). The presence or absence of a "backside" relay simply influences percent coverage.

SUMMARY OF REPORT. Beginning with a brief qualitative description of the TDRS environment, Section 2 develops the concept of a burst communication system for overcoming multipath. In Section 2.3 a heretofore unavailable model of the diffuse multipath return is developed. Rough earth reflection theory is combined with measured data from radar research to provide the first available model showing the time domain response of the TDRS medium. This impulse response is used to determine the response to the ABC burst and this in turn is used to establish the ABC format. The model is used to show that the multipath is always at least 30 dB below the direct signal so that the TDRS medium has been effectively reduced to a free space line-of-sight path without multipath. An important result of this is that the ABC system is not limited by self-jamming and hence can effectively use power increases to enhance transmission performance if so desired. Present channel allocations are followed in the development of the signal. Section 2.4 shows that the channelized burst communication technique is highly suited to combating the anticipated RFI and in fact should be superior to wideband spread spectrum techniques. An example is given where the channelized system is almost 40 dB better than a spread system.

In Section 2.5 it is shown that the ABC system is able to work with linear, processing or hard limiting repeaters. Though a processing repeater is the best choice for <u>any</u> candidate TDRS modulation technique, the performance of the others is adequate for all TDRS requirements, especially in view of the +7 dB process gain offered by the ABC system as a result of the duty cycle chosen.

In Section 3 it is shown that there are no difficulties in maintaining carrier coherence to better than a degree at VHF and to better than 10^{o} at UHF. In fact, the problems are less severe than that posed in the reception of the color burst in the common color television set. This important result assures that carrier Doppler can be used for range rate measurement.

Section 4 shows that the ABC system (or any system which eliminates multipath effects) will perform to within about 1.4 dB of the ideal but impractical receiver that uses all of the multipath and direct signal energy. Path length time difference and its dependence on orbit are presented and used to evolve an ABC format. This format results in a thru-put rate of 4,000 bits/second, a 400% increase from the minimum TDRS requirements. It is shown that for the vast majority of TDRS users, a fixed duty cycle will suffice with only the burst duration tailored to the approximate s/c altitude. In any event, no more than four changes of burst duration are required for the most elliptical of orbits. It is shown that there are no special timing requirements between users or between relays in order to use ABC.

Operational considerations are treated in Section 5 starting with a typical sequence for telemetry and command. Present operational procedures are discussed from the vantage point of field observation and interviews. By the same token, actual RFI experience is discussed. Common coverage of a user s/c is shown to be possible using ABC for a period of approximately five to seven minutes. Coverage on the short arc at launch is discussed and it is concluded that usual practices will provide such coverage even with TDRS.

Section 6 shows block diagrams of system implementations for ABC. It is stated that the required changes in existing ground equipment is minimal, even for GRARR use with ABC. The small size, power economy and simplicity are noted for the ABC realizations.

ABC system performance is presented in Section 7. Analysis of the planned RFI tactics is presented showing the viability of the notion. It is shown that range and range rate performance requirements can be met. It is shown that the telemetry and command 10^{-5} BER requirement can be met with DPSK modulation, no error correction coding and using only 11 mw per user in the ground-relay link and 1 watt of user power and 0.1 watt of relay power per user in the relay-user link. For this reason no form of coding is required for ABC although such coding may be used, if desired, without any impact on the ABC system.

Section 8 presents two ways of achieving a voice capability at VHF using the ABC system. The first mentioned is a vocoder scheme of established design that works with high intelligibility in 10^{-2} bit error rate channels and requires only 2.4 kb/s. The second technique would use analog pulse modulation and would require a minor amount of hardware for realization.

Section 9, "Conclusions" summarizes the advantages of ABC and presents the position that ABC is truly a powerful system for TDRS and should be most seriously considered.

Section 10, "Recommendations" lists a number of suggested actions for NASA. In particular, it is recommended that exclusive allocations be sought for telemetry and command at VHF, that NASA plan to use the 400 MHz band as soon as possible and that an RFI experiment be flown as soon as possible in order to obtain real RFI data at VHF. Three programs are suggested in regard to ABC. The first is to investigate a novel means of doubling the number of users that ABC could handle. The notion is based on the well-defined burst relationships within a channel of ABC. The second is a recommendation for a GRARR-ABC compatibility demonstration and the third is for an experimental demonstration of the analog voice technique proposed in Section 8.

2. TDRS ENVIRONMENT

2.1 QUALITATIVE DESCRIPTION. If we consider the medium in which TDRS operates to be a generalized transducer, we can see immediately that there are a number of considerations that make it different from many terrestrial multipath environments. The situation is different from terrestrial HF multipath or even from terrestial VHF/UHF propagation. In the former case, there is often strong multipath, but generally both the "main" path and the multipaths fluctuate in range and polarization because of the magneto-ionic interaction. In the latter case, reflections and scatter cause multipath, but again, on both the "main" and indirect signals. Moreover, these paths do not show a significant difference in signal diffusion, Doppler shift, fading bandwidths, or coherent bandwidths. The NASA Tracking and Data Relay Satellite System situation is unique because of the following:

(a) The direct path is free space and nondiffuse.

(b) The indirect path is diffuse, with attenuation and phase shift corresponding to a single-hop earth reflection.

(c) The path-length time difference (PLTD) between the direct and indirect signals is large, compared to the reciprocal of the signaling bandwidth.

(d) Doppler is different, in general, for the direct and indirect paths.

(e) Doppler change is relatively slow and smooth.

(f) Doppler shift and delay as a function of position (time) can be ephemerized after orbital data is obtained, thus allowing prediction.

(g) Except for multipath, the channel is almost stationary, with additive Gaussian noise.

Because of (a), (b), and (f), the direct path has a large capacity for information transmission; there is no spontaneous Rayleigh fading as on ionospheric and tropospheric paths, and unlike HF multipath, the multipath is almost predictable.

The TDRS medium may be characterized as shown in Figure 2-1. The received signal is the linear sum of the direct signal as delayed by the line-of-sight propagation time t_1 and attenuated by the free-space path loss A_1, and the multipath elements. The multipath components all suffer a common time delay t_2 that is always greater than t_1 plus additional small differences in time delay due to the particular ray path under consideration. Additionally, these components suffer path losses and phase shifts not only representative of the geometrical path length (which is always longer than the direct path) but also from the loss and phase shift due to earth reflection and other second order effects. Since the path lengths for the multipath signals are all approximately the same (and in fact usually merge into an indistinct continuous span of delays), it is appropriate to treat the multipath as a diffuse and random single component of the received signal. Time dependence of delays results in Doppler effects. In general, the direct signal Doppler is significantly different from the multipath shifts. The latter tend to be similar in magnitudes. Both the direct and multipath Doppler are slow, gentle functions of time for all user spacecraft (s/c) altitudes.

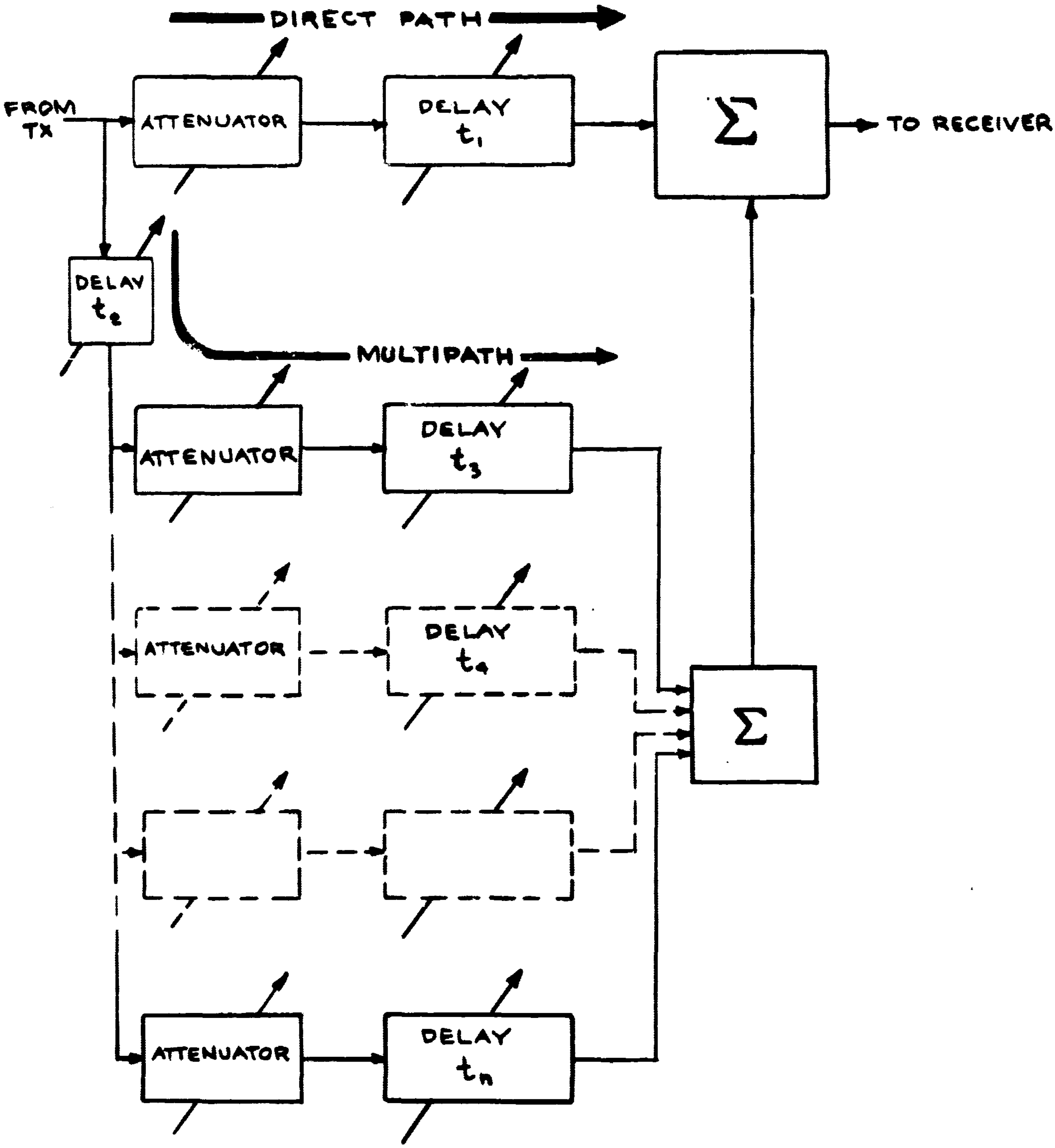


FIGURE 2-1 TDRS Propagation Model

2.2 THE CONCEPT OF A BURST COMMUNICATION SYSTEM. The ABC system created by HLI is a burst-blank transmission system that is matched to the TDRS environment. It takes advantage of the unique properties of the relay satellite-earth-user complex to allow communication that is free of multipath. Data is transmitted in bursts of a duration that is less than the path length time difference (PLTD) existing between the direct path signal and the first multipath return. The inter-burst interval is chosen so that the direct path signal of the next burst will not overlap the energy of the previous burst. If the signal bandwidth allocation is adequately large compared to the minimum PLTD anticipated, each burst can consist of a number of signaling elements, and each signaling element may, in turn, convey one or more bits of information. Frequency channelization is used to make the various users completely orthogonal so there is absolutely no requirement for burst coordination between ABC users or between relays. The appearance of a user signal in a channel at any relay does not conflict in any way with other users. This user signal can be received at any earth station able to work the particular relay satellite(s) that are transponding this signal. The only synchronization required beyond normal carrier and data clock acquisition is to lock to the ABC burst interval. Since this is either known a priori (or is evident by inspection with an oscilloscope in the absence of any knowledge!), simple framing synch can be achieved easily. Simple buffer storage of the staccato bursts of ABC data then produces a smoothed data flow as if the ABC system were completely transparent.

The minimum value of the interburst interval is determined as above; the maximum value is determined by considerations of average channel data rate (thru-put) requirements, carrier coherence requirements, and the number of times a user spacecraft (s/c) channel would have to change format because of changes in PLTD as a function of orbital position. Within these constraints it is possible to design a burst-blank system that is immune to multipath.

An important result of the present Study has been to show that it is indeed possible to design such a system for the TDRS. The system has been named the Adaptive Burst Communication (ABC) system. The term "adaptive" derives from the fact that the format is tailored to the user s/c altitude and in principle, may be locally optimized as a function of orbital position. These notions were anticipated prior to the initiation of the Study and were proven to be valid.

Figure 2-2 is an illustration of the ABC signal in the TDRS environment.

Noting from the figure that the PLTD is the same for reception at the user s/c or at the relay, a common pair of burst and blank intervals will suffice for command, telemetry, and range and range rate applications.

Notice that the temporal relations of the direct and multipath signals are established at the relay and s/c and are not altered by the relay-to-ground link. No relay processing is required in order to retain these relationships at the ground.

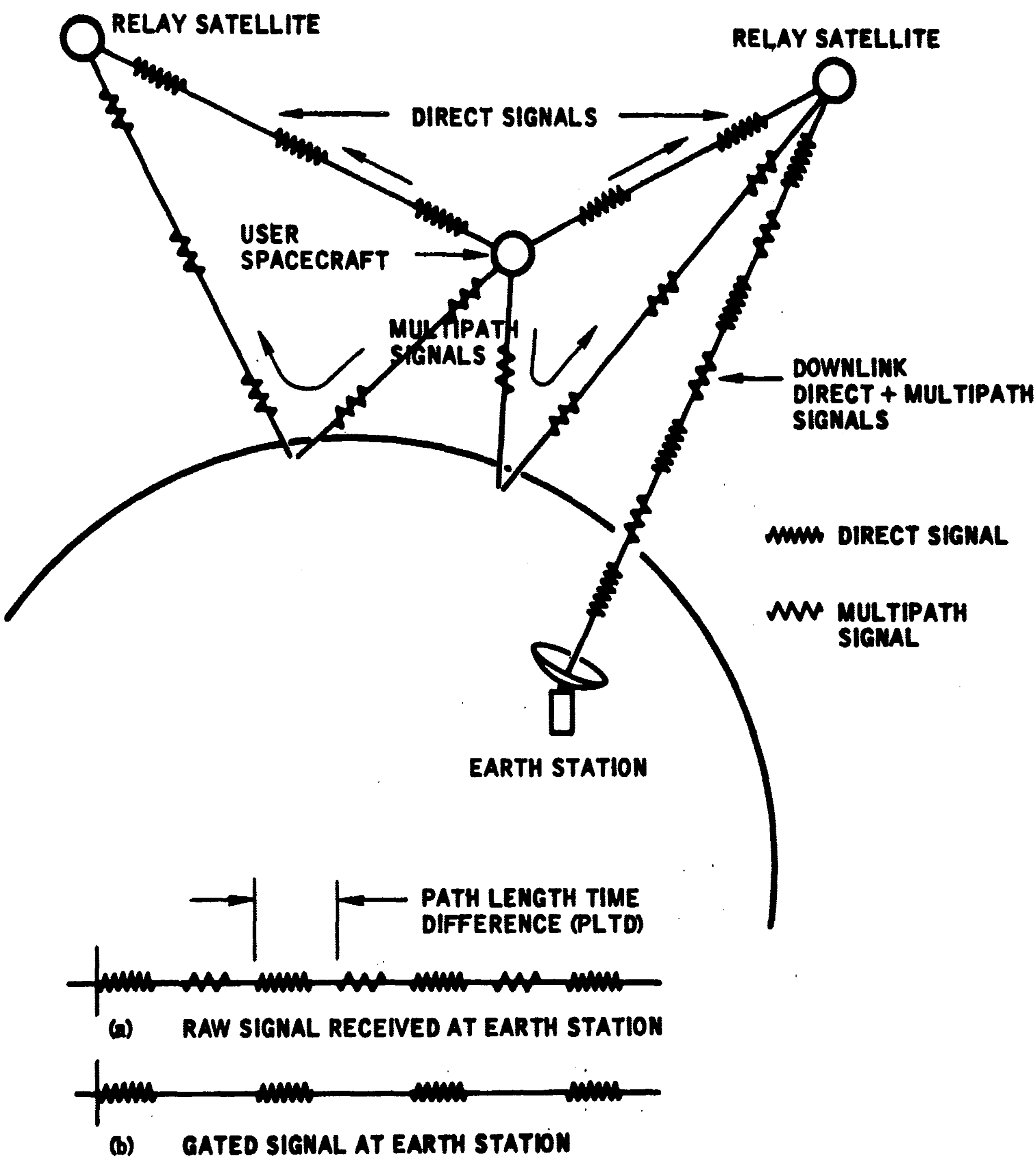


FIGURE 2-2 The ABC System for TDRS

Multiple overlapping coverage of a s/c by several TDRS relays will be possible so long as the multipath is effectively reduced by the ABC format. This period of overlap thus depends on (1) TDRS deployment, (2) ABC duty cycle, (3) s/c altitude, and (4) s/c inclination. Because of the vagaries existing at present in (1) and (4), detailed calculations are not included in this report. Results are presented, however, for equatorial orbit coverage as a function of s/c altitude on the assumption that common coverage would be possible for ABC for $\pm$ 20° each side of optimum handover angle.

A major result of the Study has been to shown that the ABC approach would permit the use of a fixed format without adaptation during orbit for all essentially circular orbits and that a fixed (20%) duty cycle (burst to blank ratio) could be used irrespective of altitude. This surprising result is one of the major achievements of this Study and one that makes the ABC system very attractive for use in the TDRS.

Because of the way the PLTD numbers came out in computation, it has been possible to adhere to the present VHF channel allocations of 30 kHz and still provide at least a 4 kb/s channel capacity, a 400% increase beyond the stated requirements. Using this allocated bandwidth for each user s/c, 60 simultaneous users would require only 1.8 MHz of spectrum. Considering the difficulty in obtaining new allocations from the Interdepartmental Radio Advisory Committee (IRAC), this compatibility with the way allocations are presently being made is considered highly desirable.

Another unanticipated but most desirable result of the Study has been the demonstration of the ability to maintain carrier coherence from burst-to-burst. This capability permits the use of coherent or differentially-coherent modulation and detection schemes without penalty in the ABC system. This capability means that carrier Doppler can be used for range rate measurement. It is shown later that range rate performance will be virtually unimpaired when using ABC.

Since the ABC notion relies upon a knowledge of the multipath duration, and since it is readily shown that the multipath energy is diffused in time, it became essential to determine the duration of any significant multipath energy. A notable achievement of the Study has been the development of this heretofore unavailable result for a rough-earth model. Using this model HLI has created a simple signal design procedure that insures that the multipath is more than 30 dB down compared to the direct signal under worst case conditions. This model is an achievement of the Study that may find application elsewhere.

In summary, it can be stated that the Study has evolved a new system - ABC - for the TDRS. The ABC system is channelized in frequency along present standards and utilizes a burst-blank format to avoid the well-defined multipath energy while still permitting carrier coherence. It will be shown later that ABC is compatible with all forms of relay satellite repeater design and that it affords an effective means of combating RFI.

2.3 MULTIPATH CHARACTERIZATION. Few attempts to characterize the TDRS multipath medium have been made due to the complexity of the reflecting surface (i.e., the earth). However, any meaningful design of the ABC system requires that an estimate be made of the duration of the significant received multipath signal. The analysis developed herein by HLI employs these assumptions:

(a) Depolarization effects upon reflection are ignored.

(b) Symmetrical configuration (relay overhead user) represents worst-case conditions.

(c) The surface is considered to be rough since, at a frequency of 140 MHz, the rms surface height will essentially always be greater than $\left(\frac{\lambda}{8 \sin \gamma}\right) \approx$ (1 foot) for grazing angles contributing the majority of the multipath (i.e., $60^{\circ} < \gamma < 90^{\circ}$).[1]

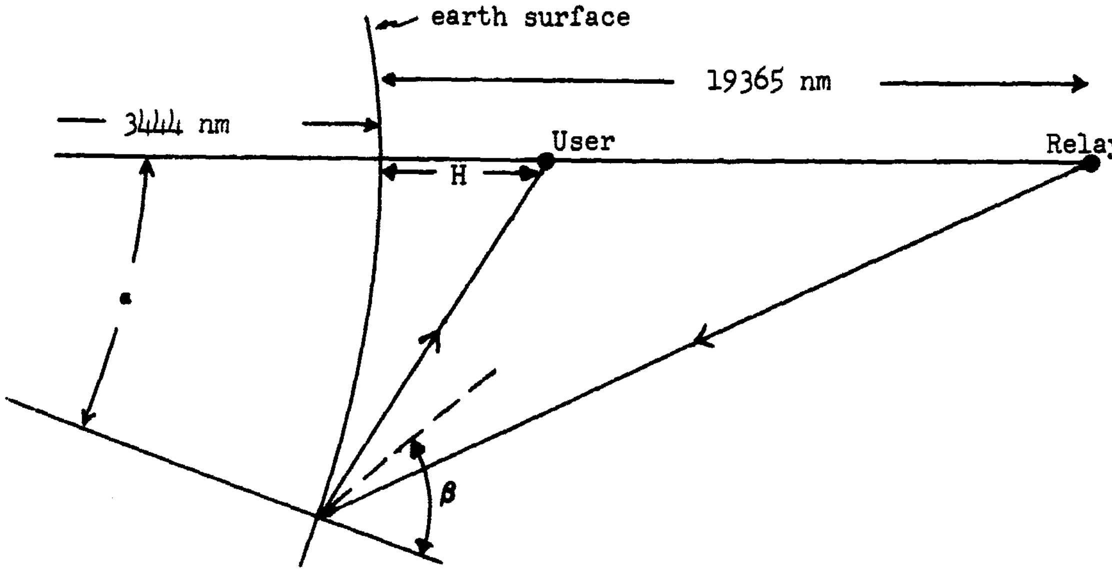
(d) Sea-clutter measurements are used as a guide to determine the reflectivity due to the predominance of ocean on the earth's surface.[2]

(e) The surface is random in nature and exhibits an exponential autocorrelation.[3]

(f) The height of the surface has a Normal distribution.[4]

The signal that is reflected from the surface of the earth will <u>begin</u> to arrive at a time corresponding to the path length time difference after the direct path signal. Since the maximum permissible duty cycle of the ABC system will depend upon the amount of multipath stretching that occurs due to the diffuse reflection, it is desirable to calculate the received multipath as a function of time-after-PLTD.

The reflection configuration geometry is shown below:



where β is the angle measured from the bisector of the incident and reflected rays to the vertical at the point of reflection and H is the user altitude in nautical miles. For values of α up to 10 degrees, it follows that:

$$\beta = \left(1 + \frac{H}{38730}\right)\alpha + 45^\circ - \left(\tfrac{1}{2}\right)\tan^{-1}\left(\frac{H + 0.525\,\alpha^2}{60.2\,\alpha}\right)$$

where β and α are given in degrees. The path length difference between the direct path and the path in the specular direction will be 2H nautical miles. The path length difference for the reflected ray as illustrated will be approximately:

$$\sqrt{3620\,\alpha^2 + H^2 + 1.05H\,\alpha^2} + H$$

Therefore, the <u>difference</u> in path length <u>time</u> difference between the "specular" path and the illustrated path will be:

$$\Delta PLTD = \left(\frac{1852}{300}\right) \left(\sqrt{3620\,\alpha^2 + H^2 + 1.05H\,\alpha^2} - H \right)$$

where $\Delta PLTD$ is expressed in microseconds.

The fact that the surface appears rough at 140 MHz implies that the <u>relative mean reflected power</u> (relative to the direct path) as a function of β will be given by:

$$RMRP = \left(\frac{S \exp\left(- \frac{\tan^2(\beta)}{K}\right)}{4\pi H^2 K \cos^4\beta} \right) \left(D_H^2\right) \left(\frac{19365-H}{19365} \right)^2$$

where S is the pertinent reflecting area at the point of reflection associated with the angle β , K is a constant that is proportional to the variance of the surface slope, D_H is the divergence factor for a given user altitude, H, and the last factor is due to the different direct path length for different user altitudes. The above relation is based upon the surface height having a Gaussian amplitude distribution and an exponential autocorrelation function. An elaborate derivation may be found in Beckmann and Spizzichino[5]. A suitable value of K was determined by fitting the above variation to the averaged measurements recorded by Daley et al[2]. The value K=0.0524 was found to provide excellent correspondence with the experimental data for values of β from 0 to beyond 20 degrees. The value of the divergence factor, D_H, is easily calculated using the result derived in Kerr[1]. The lowest and highest user altitudes considered in this report are 100 nautical miles and 1000 nautical miles, and the corresponding divergence factors are:

$$D_{100} = 0.958, \text{ and } D_{1000} = 0.724.$$

The reflected power received at the user will be directly proportional to the pertinent area at the point of reflection. The user resolution of 30 μsec (due to the 30 kHz channel bandwidth) determines the size of the pertinent reflecting area around any given reflecting point assuming that β is essentially constant over this area. The pertinent area is a zone on the earth's surface, with boundaries α_1 and α_2 such that $(\Delta PLTD)\alpha_2 - (\Delta PLTD)\alpha_1 =$ 30 μsec. This area is given by:

$$4\pi A^2 \sin\left(\frac{\alpha_1 + \alpha_2}{2}\right) \sin\left(\frac{\alpha_2 - \alpha_1}{2}\right)$$

where A = 3444 n.m. = radius of the earth. The value of β for this area is determined using $\alpha = \frac{\alpha_1 + \alpha_2}{2}$, which is the angle to the center of the zone. Therefore, the overall expression for the mean reflected power from a segment at $\alpha = \frac{\alpha_1 + \alpha_2}{2}$ relative to the direct path power is given by:

$$RMRP = \left(\frac{\exp\left(\frac{-\tan^2(\beta)}{0.0524}\right)}{4\pi H^2(0.0524)\cos^4\beta}\right)\left(4\pi A^2 \sin\left(\frac{\alpha_1+\alpha_2}{2}\right)\sin\left(\frac{\alpha_2-\alpha_1}{2}\right)\right)\left(D_H^2\left(\frac{19365-H}{19365}\right)^2\right)$$

Given a value of α, both RMRP and PLTD can be determined. Using these values, RMRP can be directly related to PLTD which becomes the impulse response of the multi-path medium as shown in

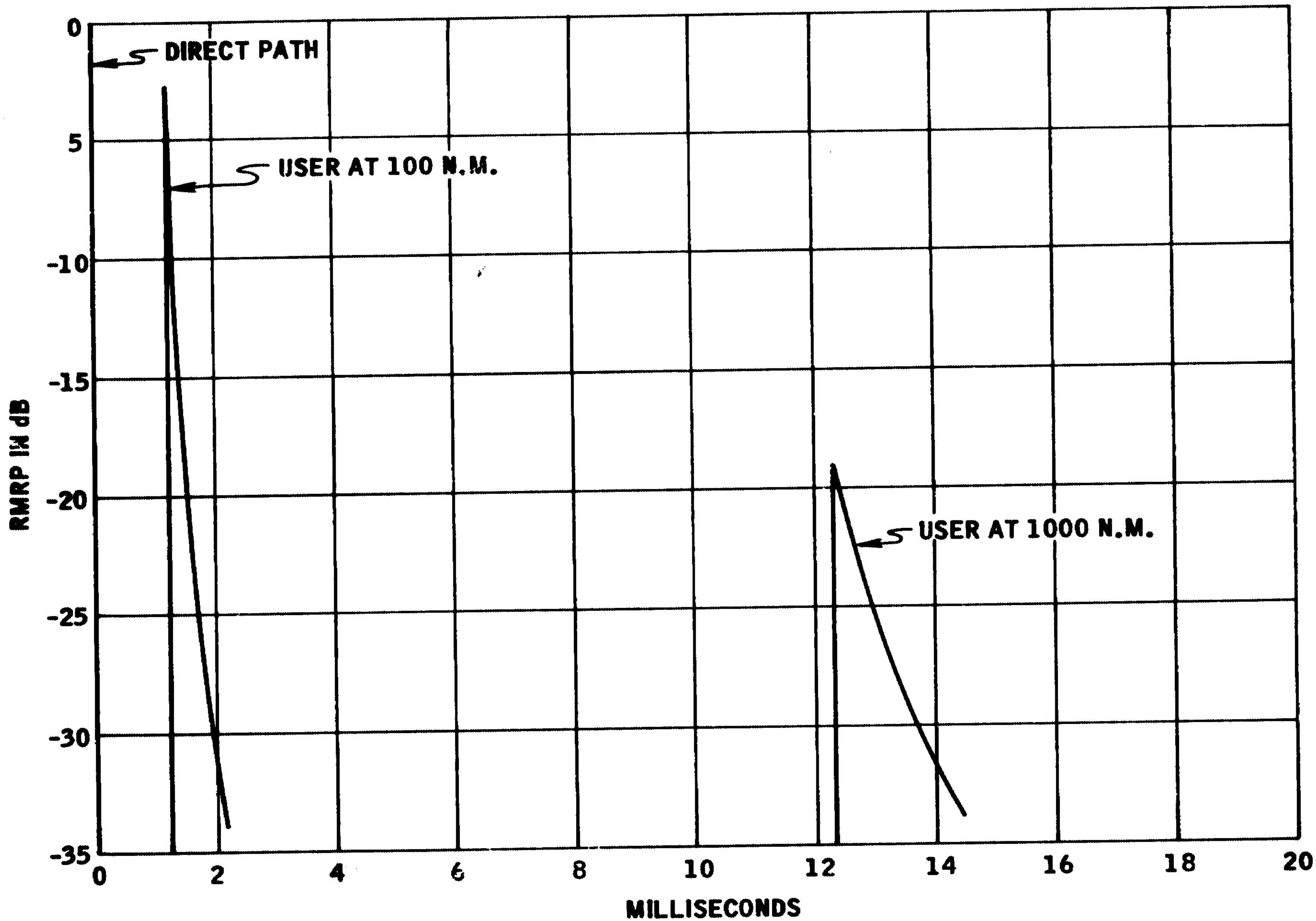


Figure 2-3 Impulse Response of TDRS Medium

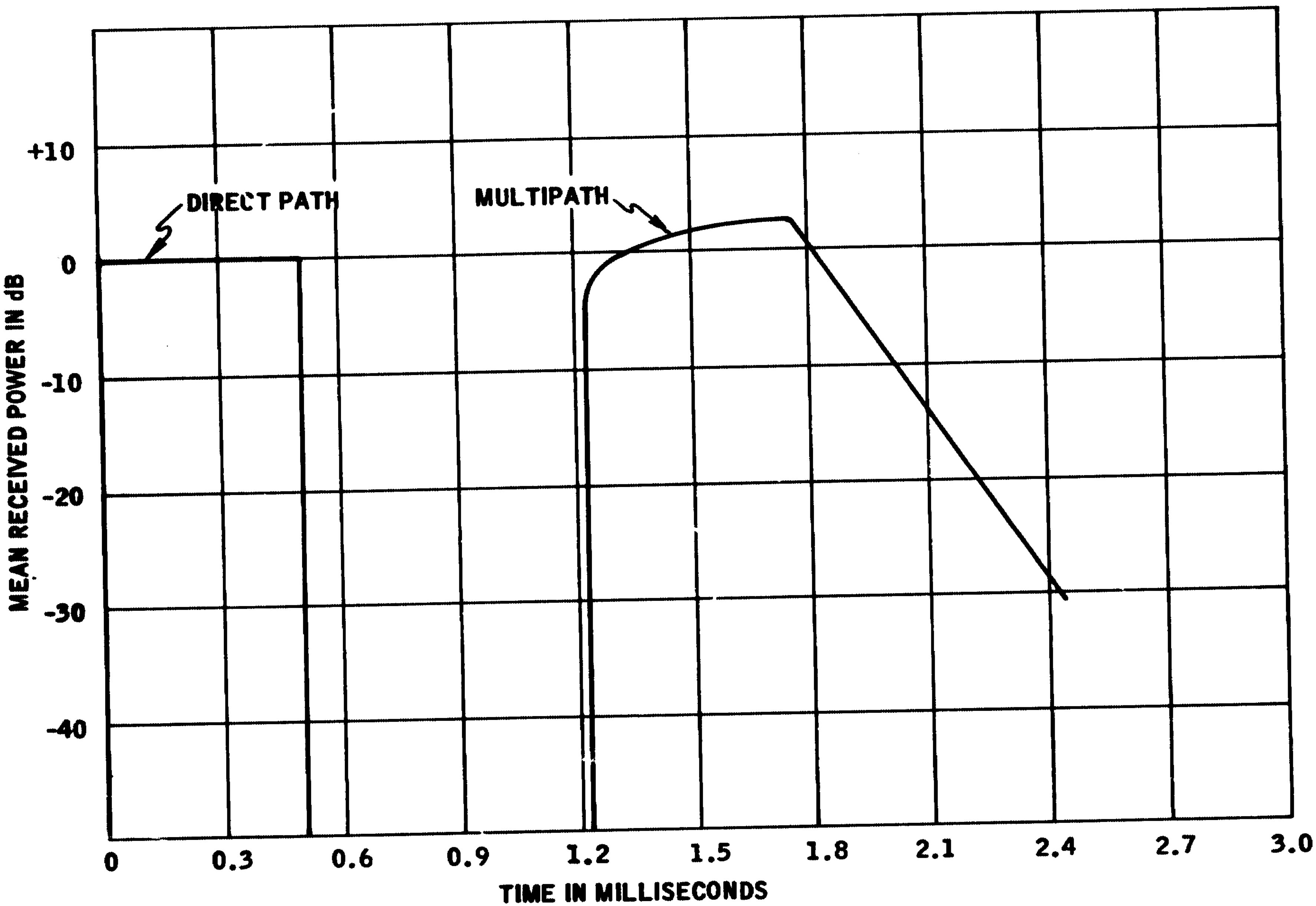


Figure 2-4 Response to _BC Burst for User at 100 Nautical Miles (Relay Overhead)

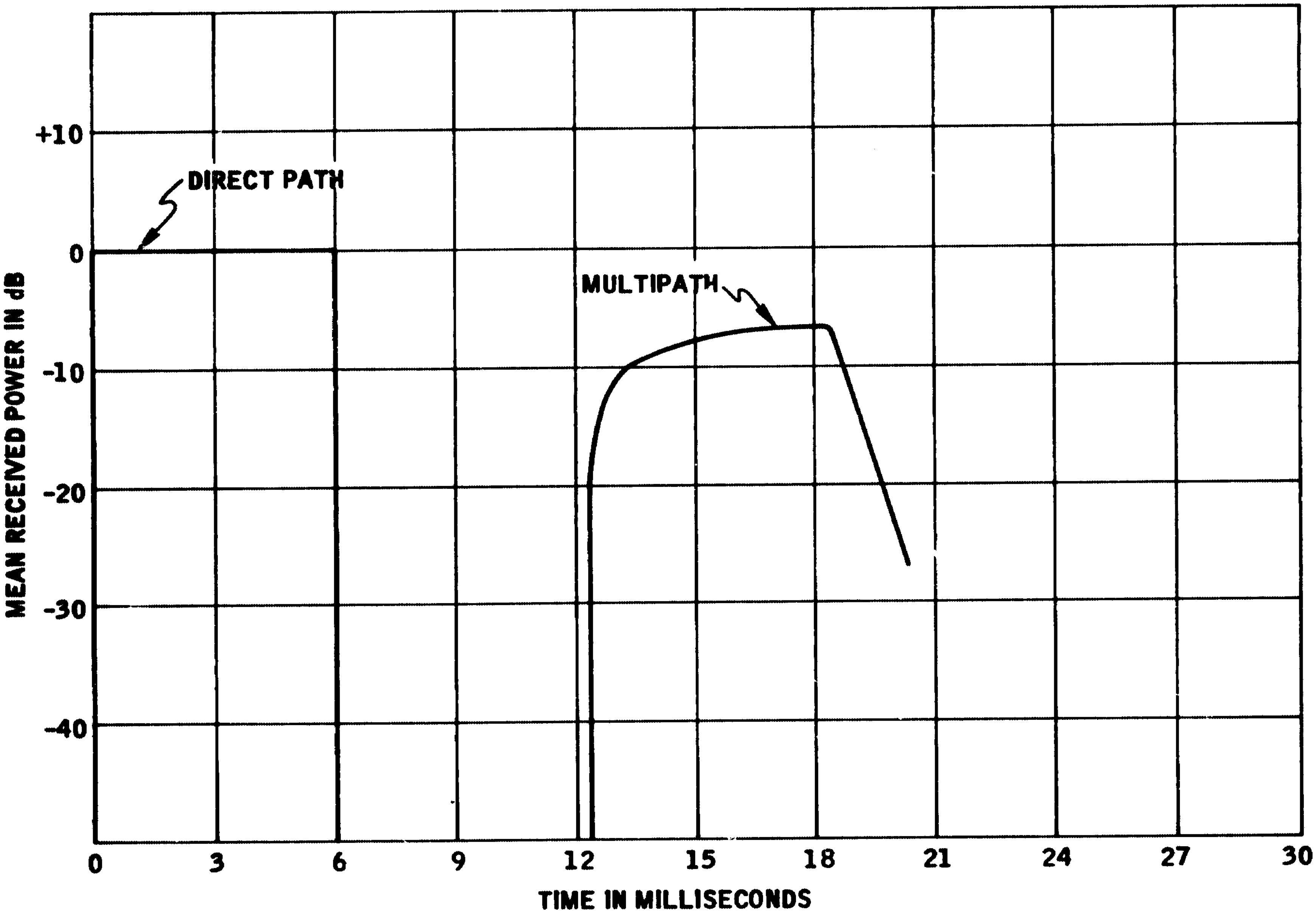


Figure 2-5 Response to ABC Burst for User at 1,000 Nautical Miles (Relay Overhead)

Figure 2-3. Design of the ABC system requires that the multipath return be characterized for a burst of finite duration. This is easily determined, and for a burst duration of 0.5 ms and a user altitude of 100 nautical miles, the result is illustrated in Figure 2-4 as a function of PLTD. It should be noted that for a 0.5 ms burst duration, the calculated value of the mean reflected power is 2.9 dB above the direct path power but that the mean reflected power is more than 30 dB below the direct path power at the time corresponding to the reception of the next direct path burst (i.e., 2500 usec for a 500 usec burst duration and a duty cycle of 20 percent). Power will continue to be reflected from the earth's surface for PLTD's up to about 6500 usec; however, Figure 2-4 actually represents the steady-state multipath return since the contribution of the previous burst to the present multipath return is essentially negligible.

Given a user at 1000 nautical miles and a burst duration of 6000 usec, the result is illustrated in Figure 2-5. The maximum value of the mean reflected power is 7.2 dB below the direct path power. The maximum PLTD will be about 29 milliseconds; therefore, there will be no multipath return at the time corresponding to the reception of the next direct path burst (i.e., 30 ms for a 6-ms burst duration and a duty cycle of 20 percent).

One comment on the preceeding derivation is in order. It must be stressed that the computation used worst-case techniques throughout in order to provide a most conservative design for ABC. As a result, the calculated level of +2.9 dB was obtained, a result that could not occur for a convex rough surface such as the earth on a statistical basis. Physical arguments show that such a surface must have an average power level that is always less than the direct signal power level for an omnidirectional user s/c. The computations thus are conservative by at least 3 dB.

The maximum values of RMRP of +2.9 dB for 100 n.m. and -7.2 dB for 1000 nautical miles, calculated for the burst durations of 0.5 and 6.0 ms respectively, are essentially the steady-state values for the multipath return in a C.W. system. This is easily verified by inspection of Figures 2-4 and 2-5. In each case, the reflected power reaches its maximum at a time (one burst duration) after the beginning of the received multipath. Therefore, the above values also represent the mean reflected powers relative to the direct paths for a C.W. system as well as a 20-percent duty cycle burst-blank system.

The relative reflected power, RRP, has an exponential distribution (Rayleigh power distribution) with mean value equal to RMRP and variance equal to $(RMRP)^2$. This is due to the absence of any specular reflection component which is a result of the rough reflecting surface (Beckmann and Spizzichino[5]). The probability that RRP is less than or equal to (x) RMRP is then given by:

$$\text{Prob}(RRP \leq (xRMRP)) = 1 - \exp(-x), \quad 0 \leq x < \infty$$

Therefore, the statistical distribution of the received multipath is completely characterized by knowledge of RMRP. Note that:

$$\text{Prob (RRP > RMRP)} = \exp(-1) \approx 0.37.$$

Thus the mean return will be exceeded approximately 37 percent of the time. It should also be noted that a level of 6 dB above the mean will be exceeded less than 2 percent of the time. The above distribution function is plotted in Figure 2-6 as a function of power above the direct path received power for altitudes of 100 and 1000 nautical miles for a CW system.

It is seen by inspection of Figures 2-4 and 2-5 that the use of a 20-percent duty cycle burst-blank technique will completely avoid the multipath interference.

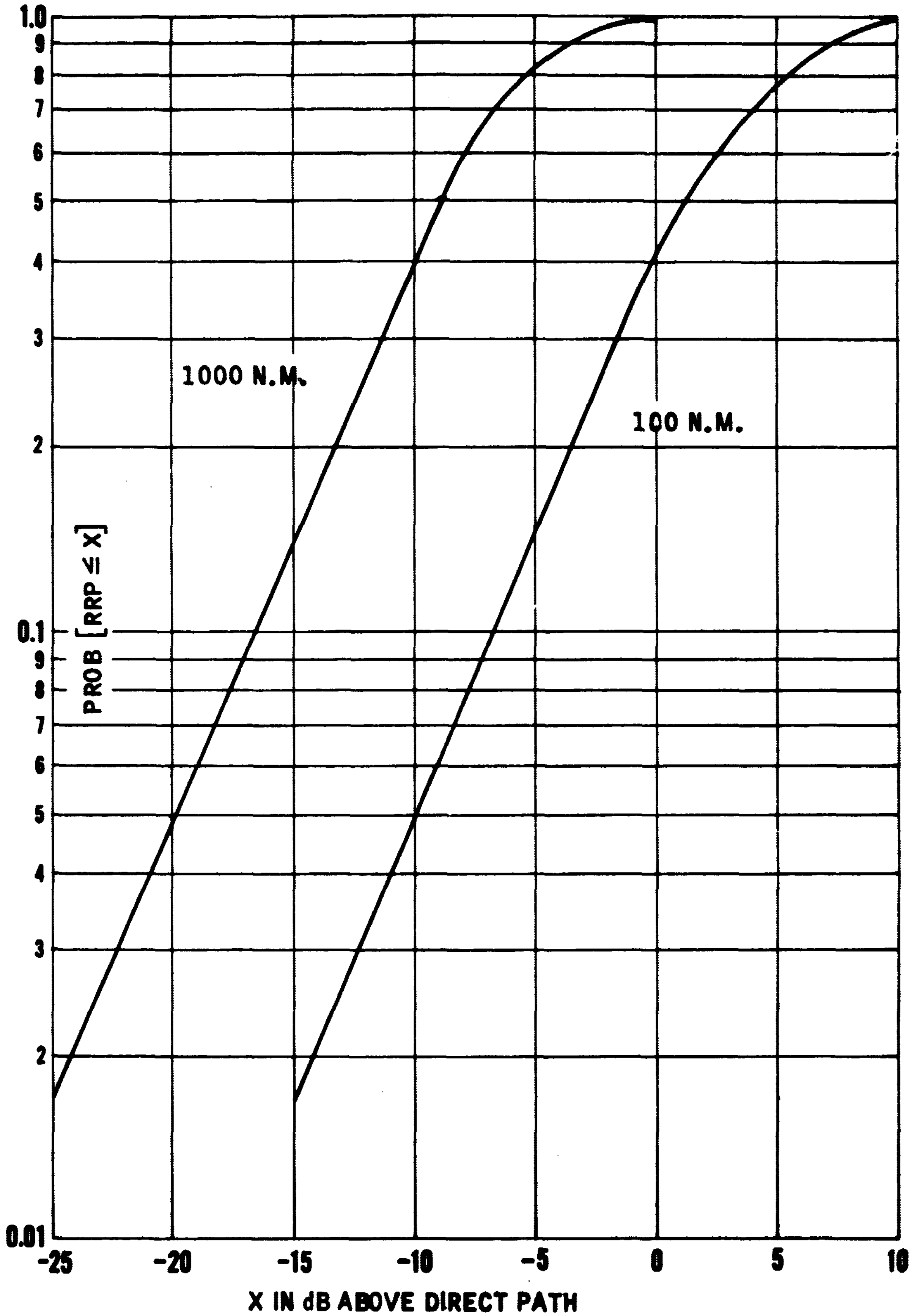


FIGURE 2-6 Distribution of Received Multipath (Relay Overhead)

2.4 RFI CONSIDERATIONS. HLI, in section 2.3.8, page 2-42 of its proposal, recommended that the Electromagnetic Compatibility Analysis Center (ECAC) be contacted with regard to predictions of radio frequency interference (RFI) for the bands of interest to the Data Relay Satellite System. HLI was unaware that NASA/GSFC currently has a program (under Mr. John Bryan) for the selfsame purpose. Studies of the ECAC computer runs and interpretations of these print-outs result in some very interesting conclusions:

(a) The data link from the s/c in the 136-MHz band is likely to be usable without disastrous interferance problems.

(b) The command link at about 148 MHz will suffer from severe RFI.

(c) Of the four allocated command frequencies, only the highest one is relatively free from RFI.

These conclusions may be reached despite several mitigating factors concerning the utility of the ECAC data. Separating those effects that tend to make the ECAC read-out seem overly pessimistic from those that tend to make the data overly optimistic, these influences may be listed as follows:

(a) A lack of duty cycle, percent usage information, or dead storage information forces a pessimistic assumption of 100% utilization for listed radiators.

(b) Excepting those radiators with specific frequency assignments, the remainder of the listings were on a "possible" use basis, i.e., all sources with a capability of covering the particular band or any part thereof are listed.

(c) Omni-antenna coverage was assumed to apply uniformly and independent of polarization.

(d) No consideration of absorption was made.

On the other hand, the following factors tend to make the data seem too optimistic:

(a) No consideration is given non-US or other non-cooperating users; only those filing responses to requests for cooperation in the effort were listed.

(b) No consideration was given to reflected energy.

(c) No consideration was given to harmonic and spurious radiation falling in-band from other out-of-band sources.

The conclusions outlined above plus reduced tabular listings showing expected radiated power levels represent the maximum useful information obtainable from ECAC data. There is no sense in trying to extend these data nor in reading any deep significance into the detail they offer. Bryan has prepared a comprehensive compilation of ECAC data for the purpose of defining the VHF RFI environment. His results are sufficient for the purposes of this analysis, and it is the considered judgement of HLI that further statements on VHF RFI should await the calibrated measurements of short-term power spectra made from an orbiting spacecraft.

HLI also pursued another course in considering the effect of RFI on the TDRS. Considerable information was unearthed relating to the experiences various NASA users have had with RFI. Messrs. John Bryan, Ralph Taylor, Morton Foxe, and John Treimer provided "case history" information, some of which is available in documental form. See the references 6 through 10 at the end of this section.

Considering just a simplified model of the RFI situation, the considerations for commands and for communications are seen to be substantially different. In the case of the command link, the relay satellite is transmitting earthward from a distance of approximately 19 kilonautical miles. The spacecraft will be between 100 and 1000 nautical miles from the earth, which is the source of the RFI. Simple free-space inverse-square loss ratio shows a range disadvantage of between 46 and 26 dB disregarding such things as antenna gain for the RFI sources. On the other hand, the communications link geometry from the s/c to the relay satellite is such that earth and spacecraft are nearly equally distant from the relay so that range disadvantage figures are in the order of 0.5 dB since the orbit of 1,000 miles or less is about 5 percent of the range to the satellite.

The nature of the RFI can also be expected to be different for the two situations. In the case of the command link, the orbiting s/c will pass through relatively localized centers of interference because of its proximity to the earth; a s/c at 100 nautical miles will have a horizon that is approximately 1,100 nautical miles distant, while one at 1,000 nautical miles will view a substantial part of a hemisphere. The relative earth coverage (see Appendix A) is then 1.4% and 11.2% respectively out of a possible 50%. These s/c will receive varying degrees of the "small picture" of the RFI environment, changing as the s/c orbits. The relay satellite, on the other hand, will receive an RFI-integrated overview of 42 percent of the earth on a continuous basis, assuming that the significant RFI sources are at least approximately stationary on the earth's surface.

The implications of the above are that the RFI may well pose a limiting constraint on the command channel because of the higher powers listed for sources in the command band and because of the large satellite signal range disadvantage. Statistical averaging of command interference is hard to support on the basis of such a localized aperture effect as described; however, the communications signal RFI, as received at the relay satellite, can probably be easily estimated statistically. The severe command channel RFI can be attacked in a number of ways; anti-jam spread spectrum techniques can be used, other command channels can be sought, and the special channelized nature of the RFI can be exploited by "channel hopping".

The use of spread spectrum against RFI has limited ability for the VHF situation but is a good candidate for use at S-band/UHF. The reason for the limitation is that the available process gain or spreading factor is limited by allocation on the one hand and by the required data rates on the other. Process gains of perhaps 30 dB or slightly more may be employed, but since all user s/c must utilize this band, there is a system self-jamming of 10 log (# of users). For the objectives of, say, 30 users, this is about a 15 dB penalty plus an additional penalty of a few dB for the reflected multipath of <u>all users</u>, including the particular signal under consideration. With less than 15 dB of process gain remaining, this must be used to combat all possible in-band (and this is the entire allocated band) RFI sources. It is quite doubtful that any noticeable improvement could be observed even assuming the spread system remained in lock, a most doubtful state in the probable RFI environment. The situation at S-band/UHF is much better since the available bandwidth is larger and the anticipated RFI environment is less severe.

The seeking of new allocations dedicated to NASA use is the best possible solution but one that is politically the hardest to achieve. Allocations in the vicinity of 400 MHz are becoming accessible and may provide relief for TDRS, assuming TDRS will be designed to accommodate this part of the spectrum.

The ABC system is a channelized system, compatible with the GSFC frequency and bandwidth assignment standards. At VHF the channelization is assumed to be 30, 60, or 90 kHz, and at 400 MHz it is assumed to be multiples of 50 kHz up to 300 kHz. This use of a channelized system allows the possible use of alternate assignments to "side-step" the RFI. Although command bandwidth allocations are not standardized as are telemetry allocations, HLI has adhered to the latter as being useful and representative. Further, the RFI channelization tends to be quite similar in structure.

The advantages of a channelized system in the presence of RFI can best be seen by example. Support that there are ten high-powered RFI sources in the band under consideration. Assume these are each 5,000 watts and 13 dB antenna gain. These are thus at +80 dBm levels. The ten taken together represent +90 dBm. For a s/c at 500 nautical miles, the path loss is about 135 dB, resulting in a RFI level of -45 dBm. If spread spectrum process gain of 35 dB is available, the required strength for the desired signal is - 45 - 35 + P_{min}, where P_{min} is the required carrier-to-noise after process gain, a number commonly taken to be 10 dB. The required signal level is thus -70 dBm. On a channelized basis, however, it is likely that the channelized interference will not fall co-channel. Assume P_{min}= 10 dB and s/c noise figure to be 10 dB. In a two megahertz band there are well over 50 possible assignments, and there is a random chance of more than 80 percent that a free channel could be chosen. Unfortunately, at the present time, NASA has little freedom insofar as choice of command channels is concerned, but the example remains valid when the RFI itself is assumed to be randomly channelized. Note that in the channelization to a free channel, the same P_{min} could be realized at a level of -109 dBm, a difference of 39 db in favor of the channelized approach.

The striking result above deserves some comment. The spread system must perforce look at the entire spread bandwidth and must, therefore accept all signals in that band, strictly on a power-for-power basis. The channelized approach depends upon the usual selective equipment to obtain higher rejections than have ever been realized via spectrum spreading. The trade-off in the channelized approach is in the availability of channels and in the ability to command their selection. This will be discussed more fully in a later section.

2.5 RELAY DESIGN. Since the relays form part of the TDRS environment, it is necessary to consider the possible effects of choosing a particular type of relay. Relay satellite repeater designs usually fall into one of three categories: linear, limiting or processing. Each will be discussed in this section.

2.5.1 Linear Repeaters. The linear repeater simply receives a signal band, amplifies and translates the band to a new frequency range, and retransmits the signal linearly. Because of the possibly large peak to average ratio or crest factor, linear transmitter requirements can be severe if very low levels of intermodulation are demanded. Additionally, the final amplifier may operate with low efficiencies if, for example, a traveling wave tube (TWT) is used because of the characteristics of the device when used as a linear amplifier. Since the TWT is the device generally used at S-band and above, it is commonly heard that all linear repeaters must operate with low efficiency. This need not be the case at VHF and even at low UHF.

Full advantage can be taken of conventional amplifiers such as solid-state, class B or C amplifiers to obtain better efficiencies and linearity. In an internal memorandum, Mr. John Bryan of NASA/GSFC has computed that a linear repeater of modest proportions could, in fact, operate within the RFI vironment. Moreover, proper AGC of the input composite signals result in more efficient utilization of the power capability a all penalty. However, it is important to note that a high degree of linearity is not really required for ABC use since the channelization works even with a limiting repeater; the main attribute of the linear repeater would be to reduce the intermodulation level to a trivial amount.

2.5.2 Processing Repeaters. The processing repeater accepts signals in a band and operates on the signals beyond the constraints of linear filtering, amplification, and frequency translation. It transmits a repeated signal that generally differs in format and structure from the received signal. Typically, the received signal is demodulated, and the demodulated signal is used to modulate a separate transmitter; a form of processing called "demod/remod". Note that the modulations for the transmitted signal and the received signal need have no relationship to one another. This form of relay design is the most complicated but affords the maximum possible flexibility in optimizing performance. Design sophistication can include protection against friendly or hostile jamming, ability to take advantage of traffic flow fluctuations, and flexibility in the mixture of missions that can be handled at any time or by program. Since the local RFI and noise environment at the earth and satellite terminals are usually quite different, separately optimized modulations can be introduced in a processing relay system design. Commercial communications satellites generally do not use processing repeaters because of the complexity of on-board electronics, the very wide bandwidths demanded from economic considerations (i.e., the need to handle a large number of subscribers for both multichannel telephone and television), and because the system users do not anticipate jamming or interference.

In the communications satellite case, all user antennas are highly directive and are pointed skyward. This should be clearly distinguished from the case of the NASA data relay satellite system at VHF where the user spacecraft will not enjoy antenna directivity and will be looking at the earth as well as at the relay(s). Indeed, the relay signal will have a severe range disadvantage compared to terrestrial sources, insofar as the user spacecraft are concerned. Further, this environment is not fixed in time, especially for the user at low altitudes when attempting to receive commands from TDRS. Moreover, it should be noted also that the TDRS mission requirements are not those for a commercial satellite; there is a limited variation in what types of transmissions need to be accepted by TDRS, and these are under the jurisdiction of NASA rather than an international consortium. An important consideration is that TDRS must accommodate the VHF user who may be in a rather bad RFI environment. These considerations should provide strong motivation for considering processing repeaters for the TDRS requirements at VHF.

2.5.3 Limiting Repeaters. The limiting repeater is the most popular form of repeater in commercial use. Pre-limiting of the signal fed into the TWT final amplifiers allows efficient use of these wide-band microwave power devices at an intermodulation penalty that is acceptable. Strict adherence to a power control assures that each user has his fair share of transmitted output power. Intermodulation products generated in the so-called "ideal limiting" process result in noise that sets an upper bound of about +9 dB on the available carrier-to-noise ratio in each user band, a result first shown by Worthy Doyle.[11] A simplified derivation is given in Appendix C. This result is for the hard-limiter and assumes that each signal passed through the limiter is small compared to the total signal strength passed through the limiter, that the signals are all equal and that the limiter input passband is essentially completely occupied. Should a particular signal be, say, larger in amplitude than the typical small input signal by x dB, it should be noted that at the output this signal's component will also be about x dB larger in absolute level as well as in signal-to-intermodulation plus noise ratio. In other words, raising the amplitude of a single input signal slightly does not raise the IM level appreciably though it does raise the output signal level proportionally. Thus, it is possible to realize a process gain advantage that is 10 log (1/duty cycle) for ABC sent through a limiting repeater. The situation also is somewhat better for the case of a "soft" limiter, i.e., where the output of the limiter is not simple two-level but retains some of the information about the input amplitudes. The literature abounds with references on the behavior of both hard and soft limiters with various types of input signals; a few are listed for reference. Appendix C shows a simple derivation of the suppression that occurs with just two narrow-band signals fed through a hard limiter. The effects of intermodulation are not included. However, with two cooperative signals, it is possible to choose frequencies of operation so that IM products pose no problem, irrespective of the type of limiter, i.e., hard or soft.

Summarizing the limiting repeater, it may be stated that (1) the output ower is distributed among the signals in approximately the same ratio as at the input, much the same as for a linear repeater, (2) IM products are generated which are at worst 9 dB below the signal at the output, (3) softening of the limiter characteristic, the use of ABC process gain, and the use of guard bands can improve the signal-to-intermod ratio, and (4) an input signal that is as strong as the rest of the input signals combined can cause an additional loss of about 6 dB in output signal power of the lesser signals.

2.5.4 <u>Summary</u>. Summarizing the study of the effects of relay repeater design on the ABC system, it may be stated that the ABC system can work with all forms of repeaters. In all three cases, the operation with channelized signals such as ABC can be enhanced by pre-selection (channelized filtering) of the input signal to the repeater. This would attenuate undesired out-of-channel signals and effectively prevent the resultant waste of repeater power and concomitant suppression of the desired signals caused by these signals appearing in the output of the relay. Most advantageous performance would, of course, be had with a properly designed processing repeater wherein maximum advantage would be taken on the burst-blank format and total signal regeneration prior to retransmission. A linear repeater would perform better than a hard-limiting repeater insofar as low IM is concerned, although a soft limiter would prove quite as satisfactory in a well-regulated environment. The 9 dB "penalty" of a hard-limiter is eased in practice by the use of limiters that are not hard and by the use of guard bands. It should be remembered that the ABC design is predicated on the use of a 30 kHz allocation with a 20 kHz occupancy, thereby affording over a 30% margin for the TDRS. The ABC burst-blank duty cycle of 20% actually affords a process gain of 10 log 5 or +7 dB in time-gated reception so that adequate error rate performance is realizable even with a 9 dB IM base. Although Sevy[12] shows several cases where frequency allocations can be made to minimize the in-band IM products for all users, it is not considered practical to expect that the TDRS frequency allocations would permit such detailed design.

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3. MAINTENANCE OF COHERENT COMMUNICATION. In order to maintain coherence from burst to burst, it is necessary to have the carrier phase remain in alignment with the local replica in the receiver, at least within certain usable bounds. The particular bounds, in turn, depend upon the type of modulation. For antipodal phase-shift keying, the phase error can approach 90^{o} without causing crosstalk and then only a cosine-squared power penalty. On the other hand, four-phase quadrature keying requires 3 dB more power and becomes crosstalk limited for phase errors approaching 45^{o} even in the absence of other noise.

Phase error will arise from two major causes: vehicle radial acceleration with respect to the relay satellite and oscillator drift during any uncontrolled idle period between bursts. It will be shown that the latter is likely to be the more serious, especially at S-band.

3.1 EFFECT OF DOPPLER SHIFT. If it is assumed for the moment that the receiver is phase coherent with the received signal just before the end of a transmission burst, and that the received frequency at that instant is retained perfectly during the idle period in the transmission, then, when the signal reappears, there will be a phase misalignment due solely to the zeroeth-order prediction of a changing frequency. Analysis of computed data shows that Doppler frequency as a function of time is a well-behaved variable which can be described adequately over short intervals by just the linearized portion of the functional expansion into a power series. By assumption, the constant term will be tracked and compensated for, leaving only the linear term to be considered. Again, from analysis of the computed data, worst-case values for the <u>Doppler frequency rate-of-change</u> are found to be approximately the values shown in Table 3-1.

The Doppler frequency rate-of-change can be converted into phase error at the end of a time T between bursts by the formula:

$$\theta = 2\pi \int_0^T f(t)dt = \pi KT^2$$

where f(t) is the frequency as a function of time, and K is the Doppler rate-of-change. Table 3-1 gives the corresponding phase errors for the extreme values of time delay associated with the limit cases of altitude of the orbiting spacecraft for nominal VHF and S-band carriers. It is seen that the worst value of phase slippage due to Doppler rate-of-change is less than 10° of carrier angle. This surprisingly small phase error is due in large part to the assumption of perfect memory and to the initial tracking of the Doppler frequency at the end of the burst. These results indicate that radial acceleration between spacecraft and relay satellite poses no problem for coherent communications.

3.2 OSCILLATOR STABILITY REQUIREMENT. Neglecting for the moment the previously discussed phase error due to acceleration, consider the phase error arising from short-term oscillator instability that results in the received frequency and the local replica within the receiver drifting apart during the idle period between bursts. It is assumed that the oscillator drift, expressed in negative exponent form, is a linear walk, although there will be a large amount of random behavior in the real case. A linear walk will give a worst-case estimate since any central tendency will reduce the end value of the phase error. Table 3-2 contains the results for similar cases of altitude and carrier frequency as in Table 3-1. Short-term stabilities (in parts per carrier Hz) are shown for 10^{-6}, 10^{-8}, and 10^{-10}, since it is likely that actual short-term stabilities will be within these intervals, depending on the investment made in on-board electronics. From Table 3-2, it can be seen that for the longest blank cited (30 ms), the required VHF stability will be in the order of 10^{-8}, whereas the required S-band stability will be in the order of 10^{-9}. It should be noted that these are short-term stabilities; stabilities over intervals of 30 milliseconds. Short-term frequency stability usually is about an order of magnitude better than the quoted long-term (e.g., one day) stability so that is is possible to realize the requisite short-term stability of 10^{-9} for S-band by utilizing a 10^{-8} oscillator. Since the S-band applications most likely will involve larger and more sophisticated on-board electronics for the spacecraft, assuming manned spacecraft for S-band applications, it is almost certain that the requisite stability will be available. The VHF requirement of 10^{-8} short-term and the corresponding long-term requirement of about 10^{-7} are easily met.

Table 3-1. Carrier Coherence Error Due to Doppler Rate in ABC System

S/C altitude in Nautical Miles	Carrier Frequency in Megahertz	Maximum Doppler Rate in Hz/sec. (K)	Time Interval (T) in Milliseconds	Phase Error in Degrees = $180KT^2$
100	140	5.13	2.5	.0057
1000	140	3.43	30	0.555
100	2300	84.3	2.5	.0949
1000	2300	56.3	30	9.09
Elliptic	140	6.5	1.25	.0018
(100 to 2000)	140	1.3	24.7	0.143
Elliptic	2300	106.8	1.25	.297
(100 to 2000)	2300	21.4	24.7	2.35

Table 3-2. Carrier Coherence Error Due to Oscillator Drift

Carrier Frequency in Megahertz	Oscillator Short-term Stability (S)	Worst-Case Phase Error in Radians (θ)	Worst-Case Phase Error in Degrees
140	10^{-6}	26.4	756.69
140	10^{-8}	0.264	7.57
140	10^{-10}	0.00264	0.0757
2300	10^{-6}	434.	12439.
2300	10^{-8}	4.34	124.39
2300	10^{-10}	0.0434	1.244

$\theta = 2\pi fST$, $T = 30$ ms

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4. ABC FORMAT AND SIGNAL DESIGN

4.1 OPTIMUM DEMODULATION OF MULTIPATH PERTURBED SIGNAL.

Since the TDRS Medium is a linear, quasi-stationary transducer, the optimum reception strategy can be easily stated. Proper alignment in time and phase of the signal components should allow the received signal energy to be that corresponding to the sum of the voltages of all signal components whereas the received noise would add only on a power basis. Utilizing the results of Durrani and Staras[1] and using Figure 4-1 yields the fact that optimal combining of the direct signal and the expected multipath return at -4 dB relative level will improve the performance by about 1.4 dB.

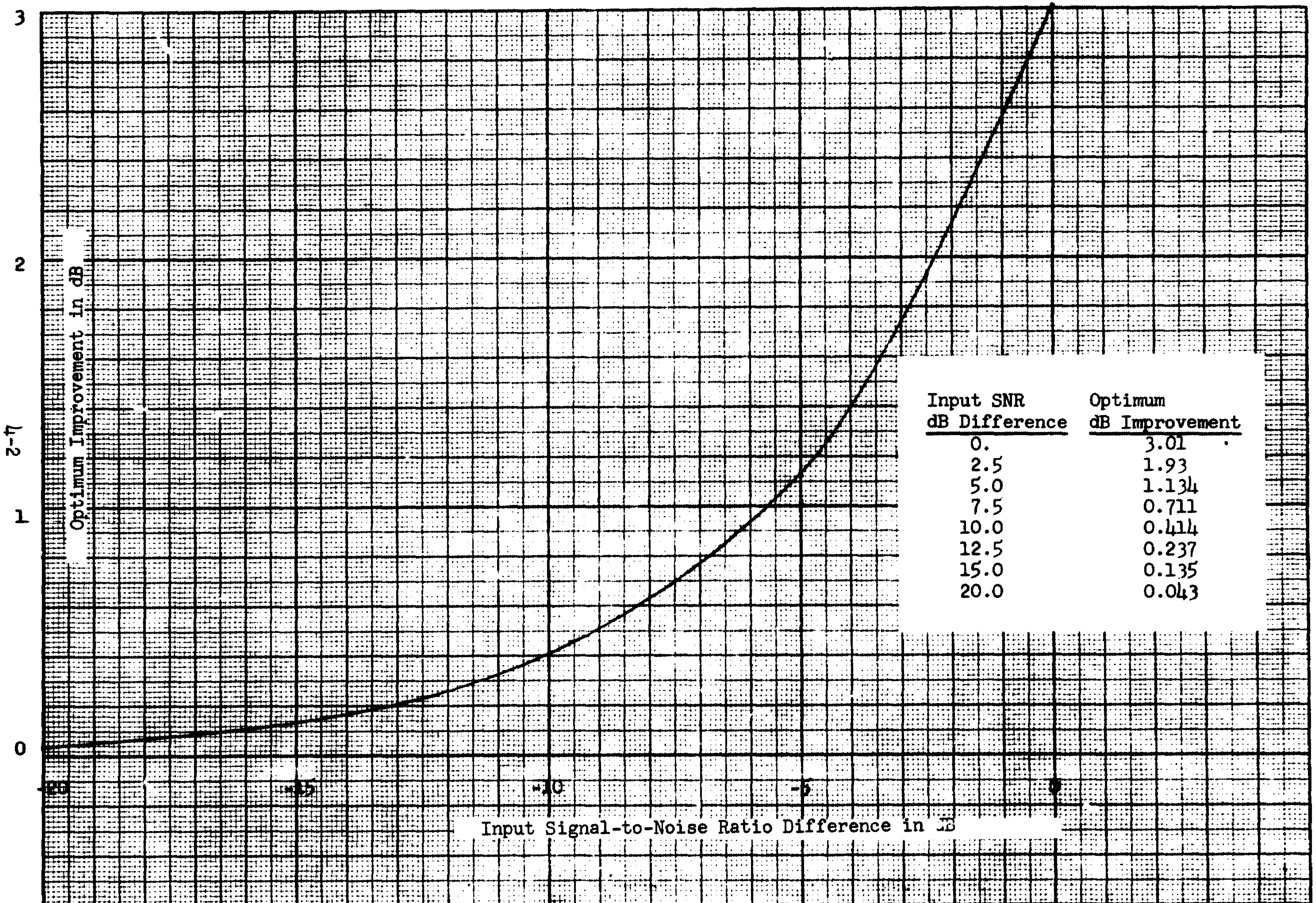
To obtain this improvement, Hekimian[2] showed it is necessary to:

(a) Match to each and every multipath component and compensate for phase shift and Doppler offset

(b) Optimally weight and sum, in the Kahn Maximal Ratio Combining sense, the separate signal and noise components of each multipath signal.

(c) Maintain the above performance in the quasi-stationary environment.

It is readily apparent that the operational requirements for such a system would be quite severe. Such multipath reception techniques have been used, although primarily for measurements of the mediums involved. These receivers were realized through the use of tapped delay lines in a multiple transversal filter arrangement. The s/c on-board complexity seems hardly worth the asymptotic improvement over a scheme wherein the direct ray alone is used and where the



Input SNR dB Difference	Optimum dB Improvement
0.	3.01
2.5	1.93
5.0	1.134
7.5	0.711
10.0	0.414
12.5	0.237
15.0	0.135
20.0	0.043

Figure 4-1 Signal-to-Noise Improvement for Optimum Receiver

multipath is avoided rather than make any attempt to "use" it, especially in view of the fact that completely adequate TDRS performance can be obtained with the ABC system operating at reasonable power levels and with minimal complexity.

4.2 EFFECT OF PLTD VARIATION. The path-length-time difference (PLTD) at hand-over of a spacecraft from one relay satellite to the next is a function of s/c altitude and the orbital position when handover is performed. If it is assumed that hand-over occurs when the s/c is midway between the two relay satellites, then the PLTD is seen to be the same for both relays. Further, since the PLTD is monotonically decreasing on each side of the relay overhead point (more properly, for either side of the point where s/c and relay are closest) this is also the point of minimum PLTD insofar as a particular communications link is concerned. Figure 4-2 shows the PLTD at handover as a function of s/c altitude and angular separation between relays. It should be noted that the effect of s/c altitude is primarily a translation since the shape of the curves is only slightly different for altitudes from 100 to 1,000 nautical miles. It can be noted also that the primary effect of increasing altitude on shape is to flatten the curves; i.e., the higher the s/c, the less spread in PLTD between hand-overs. It should also be pointed out that the PLTD for 0° corresponds to the maximum PLTD for a given circular orbit.

Since at the time of this report the TDRS relay satellite deployment

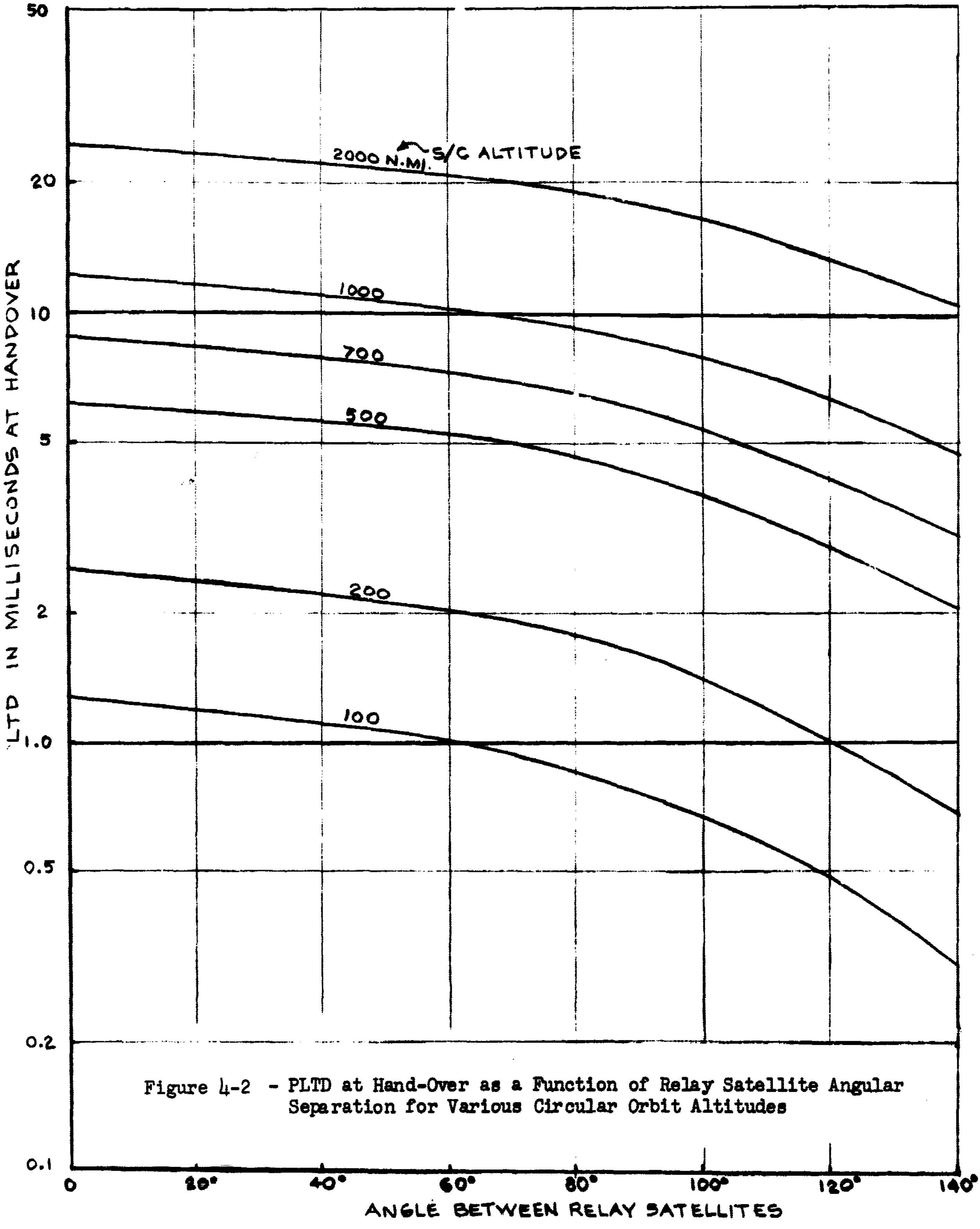


Figure 4-2 - PLTD at Hand-Over as a Function of Relay Satellite Angular Separation for Various Circular Orbit Altitudes has not been firmly determined, explicit statements concerning the ABC system parameters cannot be made; only implicit relationships are possible. Additionally, since the "modus operandi" is not determined for TDRS, there is room for variation here also. For example, if it is assumed that TDRS relays are deployed at near equatorial latitudes and at 88°W, 144°W, and 28°W, with a "back-side" relay at about 266°W (94°E), then the handover angles between the three "front-side" satellites is when the PLTD ratio is less than 1.3:1 whereas the PLTD at handover for the back-side occurs at a PLTD ratio of about 2.6:1. A uniform deployment of three relays at the equator would result also in about a 2.6:1 ratio of PLTD. Several possible operational considerations would greatly modify this configuration:

(a) The front-side relays may not all be used <u>in sequence</u> for every s/c, or

(b) Full-orbit coverage may not be desired or required, or,

(c) Flexible operation may be desired, thus allowing a change in operations.

Assuming the uniform model, it will be shown that it is possible to use a fixed ABC format for a given s/c in circular or near circular orbit. This highly desirable condition will be shown to be entirely practical and can provide channel capacity in excess of that required.

A comprehensive summary of tracking and data support requirements through 1980 has been prepared by Habib.[3] Reference to his "Summary of T & DS Project Development Questionnaires" yields the following representative estimates of future spacecraft orbit categories:

(a) 51% will have circular orbits within a 100-2,000 nautical mile altitude.

(b) 15% will have elliptical orbits entirely within a 100-2,000 nautical mile altitude.

(c) 20% will have elliptical orbits whose apogee is greater than 2,000 nautical miles.

(d) 10% will have circular orbits outside the 2,000 nautical mile altitude. The remaining 4% will be non-geocentric.

Thus, approximately 66% of the projected missions will be possible full-time users of TDRS. Of these, about 77% will have circular orbits and require absolutely no ABC format changes. The remaining 23% may or may not require some format change, albeit never more than four per orbit. The requirements for these (and the projected 20% having apogee outside of TDRS coverage) will depend on data rates and mission requirements.

From the above, it is seen that a fixed-format ABC system will be adequate for more than three-quarters of the projected missions, and quite possibly much more.

4.3 SYSTEM FORMAT AND DATA RATE. The Adaptive Burst Communication (ABC) system transmits data in bursts of a duration such that the delayed multipath return does not overlap the direct path signal. Time-gating is then used to provide complete immunity to the earth-reflected multipath return and thus reduce the TDRS multipath medium to a simple line-of-sight path. This immunity is achieved by choosing the burst duration to be slightly less than the minimum path length time difference (PLTD) encountered during an orbit. The ABC system is properly called adaptive due to the fact that the burst duration employed for a given user must be a function of the altitude of the user. For users in circular orbits, the minimum PLTD of interest during a full orbit occurs at handover which, for a relay spacing of 120 degrees, causes minimum values of about 0.5 ms for a user at 100 nautical miles and about 6 ms for a 1000 nautical mile user. It should be noted that users in approximately circular orbits will employ a fixed burst duration throughout the orbit.

Having determined the burst duration, choosing a minimum inter-burst interval will provide the maximum duty cycle for a given configuration. The length of the interval between bursts is determined by the maximum PLTD for a given user altitude and the amount of multipath spreading that occurs. The maximum PLTD will occur when a relay is directly above a user and will be 1.24 ms for a user at 100 nautical miles, and 12.4 ms for a 1000 nautical mile user. Reference to Figures 2-4 and 2-5 in the section 2.3 on "Multipath Characterization" yields the fact that a 20 percent duty cycle is feasible at all user altitudes from 100 to 1000 nautical miles. A sketch of the normalized relations between the direct signal and the time-diffused multipath signal is shown in Figure 4-3. A user at 1000 nautical miles employing a 6 ms burst duration will receive a negligible amount of multipath at the next burst which is 24 ms after the direct path burst. The mean reflected power at a 100 nautical mile user will be more than 30 dB below the direct path

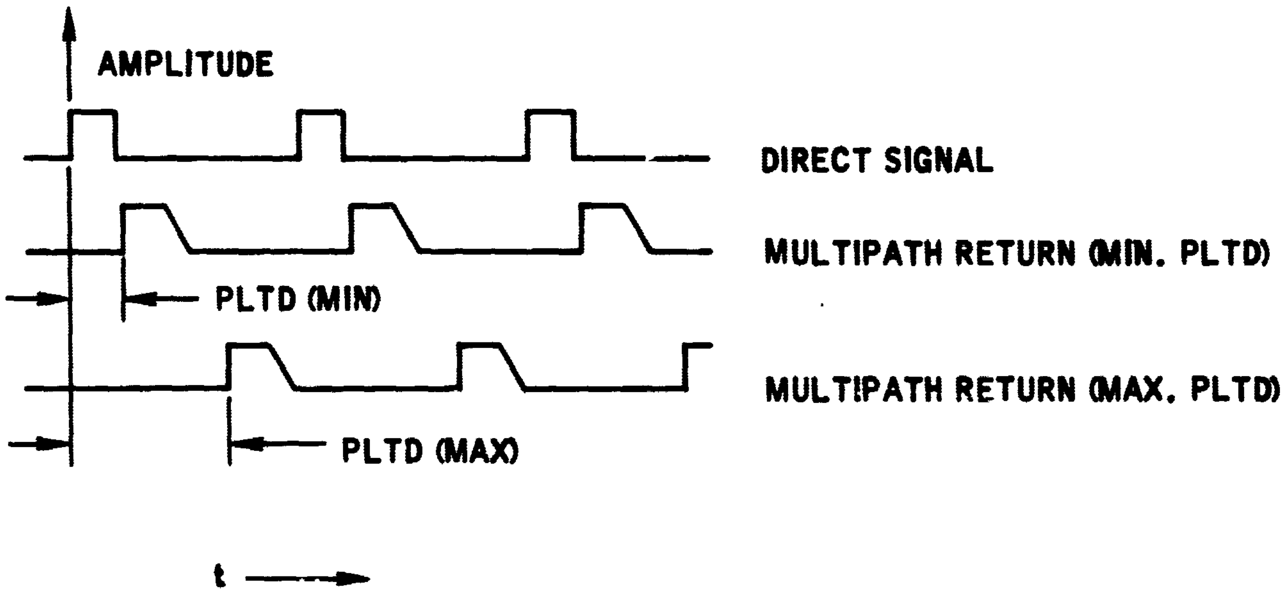


Figure 4-3 Received Direct and Multipath Signal Relationships

power at the time corresponding to the reception of the next direct path burst, i.e., 2 ms after receiving a 0.5 ms direct path burst.

The 30 kHz channel bandwidth of the ABC system permits a bit rate of 20 kilobits/second during the transmitted burst. The combination of this bit rate with the 20 percent duty cycle permits a data rate of 4000 bits/second. Compared to the specified data rate for the TDRS of 1000 bits/second, the ABC system is operating well below its maximum possible rate. Trade-offs can be made for specific mission purposes, of course. There are no special timing requirements necessary to maintain this data rate. Only locally generated bit synch and phase lock are needed, as in any digital data system with carrier coherence. If frequent format changes are permitted, the ABC channel capacity can be raised twofold for circular orbit users. In view of the capacity already shown for ABC, it does not seem necessary to introduce such changes at present.

The TDRS in its present configuration considers only those users having altitudes from 100 to 1000 nautical miles. As described previously, all users with essentially circular orbits can be serviced with a 20 percent duty cycle and no format change. If users having elliptical orbits with perigee greater than 100 nautical miles, and apogee less than 1000 nautical miles are considered, then at least one (but no more than four) format changes will be required. Two design examples requiring format changes are illustrated in Appendix B. Table 4-1 is a condensation of the pertinent parameters for TDRS.

ALTITUDE	s/c POSITION	PLTD	DOPPLER	DOPPLER RATE	PLTD MAX/MIN
100 nm	0^o(relay over-head)	1.24 ms	0 Hz	5.1 Hz/sec.	2.52
100 nm	120^o(handover)	0.49 ms	3.39 kHz	1.73 Hz/sec.	
1000 nm	0^o	12.35 ms	0	3.4 Hz/sec.	1.99
1000 nm	120^o	6.2 ms	3.07 kHz	0.99 Hz/sec.	

Table 4-1 Multipath Parameters for Near-Circular Orbits

REFERENCES FOR SECTION 4

1. Durrani, S.H. and Staras, H., Multipath Problems in Communications Between Low Altitude Spacecraft and Stationary Satellites, RCA Review, March 1968.

2. Hekimian, N.C., A Simple Derivation of the Matched Filter Concept, PIEEE, Feb 1963, pp 373-374.

3. Habib, E.J., T&DS Mission Model and Project Spacecraft Support Requirements through 1980, NASA/GSFC Report X-520-69-110, March 1969.

5. TDRS OPERATIONAL CONSIDERATIONS. In the TDRS there are essentially four operational modes: acquisition, tracking, telemetry and handover. Acquisition consists of successfully addressing and commanding the user, perhaps into the tracking mode. User range and range-rate data are obtained during the tracking mode, and range-rate can be continuously determined throughout the telemetry mode during which user data is relayed to the ground station. Handover consists of transfering the relay function to the next relay satellite.

The link from relay to ground station is anticipated to occur at X-Band, so there will be no bandwidth restriction problem on this link. The bandwidth presently utilized in the 148 MHz link is only about 300 kHz; therefore, there will be only ten 30 kHz channels available. The full 30 kHz is not required for command but is necessary for range accuracy.

As presently proposed, the ABC system would employ a 20-percent duty cycle for all users, and the burst duration would be a function of user altitude and would be preset for circular and near-circular orbits. This duty cycle and the preset burst duration allow the multipath return to be ignored. The only other environmental element that affects the operation of the system is the presence of RFI.

An important point to note in the proposed TDRS is that the earth stations can monitor all of the 136 MHz channels and by such spectrum surveillance can passively determine the RFI and user activity. This direct observation is not possible for the command channels. It is possible, however, to deduce the situation by the failure of a user s/c to acknowledge or to respond.

It is highly unlikely that all command channels will be unavailable during the period required for commanding and tracking a given user. The probability of obtaining a clear command channel for a hypothetical RFI environment is calculated in a later section. Therefore, users in the ABC system will be provided the capability of monitoring more than one command channel, thus providing the ability to sidestep the RFI on the relay-to-user link. The number of on-board user command channels will be a function of desired user availability and complexity.

The bandwidth presently utilized in the 136 MHz user-to-relay link is about 1.92 MHz, permitting sixty-four 30-kHz channels. Users in the ABC system will sidestep the RFI on this link by having the on-board capability to change transmit channels upon command. A clear channel can be easily found, since the ground station has the capability of continuously monitoring any or all of the sixty-four channels at 136 MHz, as received at the relay. Therefore, the RFI can be effectively counteracted by employing user sidestepping on both receive and transmit.

The sequence of operations for a single user will be:

(a) Ground station monitors the 136 MHz channels available to the desired user and notes a clear channel.

(b) Ground station addresses and commands the desired user to respond on that channel. If no initial response is received, the other command channels available to the desired user are employed until communication is established.

(c) The user is commanded into the tracking mode with the use of the conventional 4-kHz holding tone, and range and range-rate information is transponded.

(d) After ranging is completed, the user is commanded into the telemetry mode, during which range-rate data may also be extracted.

(e) Handover to the next relay requires that the cognizant earth station for the next relay (perhaps the same station) lock a receiver to the channel in use upon being notified through any available low data rate station-to-station communication that handover is desired. Future commands will then be issued by the new ground station. Depending on mission requirements, this procedure may be relaxed to a simple time schedule based on local time at each earth station.

The above procedure can be employed to simultaneously acquire, track, and receive data from as many as sixty-four users with the present frequency allocations. This is accomplished by using a single 148-MHz channel to command and track many users. The only restrictions are that:

(a) All users of that single channel must employ the same burst duration, i.e., must be at approximately the same altitude.

(b) All of those users must be satisfied with using the same tracking period.

(c) At least one 30-kHz command channel is available to all the desired users, unobscured by RFI. Presently used allocations will permit more than 10 such channels.

These restrictions are not intolerable since, even in the sequential ranging mode, the average total time required for acquisition and ranging with the present GRARR system is approximately 45 seconds. (This information was obtained during a visit to the ROSMAN STADAN site by HLI personnel.) After this short tracking period, the users will be operating independently in the telemetry mode on their respective 136-MHz channel.

It should be noted that additional flexibility may be obtained with no degradation in performance by simultaneously utilizing identical command and telemetry channels on the front and back of the earth. This is possible because of the effective hemispherical isolation provided by the earth.

It should also be noted that although the present frequency allocations are sufficient for ABC system operation, the "as available" allocations in telemetry and the amazingly small allocation for command pose a serious problem for TDRS. Assignment of permanent clear channels for command, in particular, would be highly desirable. New and permanent assignments in the 136-MHz telemetry band, although desirable, are not as essential to the success of TDRS.

5.1 PRESENT OPERATIONAL PROCEDURES. It is instructive to note the operational procedures now in use at the Rosman STADAN station. The address-command-execute concept is in regular use on the ATS program. On OAO, verification of every command is made before execution by checking the validity of the transpondered time-reversed command. On all other programs, execute orders are sent with the command. Failure to receive commands properly is evidenced only by failure of the s/c to respond properly.

It was learned that Rosman uses GRARR only 6 to 7 times per 24 hours and only on the OGO and IMP s/c. (ATS uses a sidetone system different from GRARR.) Peak usage was about 30 times per 24 hours. Only sidetones to 20 kHz are used. Though 100 kHz is available, no present s/c are equipped to handle it. (Even the 20 kHz is attenuated by 2.2 dB because of s/c selectivity.) No digital ARC (ambiguity resolving code) is used since the 8 Hz sidetone is adequate for all of their requirements. Sidetone phase lock loop bandwidths are about 10 Hz. The least usable power is transmitted to minimize noise generation from antenna joints. Typical power levels are 1 to 3 KW. Present GRARR transmissions occupy about a 120-kHz bandwidth as observed by HLI personnel using a spectrum analyzer at Rosman.

5.2 PRESENT RFI/MULTIPATH EXPERIENCE AT ROSMAN. RFI incidence for the s/c is largely from other STADAN sites overloading the s/c receivers. At Rosman a local airport also contributes interference directly to the VHF ground station receivers. Attempts at Rosman to "notch out" this local RFI with a tracking reject filter have been abandoned since the filter rejects the strongest signal which often is the desired ranging signal. In addition, the phase perturbations introduced by the filter seem to degrade the GRARR performance more than is acceptable.

Because of the narrower beams at the ground station, virtually no multipath effects are seen (at low antenna angles) on S-band whereas some effect is seen at 400 MHz. At VHF the antenna performance at low angles is severely limited by multipath.

5.3 COMMON COVERAGE CONSIDERATIONS. For purposes of determining range from range rate measurements it is desirable that the user s/c be in view of a number of relay satellites simultaneously and that these relay satellites be able to receive the s/c signal. The amount of such common coverage depends, of course, on the s/c orbit, the number of relay satellites and their deployment. Assuming the uniform deployment model and an equitorial orbit for the s/c, Table 5-1 gives the values of common coverage angle, common coverage period, orbit period and the coverage period if the common coverage is limited to 20° each side of optimum handover for s/c altitudes of 100 and 1000 nm. Figure 5-1 shows the angular relationships for these cases.

The above relationships are in no way a result of the ABC system. They are the same irrespective of modulation technique. The ABC system does, however, impose a limitation, in theory at least, on the maximum common coverage that can be enjoyed without multipath. It should be noted that in the ABC format design a range of path length time differences was accomodated and that the range depended upon the handover angle, i.e. the angle between the relay satellites. Using the recommended value of an 0.2 duty cycle, somewhat over 120° could be accomodated with ease. If the assumption is made, therefore, that the ABC coverage will be usable in common coverage for 20° each side of handover, it is seen from Table 5-1 that between approximately 5 and 7 minutes of common time is available for any TDRS user s/c. This time is far more than required using ranging techniques such as GRARR. Typically, 45 seconds are required at Rosman to range with GRARR.

Since the ABC format is unchanging for circular and near-circular orbits and since in the vicinity of handover, the PLTD is the same for each satellite, i.e. the donor and the receiver satellite, the same ABC format is applicable to each satellite. Thus, there is no problem about "wrong" format for ABC insofar as common coverage is concerned; both satellites will relay proper ABC signals to their ground stations and both will effectively eliminate multipath effects.

If a fourth relay satellite is interposed between the 120° model relays, simultaneous coverage is possible without any complications whatever. Common coverage in this case becomes even longer in duration and can be used to achieve simultaneous three (3) relay coverage of TDRS user s/c. Note again that there is no format problem nor any problem in reception.

5.4 SHORT ARC COVERAGE CONSIDERATIONS. Consideration of the ABC format development shows that when the path length time difference for the direct and multipath signals is too small, no multipath immunity is realized. For the parameters selected, i.e. for a 30 kHz bandwidth and 20% duty cycle, it is impossible to realize ABC protection against multipath for less than three (3) miles altutide. This raises the question of short-arc coverage at launch. The obvious answer is that the TDRS would not be used for such low altitude coverage in all probability even disregarding the ABC requirements. It is hard to imagine that, with a vehicle sitting on a pad or even after launch and into its initial short arc, direct line-of-sight communications would not be the natural choice for communicating with the s/c. Taking this as the

Altitude	Orbit Period	Common Coverage Angle	Common Coverage Period	Coverage for ± 20° from Hand-over (100°-140°)
100 nm	1.47 Hr	69.98°	17.15 min.	4.9 min
1000 nm	2.07 Hr	121.04°	41.75 min.	6.9 min

NOTE: Model based on spherical earth and neglecting atmospheric diffraction.

TABLE 5-1 COVERAGES FOR 120° RELAY DEPLOYMENT

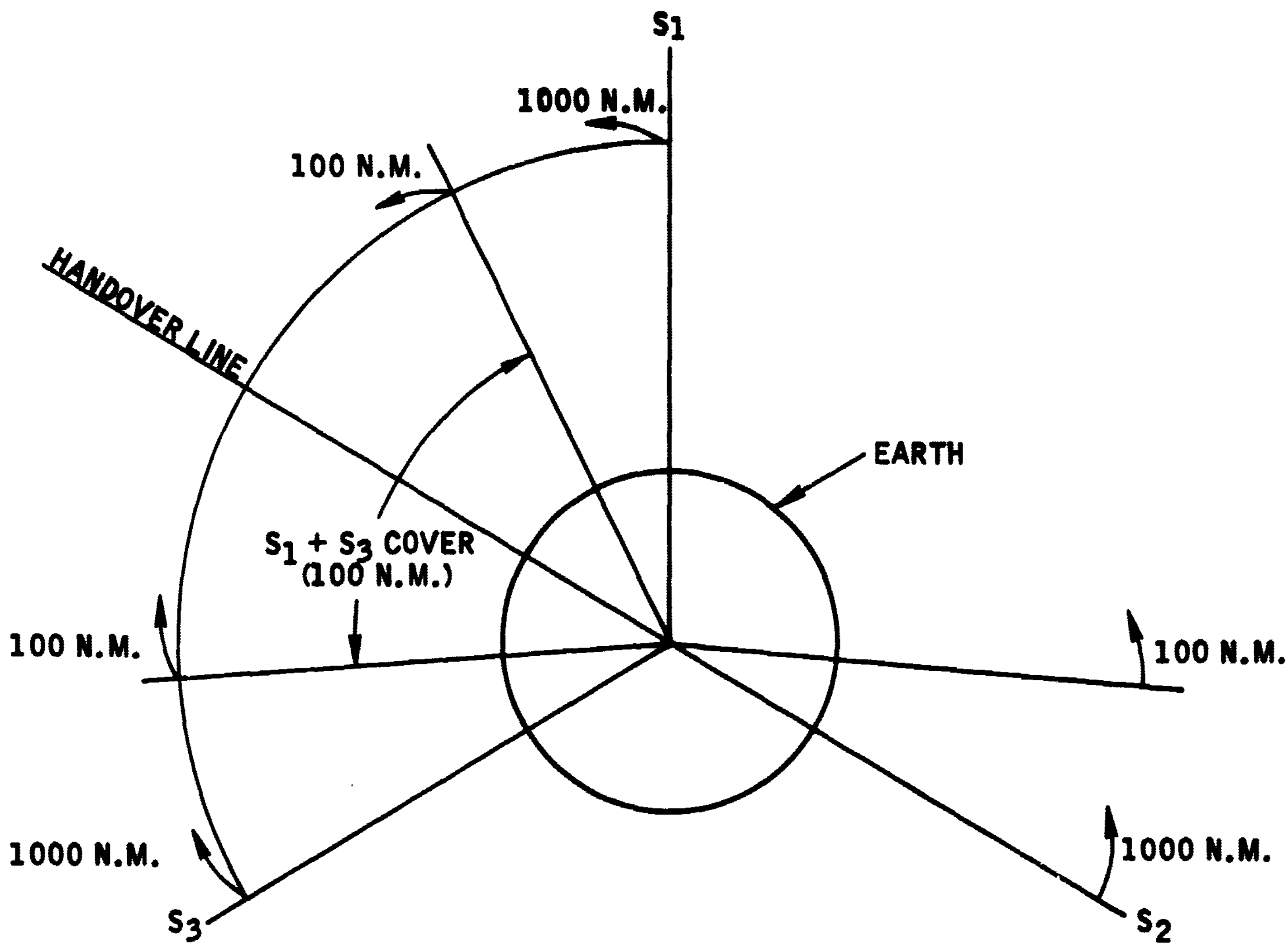


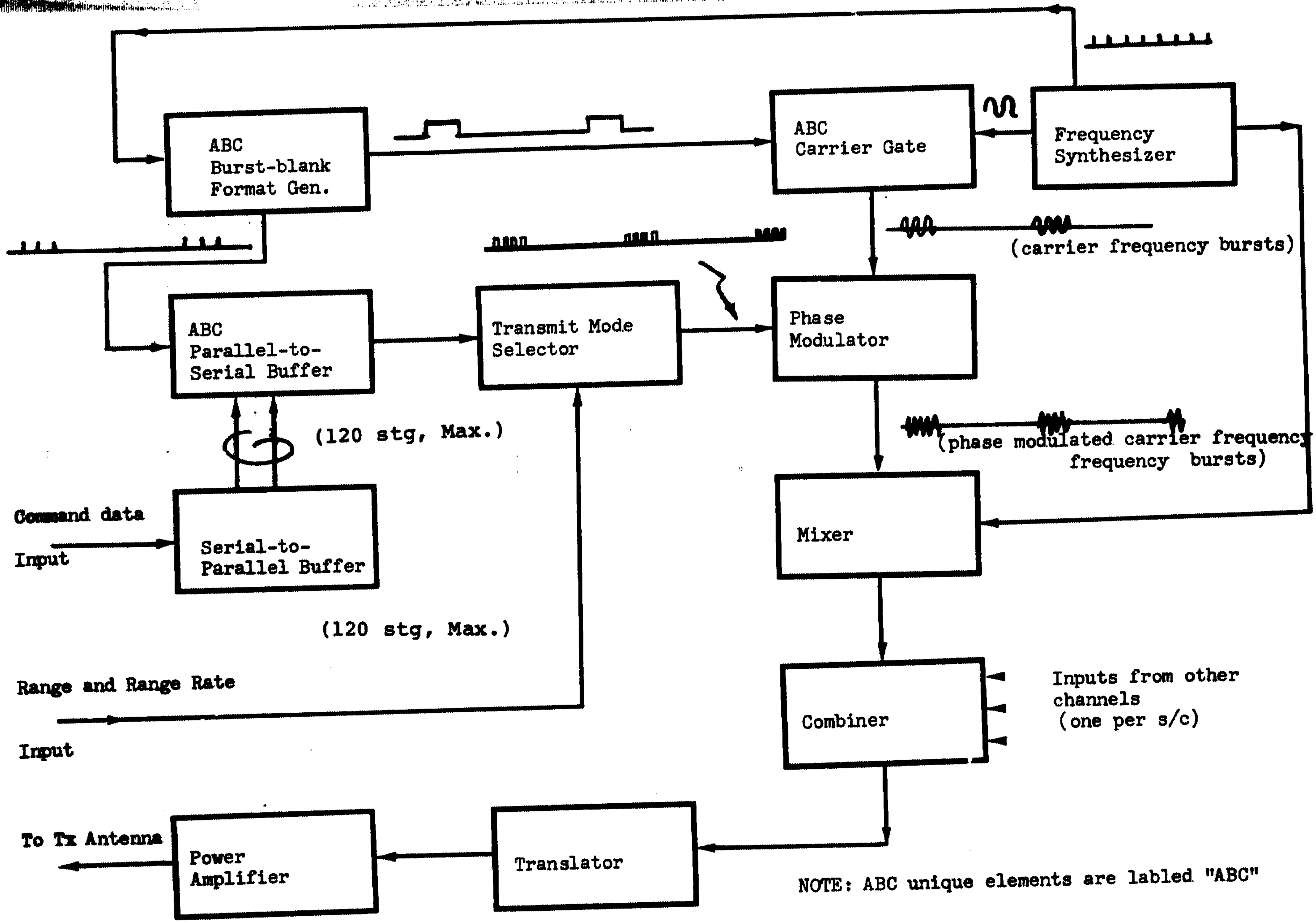
Figure 5-1 Common Coverage Angle Relations for Uniform Relay Model

logical way of operating, the ABC compatibility with presently existing equipment becomes even more significant. Note that it would simply entail the use of this existing gear to communicate with the s/c using the ABC format but not via a relay satellite. The multipath rejection would result from the ground antenna directivity as is the present case at launchings. When the s/c reaches sufficient altitude, say 80 nm, then the ground link via TDRS would become usable and the direct ground-to-s/c link could be abandoned. Note that there is no conflict in permitting the TDRS and direct links to coexist so that overlapping coverage would be a distinct possibility.

6. ABC SYSTEM IMPLEMENTATION. Realization of all of the performance advantages offered by the ABC system requires proper implementation of the system at transmitter and receiver. It is assumed to be necessary to accept data at the transmitter input in the form of a continuous serial stream of digital data. Buffer means must be supplied to accumulate and dump this data in the proper burst-blank format for the particular s/c altitude and the transmitter carrier must be cut off effectively during the blank interval. Optimum ABC reception requires that the burst-blank format be regenerated and used to gate the receiver output off during the blank interval of the direct signal to avoid the multipath energy and to realize the available process gain (7dB) against RFI. Since the demodulated data will come in bursts with blank intervals periodically interposed, it is assumed to be necessary to provide a smooth output flow of data by buffer sequence conjugate to that used in transmission. When these steps are realized, the ABC system will appear to be transparent and system operation will be essentially equivalent to a free-space link.

The following sections describe the system block diagram of one possible realization of the ABC concept and the required changes that would have to be made in NASA ground and s/c systems typically in use. Consideration is given to the requirements to obtain range and range-rate data.

6.1 BLOCK DIAGRAM. Figure 6-1 is a block diagram of one realization of the ABC ground transmitter. Starting with the input binary command data stream, an input buffer accepts the serial input and, on command from the Burst-blank Format Generator, dumps the stored sequence into



NOTE: ABC unique elements are labled "ABC"

Figure 6-1 Block Diagram - ABC Ground Tx a second buffer where the Burst-blank Format Generator will shift it out in the proper format. This formatted data is then used to modulate a VHF carrier that is gated by the same Burst-blank pattern. VHF carrier gating is used to assure the absence of carrier during the blank interval. Selection of carrier frequency determines the command channel. Subsequent to this VHF modulation process, the carrier, along with others that may be summed with it, is translated to the earth station transmitter frequency, probably X-band. There it is amplified to high power and fed via a circulator to the antenna complex for transmission to the relay satellite(s). The discussion, so far, has centered about ABC transmission of commands. However, another important function is the determination of range and range-rate information. This is done in a slightly different manner. Instead of buffering the input data and forming it into a staccato stream, range modulation is entered directly into the ABC system. Sidetone signals are converted to gated sidetone signals by virtue of the carrier burst-blank gating without any time distortion that would result from buffering. Note that the reception of this gated range and range-rate signal is not impaired by this action; there are no problems of aliasing, since correlation is used in any form of range measurement. There is no "ambiguity" of sidetone frequency since it is originated at the same location and in the same equipment.

It should be noted that no specific form of VHF or X-band carrier modulation was assumed. This is intentional. It has been shown that the ABC system is compatible with carrier coherent modulation techniques and hence can be used with virtually any modulation. It is suggested, however, that binary differentially coherent phase shift keying (DCPSK) be adopted since it is essentially as effective as the optimum binary PSK at the error rates required for TDRS, yet being simpler to implement in terms of resolving the classical ambiguity problem of antipodal PSK. Present recommended modulations for NASA are binary phase modulation that is not antipodal; there is a shift of less than 180°, thus guaranteeing a carrier component. This is also an acceptable modulation for ABC.

ABC s/c on-board reception is shown in Figure 6-2. Starting with the antenna circulator, it is seen that a conventional receiver provided with an intermediate-frequency signal gate delivers a base-band output to an ABC Format Regenerator. This programed format generator extracts the burst timing and duration by means of a gated conventional phase lock loop and provides gate input to the receiver to quiet the receiver during the blank interval of the direct signal. Loop acquisition is no problem because the direct burst always precedes the multipath signal and is non-diffuse in timing and amplitude. With proper format re-generation, the base-band data buffer will re-time the receiver output into a properly smooth data stream that can be fed into a conventional command decoder. Command decoder outputs are used as required by the mission throughout the s/c. Commands can be reserved for format changes if so desired. This allows great flexibility in operation. An on-board capability for only four formats will permit ABC operation from 100 nm to over 1,000 nm, as well as an option for conventional 100% duty

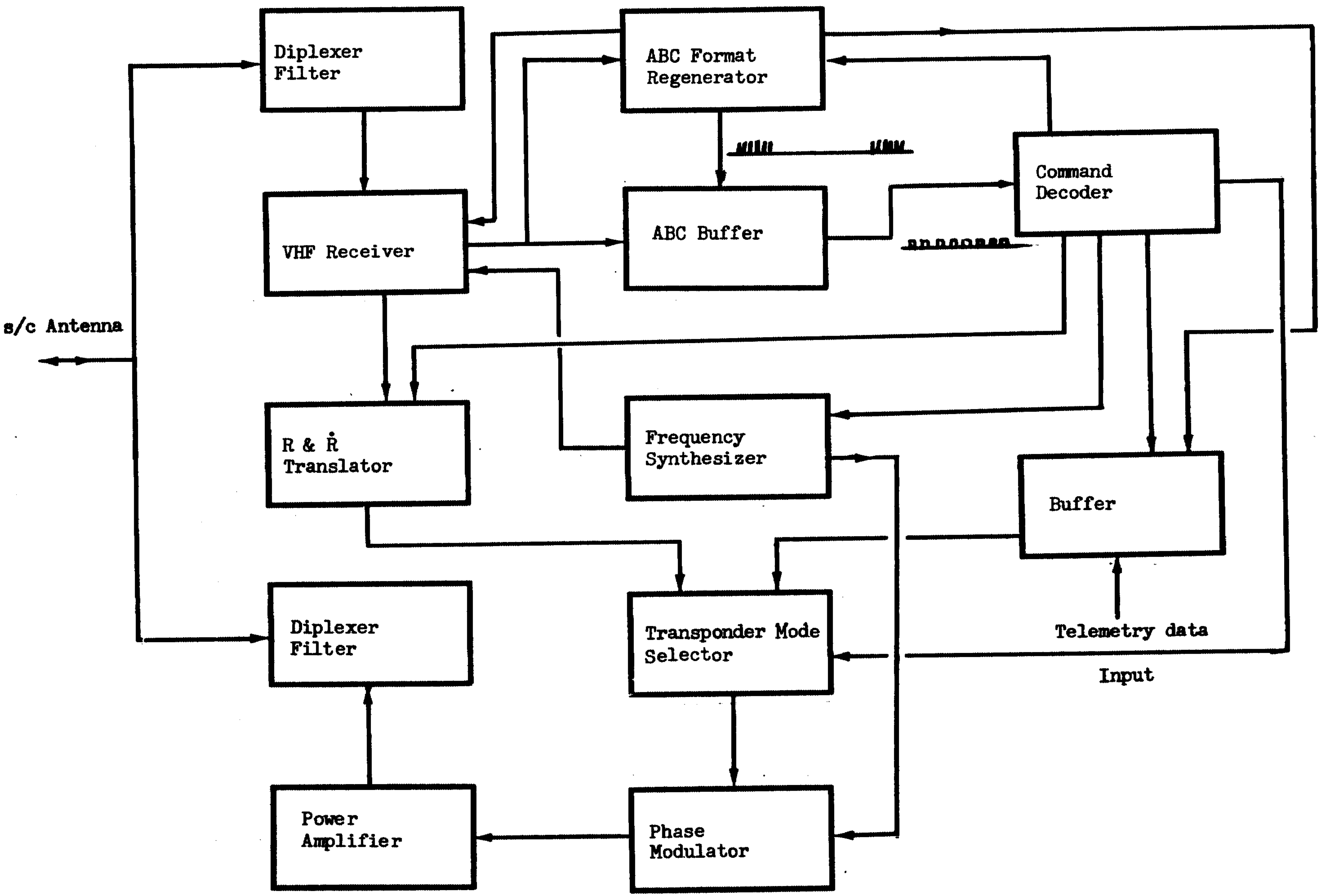


Figure 4.2 ABC s/c On-Board Reception

cycle operation. Other commands are assumed to be used for (1) ground selection of the s/c transmitter channel for RFI avoidance purposes and (2) commanding the s/c into either a range transponder mode or data transmit mode. Transmitter frequency is selected by commanding a synthesizer. Synthesizer complexity may range from a simple option of crystals to a full add-and-divide synthesizer. Present-day hand held walkie-talkie units such as the AN/PRC-25 provide 50 kHz channels from 35.05 to 76.00 MHz in small efficient packages so that on-board synthesis is quite practical. In the range mode, the receiver output is taken at the intermediate frequency and the receiver is not gated by the ABC burst-blank format. Although some additional RFI immunity may be lost, it is felt that gating is not required here and that the ability to relay the raw, non-gated command channel signal to earth may prove useful.

Ground station reception is very similar to s/c reception with the following differences: (1) there is no range transponder mode since the ground receiver terminates the two-way range configuration and (2) the signal input is derived from the received X-band signal rather than from a VHF antenna system.

Range rate information is acquired by measurement of the Doppler shift on the received carrier. It is subject to s/c heterodyning frequency errors unless the on-board frequencies are derived from the received signal. These considerations are in no way related to the use of ABC and are properly a consideration of any range and range rate system design and therefore will not be pursued further.

6.2 REQUIRED CHANGES IN CURRENT SYSTEMS. As part of this Study, HLI investigated the impact of ABC on presently existing NASA systems. Because ABC is compatibly channelized, all present transmitters and receivers are usable with ABC. Receivers should be retrofitted with IF gating for optimum results; however, HLI's inspection of the Rosman site showed that the present NASA range measurement system, GRARR, as it is actually being used, is compatible with ABC and that receiver gating can be conveniently done at coaxial jumper interfaces. The validity of this claim can be established easily and economically via a program recommended in section 10, "Recommendations".

The ability to work with the existing ground transmitters is highly desirable, although certainly not necessary for TDRS operation. This ability does mean that there would be a direct VHF link capability to back up TDRS in the event of failure, overload, or where incomplete coverage existed with TDRS. Note that there would be no need for major refurbishing of these transmitters for, say, wide-band operation. Nor would there be any need for additional s/c on-board electronics.

6.3 PHYSICAL REQUIREMENTS FOR ABC IMPLEMENTATION. In order to implement the ABC system as described, it is necessary to provide additional circuitry beyond the present-day receivers and command decoders for the s/c and to provide additional circuitry on the ground. The extent of these requirements is small. The buffer storage required is shown in Figures 6-1 and 6-2 as a maximum of 120 stages of simple binary buffer registers. These registers operate at the maximum rate of 20 kb/s and are of the maximum length only if full channel capacity of 4,000 bits/second are required at the highest altitude. Lower thru-put rates, lower altitude of the s/c or the total elimination of the need for buffer smoothing of the data rate (such as could be done very easily with computer processing of the data) would greatly modify or eliminate the need for <u>any</u> ABC buffer circuitry. However, assuming the worst case need of 120 bits of storage, this is easily done with present MOS/LSI techniques. Common bipolar technology is also quite feasable though not as economical of power as the MOS approach.

Because of the minimal speed requirements and lack of complicated circuitry it is expected that the reliability of the ABC implementation would be excellent. This should be contrasted with the difficulties being experienced on some wideband modem projects presently under contract. It should be remembered that the only significant requirement imposed by ABC is for simple serial/parallel memory; the simplest sequential data processing circuits in use with the possible exception of binary counters.

Required on-board frequency stability is well within present technology for either VHF or S-band use. VHF requirements are met by currently used s/c sources.

REFERENCES FOR SECTION 6

1. ____, Aerospace Data Systems Standards, NASA/GSFC Report X-560-63-2, April 1968.

2. ____, GSFC Specification GRARR VHF Transponder, NASA/GSFC Report S-571-P-24, March 1969.

3. Kronmiller, G. C. and Baghdady, E. J., The Goddard Range and Range Rate Tracking System: Concept, Design and Performance, NASA/GSFC Report X-531-65-403, October 1965.

7. ABC SYSTEM PERFORMANCE. The ABC system concept, signal design, carrier coherence requirements and modus operandi were described earlier. It was shown that ABC effectively eliminates multipath and reduces the TDRS medium to free space. To conclude the analysis of ABC performance, this section treats (1) the performance of the channelized anti-RFI technique proposed for ABC, (2) the relevant link power budget calculations, and (3) range and range-rate performance.

7.1 PROBABILITY OF CLEAR COMMAND CHANNEL IN SEVERE RFI. In section 5, it was proposed that channel sidestepping be used to avoid the channelized RFI. The probability that a clear (no RFI) command channel exists is a function of the RFI environment and the number of available command channels. It is very difficult to predict the magnitude and distribution of the RFI; therefore, a simple model will be assumed in which p = (probability that any given command channel will be sufficiently obscured by RFI to prevent the user from properly decoding the command signal), and n = number of command channels available to - and monitored by - a given user.

If the RFI is assumed to be stationary over the period of a command and assumed to be narrowband in nature, then the interference will be essentially independent from channel to channel and therefore, the probability that at least one clear command channel exists is given by:

$$P_c = 1 - p^n$$

The value of p obviously depends upon user altitude since a given interfering radiator will produce 20 dB less power at 1000 nautical miles than at 100 nautical miles. Based on available data, a worst case assumption would place the magnitude of the received interfering power equally likely from thermal noise level to 50 dB above that level in any given channel at a user altitude of 100 nautical miles. If it is also assumed that an interfering level of 10 dB or more above thermal noise will obstruct the command signal, then the value of p will range from 0.8 for a user altitude of 100 nautical miles to 0.4 for an altitude of 1000 nautical miles. Under these assumptions, the probability that a given user has at least one clear command channel is given by:

$$P_c = 1 - \left\{0.4\left[\frac{19}{9} - \frac{A_u}{900}\right]\right\}^n$$

where A_u is the user altitude (100-1000 n.m.), and n is the number of command channels available to that user. The above expression is plotted in Figure 7-1.

7.2 LINK CALCULATIONS. The relay-to-ground link will be considered first. The frequency employed will be about 14 GHz. The relay antenna has a gain (including efficiency) of about 15 dB, and the 85-foot diameter paraboloid on the ground has an effective gain of about 70 dB. The path loss for a frequency of 14 GHz and a worst case distance of 22,500 nautical miles will be 207.8 dB, and the noise power spectral density will be -198.6 dBw/hz for a noise temperature of 1000°K. The specified bit rate for the telemetry link is 1000 bits/sec., and the

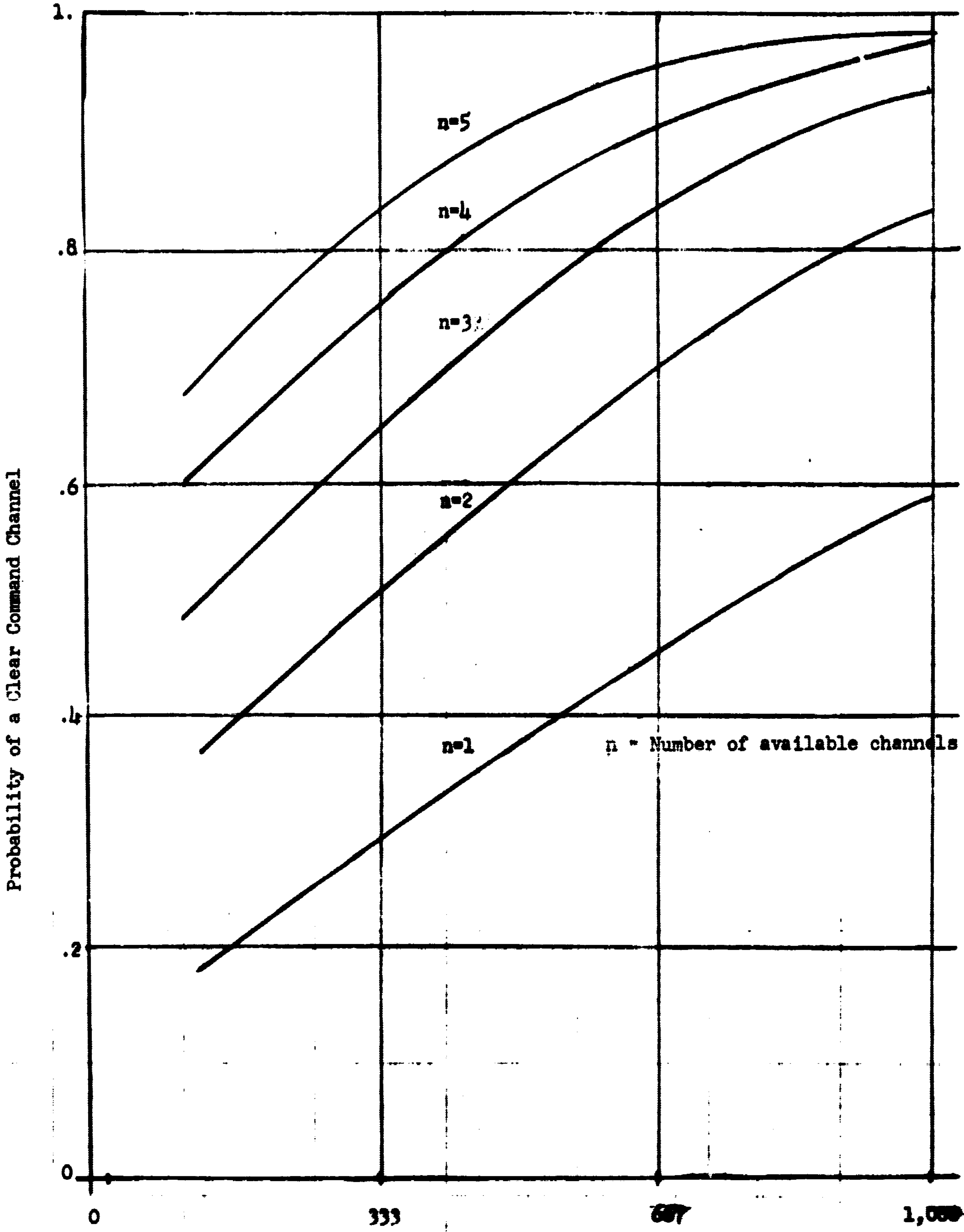


Figure 7-1 Probability of a Clear Channel

desired bit error rate (BER) is 10^{-5}. Since this figure is an overall error rate, an overall S/N considering both the user-to-relay and relay-to-ground links must be employed to obtain a BER of 10^{-5}. A preliminary examination of the required power for these links reveals the fact that, when the total relay on-board power distribution is considered, it is desirable to make the relay-to-ground S/N at least 10 dB higher than the user-to-relay S/N. If DCPSK is employed, an error rate of 10^{-5} corresponds to an E/N_0 of 10.3 dB and, if a system margin of 6 dB is desired, the required E/N_0 will be 16.3 dB. Therefore, the figure 26.3 dB will be chosen and the required relay power per user (relay-to-ground link) will be:

-15-70+207.8-198.6+30+26.3 = -19.5 dBw, about 11 milliwatts an easily obtainable amount of power.

The ground-to-relay link is not power limited, and can thus readily be made errorless. Therefore, both the relay-to-ground and ground-to-relay links will be considered errorless.

Now consider the user-to-relay link. The frequency employed will be about 140 MHz. The user antenna will be omnidirectional and the relay antenna (including efficiency) will have a gain of about 15 dB. The path loss for a frequency of 140 MHz and a worst case distance of about 21,300 nautical miles will be 167.3 dB, and the power spectral density of the noise will be -198.6 dBw/hz for a 1000°K noise temperature. As indicated earlier, the specified telemetry data rate is 1000 bits/sec., and the required E/N_0 will be 16.3 dB for an overall BER of 10^{-5}. Therefore, the required user power will be:

$$-15-0+167.3-198.6+30+16.3 = 0 \text{ dBw, or 1 watt.}$$

The relay-to-user link serves two functions, command and tracking. It will be assumed, for purposes of this report, that it is desirable to minimize the amount of relay on-board power to the value required for support of command and telemetry and to accept the tracking performance that results. An inspection of the above calculation yields the fact that a relay transmitter power of 0.1 watt per user (relay-to-user link) will support a 100-bit per second command channel. The S/N in a 30 kHz bandwidth at the user will be:

$$(S/N)_u = -10+15-167.3+198.6-44.8 = -8.5 \text{ dB}$$

and the S/N in a 30-kHz bandwidth back at the relay will be:

$$(S/N)_r = +15-167.3+198.6-44.8 = +1.5\text{dB}$$

7.3 RANGE AND RANGE-RATE TRACKING ACCURACY. Spacecraft range and range-rate data can be obtained by several methods. One possibility is to use the Goddard Range and Range Rate System (GRARR) without essential modification. The bandwidth of the carrier, subcarrier, and tone phase locked loops are sufficiently narrow to enable the VCO's to flywheel through the off periods of an adaptive burst commuuications (ABC) system. The only GRARR system modification required would be the addition of receiver blanking during the multipath reception interval in order to prevent erroneous phase perturbation of the phase locked loops.

The GRARR system, as presently used, employs a 4 kHz holding tone to maintain the user in the tracking mode, and a 20 kHz tone to obtain precise range. Tone frequencies of 4.8 kHz, 4.16 kHz, 4.032 kHz, and 4.0008 kHz are sequentially applied to resolve the phase ambiguity of the 20-kHz tone. All of the above tones are phase-modulated onto the carrier. An ambiguity resolving pseudo-random code is also employed when necessary for distances in excess of that resolved by the 8 Hz tone. Range rate is obtained by determining the received Doppler frequency.

The ABC system can generate and derive the necessary range and range rate information from entirely within a 30 kHz channel bandwidth. (This discussion will be limited to VHF, since the available bandwidth at UHF substantially eases the tracking problem.) This system is similar to the GRARR system in that the range-rate data would be obtained through the use of a carrier phase locked loop (PLL) and the range data obtained from sidetone frequency loops. There are three principal differences:

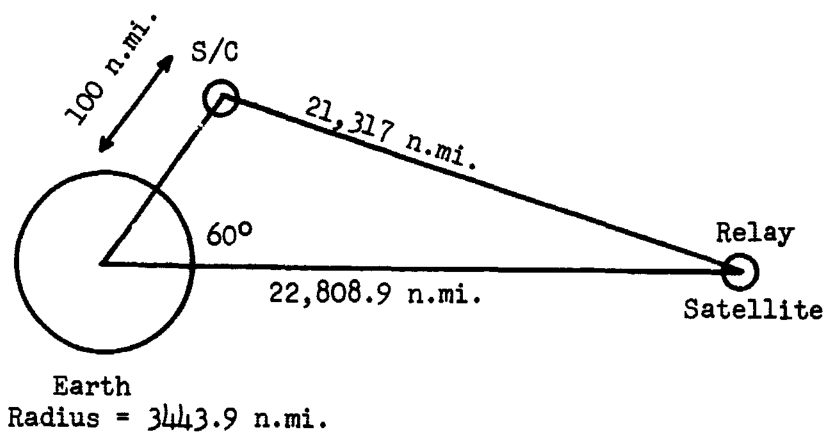
(a) The subcarrier would not be employed on the return link.

(b) The GRARR ambiguity resolving code would not be required for the present user-relay configuration.

(c) The available bandwidth restricts the highest phase modulated tone frequency to be 10 kHz.

The fact that the tracking information is modulated directly on the carrier instead of on the subcarrier eliminates the possibility of tracking and receiving telemetry simultaneously, but, for most users, this is not a serious problem.

The maximum distance between relay and spacecraft will occur when the spacecraft altitude is 100 nautical miles and handover is occurring between two relays 120 degrees apart (for the presently defined relay configuration). The geometry is shown below, and the resulting distance is 21,317 nautical miles.



The minimum distance will occur when the spacecraft altitude is 1000 nautical miles and the relay is directly overhead. This distance will be 22808.9-4443.9 = 18365 nautical miles. The difference between the minimum and the maximum distance determines the maximum value of the lowest tone frequency in order to prevent range ambiguity. This difference in distance is 21317-18365 = 3852 nautical miles, and as a result, the lowest tone frequency must be less than or equal to:

$$\frac{C/2}{3852} = 21.0 \text{ Hz.} \quad \text{(C = velocity of light in vaccuum)}$$

The lowest tone frequency in the GRARR system is 8 Hz. Therefore, the ambiguity resolving pseudo-random code portion of the GRARR system would not be required.

The use of 10 kHz instead of 20 kHz as the highest sidetone frequency would require two easily constructed applique units to be employed in conjunction with the present GRARR equipment to obtain complete compatability. First, the 20 kHz tone, as presently generated, would have to be divided to 10 kHz before modulating the carrier, and second, the received 10 kHz tone would have to be doubled to 20 kHz after demodulation but before processing by the tone PLL. Both of the above steps could readily be achieved in a phase coherent manner. Thus, the ABC can provide the required tracking data using only a 30 kHz bandwidth.

The range and range-rate performance can now be derived. The range-rate information is derived from the Doppler shifted carrier. This measured Doppler frequency is an average frequency over the measurement interval. The error involved in deriving the range rate from this average Doppler frequency will be assumed negligible compared with the thermal noise phase error. This is reasonable, since the maximum rate of change of Doppler shift rate (for the present relay-s/c configuration) is less than 0.01 Hz/sec^2.

The required sampling rate is one sample per second; therefore, the measurement interval will be chosen to be 0.8 second. Assume that a counter is actuated by the first positive going zero crossing after the start of the interval and stops counting at the occurence of the first positive going zero crossing after the end of the 0.8 seconds. Also assume that the length of the true measurement interval is determined through the use of a precise 100 MHz frequency standard. The use of this standard results in a measurement uncertainty of 10 ns.

A S/N of 20db in the carrier PLL bandwidth would result in a rms phase uncertainty of approximately 4 degrees which, at a bias frequency of 20 kHz, corresponds to 560 ns. Therefore, the measurement uncertainty due to the 100 MHz standard can be neglected. A 20 kHz bias frequency is added to the two-way Doppler frequency, f_D, before measurement in order to facilitate the determination of range rate. This bias frequency is chosen to be about five times the maximum to be encountered for any TDRS user s/c, including circular and elliptical orbits.

Range rate (at VHF) can be expressed in terms of Doppler frequency as:

$$\dot{R} = \left(\frac{f_D}{140 \text{ MHz}}\right)\left(\frac{c}{2}\right) \quad \text{m/sec.}$$

The spacecraft transponder frequency translation ratio is assumed to be unity for the purpose of this analysis since true uplink and downlink frequencies are presently undefined. The measurement uncertainty of f_D, $\sigma_{\dot{R}}$, due to the thermal noise phase error will be approximately:

$$\sigma_{\dot{R}} = \frac{\sqrt{2}\,\sigma_\Phi}{2\pi(0.8)} \approx \frac{1}{5\sqrt{S/N}} \quad \text{m/sec.} \qquad \text{for} \quad \sigma_\Phi = \sqrt{\frac{1}{2S/N}}$$

i.e., for a second order PLL with $S/N \gg 1$.

The range information is obtained from the phase at the output of the 10 kHz PLL, and the rms range uncertainty will be given by:

$$\sigma_R = \left(\frac{\sigma_\Phi}{2\pi}\right)\left(\frac{c}{2}\right)\left(\frac{1}{f_t}\right) \qquad \text{meters}$$

where c is the velocity of propagation and f_t is the tone frequency.

If f_t = 10 kHz is used, the result is:

$$\sigma_R = \frac{1687}{\sqrt{S/N}} \text{ meters}$$

It will be assumed that the peak phase deviations of the sidetones will be identical to the GRARR case. That is, the 10 kHz (20 for GRARR) tone will have a peak deviation of 0.7 radians, and the 4 kHz holding tone will have a peak deviation of 0.3 radians. Under these conditions the carrier will be 1.3 dB below the unmodulated carrier, and the sidetone will be 9.7 dB below the unmodulated carrier.

The range and range-rate accuracies can now be calculated employing a relay power of 0.1 watt per user and a user power of 1 watt. The signal-to-noise ratios at the user and the relay were previously shown to be: $(S/N)_u$ = -8.5 dB, and $(S/N)_r$ = +1.5 dB.
A simple calculation using Appendix D yields an overall S/N of -11.1 dB (in a 30 kHz bandwidth).

A carrier PLL bandwidth of 20 Hz is sufficient for all configurations that will be encountered in the presently anticipated relay deployment. Therefore, for a modulated carrier 1.3 dB below the unmodulated carrier, the resulting S/N in the carrier PLL bandwidth will be: -11.1-1.3+31.8 = 19.4 dB. The rms range-rate uncertainty will then be 0.0758 meters/sec.

The 10 kHz sidetone will be 9.7 dB below the unmodulated carrier. If the 10 kHz PLL bandwidth is 0.1 hz, then the resulting S/N in the tone PLL bandwidth will be: -11.1-9.7+54.8 = 34 dB. The rms range uncertainty will then be 33.7 meters.

7.4 SUMMARY OF ABC SYSTEM PERFORMANCE

Ground-Relay Link

Frequency = 14 GHz

Bandwidth (per channel) = 30 kHz

Ground Antenna Gain = 70 dB

Relay Antenna Gain = 15 dB

Noise Temperature = 1000°K.

Bit Rate (command) = 100 bits/second

Bit Rate (telemetry) = 1000 bits/second

Bit Error Rate is negligible.

System Margin = 6 dB (relay-to-ground)

Relay Power = 11 milliwatts per user

Relay-User Link

Frequency = 148 MHz (relay-to-user command and tracking)

Frequency = 136 MHz (user-to-relay tracking and telemetry)

Bandwidth (per channel) = 30 kHz

Relay Antenna Gain = 15 dB

User Antenna Gain = 0 dB

Noise Temperature = 1000°K.

Bit Rate (command) = 100 bits/second

Bit Rate (telemetry) = 1000 bits/second

Bit Error Rate = 10^{-5}

System Margin = 6 dB

Relay Power = 0.1 watt per user

User Power = 1 watt

RMS Range-Rate Uncertainty = 0.0758 meters/second

RMS Range Uncertainty = 33.7 meters

	GROUND-TO-RELAY LINK (14GHZ) Command/Telemetry	RELAY-TO-USER LINK (148MHz) Command	USER-TO-RELAY LINK (136 MHz) Telemetry
xmit. power dBw	-19.5 per s/c	-10 per s/c	0
xmit. ant. gain dB	70 (15 for Telemetry)	15	0
path gain dB	-207.8	-167.3	-167.3
rec. ant. gain dB	15 (70 for Telemetry)	0	15
rec. power dBw	-142.3	-162.3	-152.3
noise power dBw	-168.6 in 1 kHz bw.	-178.6 in 100Hz bw.	-168.6 in 1 kHz bw.
rec. S/N dB	26.3 in 1 kHz bw.	16.3 in 100 Hz bw.	16.3 in 1 kHz bw.
system margin dB	6	6	6
net rec. S/N dB	20.3 in 1kHz Bw.	10.3 in 100 Hz bw.	10.3 in 1 kHz bw.
BER for DPSK	negligible	10^{-5}	10^{-5}

TABLE 7-1 Link Calculation Summary

	RELAY-TO-USER LINK (148MHz) Tracking	USER-TO-RELAY LINK (136MHz) Tracking
xmit. power dBw	-10 per s/c	0
xmit. ant. gain dB	15	0
path gain dB	-167.3	-167.3
rec. ant. gain dB	0	15
rec. power dBw	-162.3	-152.3
noise power dBw	-185.6 -208.6	-185.6 -208.6
rec. S/N dB	23.3 in 20 Hz bw. 46.3 in 0.1 Hz bw.	33.3 in 20 Hz bw. 56.3 in 0.1 Hz bw.
rms range uncert.	33.7m	
rms range-rate uncert.	0.0758m/sec.	

CONTINUATION OF TABLE 7-1 Link Calculation Summary

8. ABC VHF VOICE CAPABILITY. With a through-put bit rate of 4 kb/s shown to be easily obtainable, it is a simple matter to demonstrate the feasibility of voice transmission via ABC. A direct solution is to use a voice-channel vocoder such as the Philco KY-585. This device normally operates at 2.4 kb/s, and provides over 75% intelligibility at a 10^{-2} BER and 80% for 10^{-5} BER, based on phonetically-balanced word list tests. This performance is more than adequate when projected against normal speech with correlated words and phrasing. Such equipment is in widespread use today, though not miniaturized and space qualified.

At the HLI presentation after the Interim Report, Mr. Paul Hefferman of GSFC suggested that HLI look at other means of sending non-digital voice at VHF and within the ABC concept. We have been able to show, as a result, that it is quite possible to use the ABC system to transmit voice by other means than by vocoder. For example, it is entirely feasible to use pulse-position modulation (PPM) or its "integral" form pulse-width modulation (PWM) to convey speech amplitude samples proportionally; i.e., non-quantized.

Since the PLTD values are such that the ABC burst rate is less than the lowest satisfactory sampling rate, it is necessary to transmit more than one modulated pulse during each burst. If a maximum pulse width or position modulation of one pulse width is assumed, as is typically done in terrestrial PPM or PWM systems, the conventional speech sample rate of 8 kHz would require the same pulse widths as a 16 kb/s ABC system. This could be obtained with a 90 kHz channel allocation, having a utilization of 80 kHz with the 0.20 duty cycle. For PPM, the pulses would be 12.5 ms wide, peak modulated by ±6 ms and separated by 12.5 ms. Demodulation would require PPM-to-AM conversion and sample-and-hold circuits to buffer these samples into a periodic "boxcar" output. These techniques are commonly used and are absolutely within the present state-of-the-art.

In summary, VHF voice can be supported by the ABC system either by vocoder or by analog pulse modulation. Both techniques require special circuitry, but circuitry that is well-defined and in common use.

9. CONCLUSIONS. The Adaptive Burst Communications (ABC) system utilizes the unique characteristics of the TDRS multipath medium to achieve communication and tracking performance easily surpassing the requirements. Data is transmitted in bursts of a duration such that the delayed multipath signal return does not overlap the direct path signal, thus reducing the TDRS medium to a line-of-sight path free of multipath. System performance will be close to an optimally matched multipath receiver. With a duty cycle of 0.20, no format changes are required for near-circular orbits, the vast majority of TDRS user orbits. ABC does not require error correcting codes though the use of coding is not precluded and it may be incorporated as desired without impact from ABC.

The ABC system signal design is compatible with the standard 30 kHz channel allocations at VHF and with the 50 kHz allocations at 400 MHz. System operation is based on the familiar "address-command-execute" concept. Since burst-to-burst carrier phase coherence is readily achieved, conventional coherent signal reception techniques are feasible. Signal acquisition and handover from satellite to satellite require no special considerations. These familiar techniques and procedures assure a minimum retraining of operations personnel. Utilizing relatively low-speed circuits in very simple configurations, the reliability, economy, and performance of the ground and on-board equipment should be near maximum. Presently existing ground equipment, both transmitting and receiving, will not be made obsolete by the ABC system and can provide a no-cost pre-existing backup for the TDRS.

Examination of the available data indicates the highly channelized nature of the RFI. The ABC system is matched to this environment and should combat RFI effectively by channel side-stepping.

ABC is compatible with all forms of satellite repeaters commonly used. It suffers no significant degradation when used with hard-limiting, linear or demod/remod satellites. No special timing requirements exist for the satellites or for the link. Only locally generated bit synch and phase lock are needed, as in any digital data system with carrier coherence. No code lock is required and hence no danger of loss of lock with a code sequence.

ABC is presently capable of supporting over 60 user channels. Expansion beyond the present capacity is possible through the use of discrete addresses as is done at present.

Vocoder or analog pulse modulation can provide VHF voice capability via ABC.

The system is compatible with either side-tone or p-r range techniques, and can utilize carrier Doppler for range rate measurement. Range and range rate performance will meet or exceed that required by TDRS.

The ABC system suffers no "duty cycle" penalty in signal-to-noise performance because of process gain of +7 dB realized by matched time gating in reception.

The following table briefly lists the major points of comparison between ABC and wide-band spread spectrum techniques.

TABLE 9-1 A COMPARISON OF THE ABC SYSTEM AND SPREAD SPECTRUM (WIDE BAND)

	ABC SYSTEM	SPREAD SPECTRUM
RFI	* Effectively reduced thru use of side-stepping techniques due to channelized nature of both ABC system and RFI. * Effective rejection high with conventional filters.	* Anticipated RFI may prevent acquisition. * Exposed to all RFI in the wide band. * Process-gain limited
Bandwidth Requirements	* Narrow band. Compatible with existing standards, equipment and allocations.	* Wide band. Availability of allocations questionable. * Difficult to limit interference with other sensitive users in non-interfere allocations.
System Expansion	* Up to 66 users in 2 MHz band. Can be expanded by conventional time-sharing on discrete address basis.	* Available process gain margin is insufficient to provide expansion and system margin.
Equipment	* Simple. Low-speed circuitry. * Small size, light weight, low power consumption.	* Complex. High-speed circuitry. * Larger, heavier, more power consumption.
Operational Procedures	* Conventional acquisition and handover. Simple reacquisition.	* P-R code acquisition required. * Reacquisition possibly complex. * Conventional handover.
Personnel Training Requirements	* Minimal. Easily accomplished because of simple concepts.	* Extensive educational program required.
Cost	* Very low.	* Moderate to high.
Range and Range Rate Capability	* Compatible with side-tone or p-n ranging. Accuracy determined by signal energy/noise density ratio	* P-n ranging usually used. Performance limited by signal energy /noise density ratio as for ABC.
Transponder Requirements	* Compatible with hard-limiting, linear or demod/remod satellites.	* Compatible with hard-limiting, linear, or demod/remod satellites.
RF Power Requirements	* Minimum	* Higher than ABC due to acceptance of all RFI in wide band.
Link Coordination	* None. Strictly random access.	* None. Strictly random access.
Compatibility With Existing Equipment	* Highly compatible. Simple applique equipment required.	* Incompatible with existing transmitters. Marginally usable with receivers and preamps.

10. RECOMMENDATIONS. HLI recommends several courses of action for NASA/GSFC as a result of knowledge and understanding gained during this Study. Some of these actions should be taken by NASA irrespective of the TDRS modulation technique ultimately selected. This is true of the first three. The remaining recommendations involve the ABC system.

HLI recommends that NASA seek VHF allocations for their exclusive use. Though easier said than done, nonetheless it seems imperative to make the attempt due to the severe RFI that is anticipated in the 136 and 148 MHz bands. The Interdepartmental Radio Advisory Committee (IRAC) should be approached on this matter as soon as possible.

HLI recommends that NASA plan to go to the 400 MHz telemetry band as soon as possible because of the relaxed RFI problem and for more bandwidth. We do not feel it is advisable for the unstabilized and unoriented unmanned or manned user to go higher in frequency because of the loss of omnidirectional characteristic of the s/c antennas.

HLI recommends that RFI measurements be taken in the 148 MHz command band from orbiting s/c in the 100 to 1000 nm purvey of TDRS and that 136 MHz RFI measurements be taken via the ATS stationary satellites. Until this is done, or reliable real data is obtained elsewhere, there can be no confidence in the success of TDRS. This program is considered to be crucial.

HLI recommends that the ABC system be adopted as a candidate technique for TDRS and that additional evaluations and tests be performed on it. We feel that the high potential of the ABC system for VHF should be explored as part of the planning-decision process in the evolution of TDRS.

In line with the above we suggest three programs.

10.1 ABC CAPACITY INCREASE. HLI suggests that NASA investigate the possibility of employing a system in which the user receives and transmits on the same 30-kHz channel, thus effectively doubling the available spectrum. This is easily accomplished within the framework of the ABC system. Assume, for the purpose of illustration, that the burst-blank technique is in operation with a duty cycle of 20 percent and with a user altitude such that the burst duration is 1 ms. The user (or relay) thus receives the multipath during a substantial part of the remaining 4 ms. There is no reason, however, why the user (or relay) can not transmit on the same carrier frequency during part of the 4 ms. that the multipath is being received. There are no timing problems at the user since the position of the received direct path burst can be determined through the use of envelope detection to well within the desired accuracy. For tracking, the only added user complexity will be the requirement for on-board memory in the form of sidetone PLL's. These are necessary in order to store the range and range-rate phase information during the 2.5 ms. between the time it is received and the time it is transmitted.

The timing of the relay-transmitted burst is controlled by the ground station. This timing must be varied periodically since the propagation time between the relay and the user is continually changing, and the relay transmission and reception must remain interleaved. The timing necessary for this interleaving is initially established by the ground sending several bursts through the relay to the user and back through the relay to the ground. The propagation time between the relay and the user will then be known since the propagation time between the ground and the relay will have been previously determined. It is the change in the propagation time between the relay and the user that must be continually accommodated, and this change is approximately 1 ms. every 250 ms. for a 100 n.m. user. Once the initial timing is determined, the ground then periodically delays its transmission an amount corresponding to the changing relay-user propagation time.

When the user is in a telemetry mode (or telemetry plus one-way Doppler), none of the above is necessary. Therefore, the technique described herein can be thought of as a method to achieve command and tracking on the same channel employed for telemetry.

10.2 ABC-GRARR COMPATIBILITY TEST. It would be desirable to demonstrate the feasibility of the burst-blank communication concept known as the ABC system. The fundamental precept requires phase coherence through the off periods to guarantee range and range-rate capability. A recent inspection of the Rosman STADAN facility indicated that a simple experiment would suffice to demonstrate that the GRARR system would suffer no measurable degradation when subjected to a burst-blank format. This is easily accomplished in a static (no doppler) manner by illuminating the pole beacon with the burst-blank modulated VHF transmitter operating at the reduced power output of 200 watts at 148.26 MHz. The essentially unmodified spacecraft transponder returns the signal at a frequency of around 136 MHz and the ground station tracking demodulator acquires the ranging sidetones as the ambiguities are resolved. The on-site equipment thus allows a comprehensive test of ABC-GRARR compatibility. If the transponder is assumed transparent, the burst-blank modulation can even be applied to the received signal instead of the transmitter.

The next step would be to demonstrate ABC-GRARR compatibility under dynamic conditions (i.e., in a doppler environment). An engineering test employing a convenient satellite could be performed, again modulating the transmitted waveform and noting the performance of the carrier and sidetone tracking loops. The ambiguity resolving code is not transmitted since the 8 Hz ranging sidetone would be sufficient to resolve all ambiguities encountered in the TDRS system environment.

It should be noted that neither of the previous experiments require modification of the tracking demodulator (i.e., sidetone PLL gating) and therefore, are easy to implement and also represent a worst-case, non-gated demodulator PLL signal environment.

A third experiment would be more complex but nevertheless quite desirable. This would involve tracking a cooperative satellite through ATS. The ABC system would again be employed. No insurmountable ground station hardware problems would be anticipated, but operational considerations and coordination would require a substantial effort.

10.3 ABC ANALOG VOICE DEVELOPMENT. HLI recommends that the use of non-digital voice techniques in conjunction with the ABC system be explored in a modest program. Such a program directed towards the analog pulse methods outlined in Section 8.0 could be a test vehicle for experimental and subjective evaluations of these methods in the laboratory, independent of flight tests. The simplicity and high probability of success are strong reasons for undertaking the recommended program at this time.

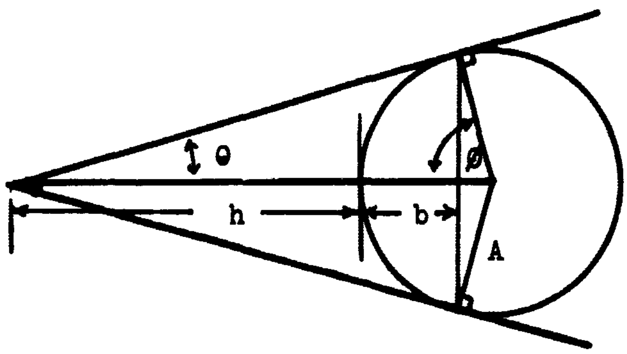
11. NEW TECHNOLOGY

There are no developments to report under the New Technology clause.

APPENDIX A

PERCENTAGE EARTH COVERAGE AS A FUNCTION OF ALTITUDE

For a spacecraft at altitude h above a spherical earth, the percentage of earth coverage is found from the following construction:



$\Theta = \mathrm{Sin}^{-1} A/(h + A)$ $\qquad$ $b = A - A \cos \emptyset$

$A \text{ (viewed)} = 2\pi A b$

$A \text{ sphere} = 4\pi A^2$

$\text{Rel. view} = \frac{b}{2A} = \frac{1}{2} - \frac{\cos \emptyset}{2} = \frac{1}{2} - \frac{\sin \Theta}{2} = \frac{1}{2} - \frac{a/2}{h+A} = \frac{h/2}{h+A}$

A = 3444 nm

For h = 100 nm

$\text{Rel. view} = \frac{100/2}{100 + 3444} = 1.4\%$

For h = 6000 nm

$\text{Rel. view} = \frac{1000/2}{1000 + 3444} = 11.2\%$

For h = 19,365 nm

$\text{Rel. view} = \frac{19,365/2}{19,365 + 3444} = 42.4\%$

APPENDIX B

ABC FORMAT DESIGN PRINCIPLES

This Appendix is included to illustrate design procedure for ABC system format when format changes are required. Format changes may be necessary when servicing users with elliptical orbits or when a higher duty cycle is desired with users in circular orbits.

Figure B-1 shows the relations between burst duration T_b, total of burst time and inter-burst interval T_o, their ratio d, and PLTD. The plots show the limiting values of burst duration as a function of PLTD for a given d. The limiting large value for d is 0.5, since no overlap is permitted. This always corresponds to the minimum PLTD that a format can accommodate.

In the lower right of Figure B-1 are simple graphs of the number of pulse (bits) that can be transmitted at the indicated bit rates for the corresponding burst durations. These values were taken as representative; others can be used as desired.

Using the information contained in Figure B-1, together with the maximum and minimum values of PLTD as determined from handover considerations for any given relay satellite deployment (see Figure 1), a signal design can be implemented. Some examples of signal design are:

1. Consider a 100 nautical mile orbit, handover between satellites up to 130° apart and an assigned bandwidth of 30 kHz of which 20 kHz will be used. From Figure B-1 the minimum and maximum PLTD values are approximately 0.40 and 1.25 milliseconds. Assuming a data rate of 20 kilobits per second, a burst will

contain at least eight (8) bits. If a channel duty cycle of 0.333 is assumed, the burst duration will have to be re-formatted to accommodate bursts of 0.4, 0.8, and 1.6 ms and reduced again as the s/c is handed to and from a particular relay satellite. With three (3) relays and a s/c period of about 1.5 hours (at 100 nm), this is only four format changes each half-hour for full coverage. Such a format change is non-critical and could be initiated either from the earth or on-board. Notice that in all cases the average information rate is fixed at 20/3 or about 6.7 kilobits per second, far in excess of the system requirements in Table 1-1.

2. Consider the same s/c and relay situation as above but determine the parameters that result if the format is to accommodate the 0.4 to 1.25 ms PLTD range without change. In this case, enter the curves of Figure B-1 at d = 0.5, PLTD = 0.4 ms and read across to PLTD = 1.25. The value d is slightly less than 0.25. If d is taken to be 0.20, to allow margin, then a data rate of (0.2) (20 kb/s) or 4,000 bits/second can be supported. Pulse rates as low as 2.5 kb/s could be used (i.e., 1 bit/burst) resulting in a 500 b/s data rate.

Familiarity with the sign design procedure is easily developed and signal designs for parti r parameters or sets of parameters can be easily accomplished.

While the burst rates, duty cycle d, and PLTD information apply to any carrier and bandwidth allocation for TDRS, it should be noted that the actual data rates depend on the assigned bandwidth since the larger the bandwidth, the higher the allowable pulse rate and more average bits per unit time can be sent. Thus, if the 400 MHz band is utilized with a full bandwidth assignment of 300 kHz, a factor of ten (10) would apply to the data rates in the preceding examples.

It should be noted that the type of modulation has not been stipulated. As shown elsewhere in this report, the ABC system as applied to TDRS is capable of using any carrier modulation technique for either VHF or S-band/UHF. The designer has full freedom in this regard, since fully coherent, differentially coherent, and non-coherent techniques are all potentially usable.

In the design consideration for a given mission or project, it is assumed that some a priori information is available as to orbit altitude and nature; e.g., circular, elliptical, or interplanetary, and that a significant uncertainty in these parameters is equated to mission failure. Thus the designer can project the approximate PLTD requirements well in advance and can provide a suitable number of format steps, the entire TDRS configuration not being required except for apogee and perigee values that exercise the limits of the TDRS coverage plan. It is suggested that each spacecraft be provided with a format position that represents d = 1. This is a full-time, non-burst mode that may be useful for command and communications with the already-existing earth stations on either a planned or emergency basis in the event of relay failure, anomalous occurances, severe RFI, or other situations. Note that this facility is "free", since no additional hardware is required for either the s/c or earth stations.

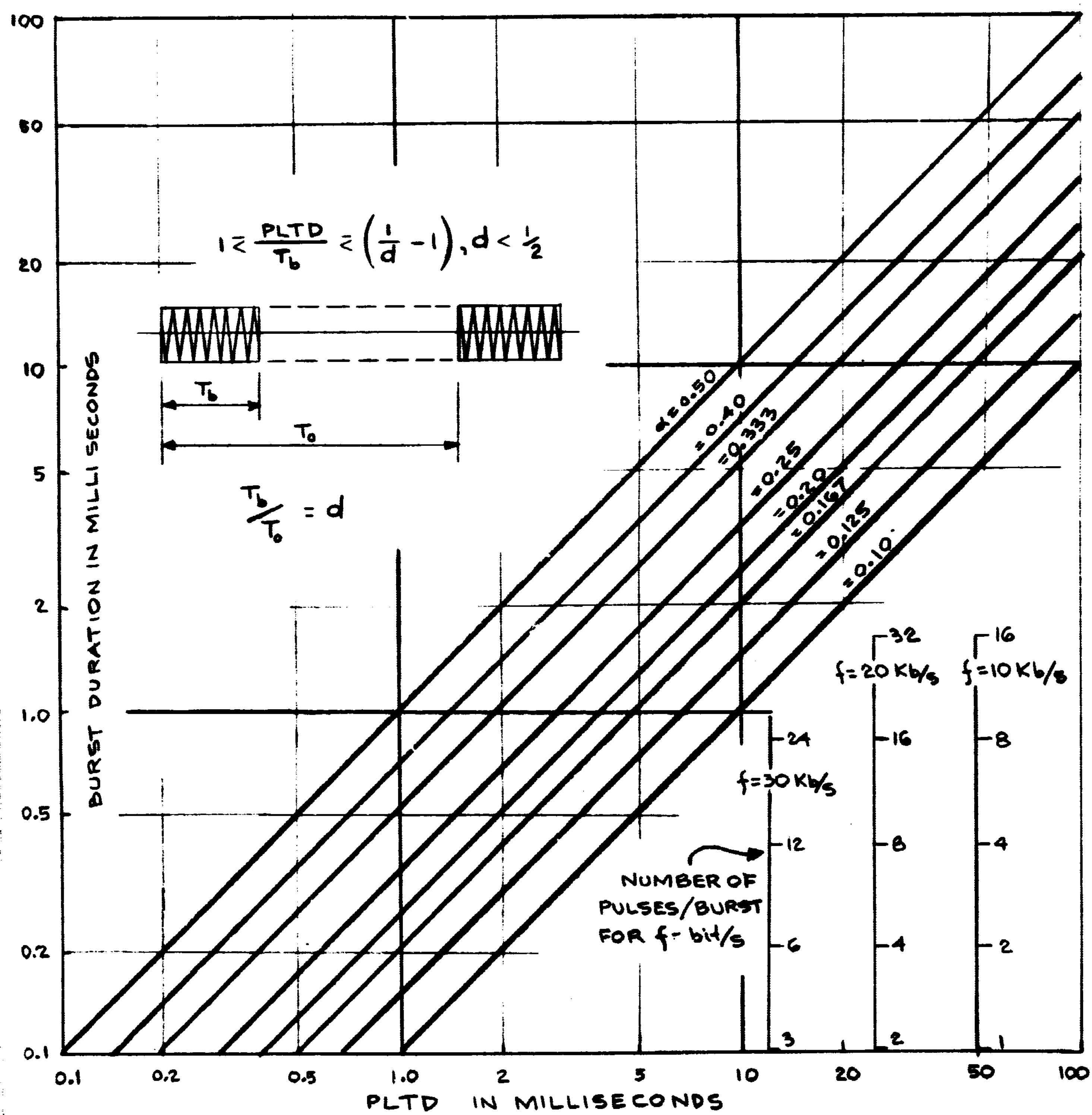


Figure B-1 - Format Relations

APPENDIX C

HARD LIMITER PERFORMANCE WITH WIDEBAND NOISE OR CW INTERFERENCE

C-1. A SIMPLE DERIVATION OF DOYLE'S RESULT.

Worthy Doyle showed that in a hard-limiting repeater under conditions wherein:

(a) the repeater bandwidth is occupied by frequency-contiguous Gaussian distributed signals and

(b) Signal powers all equal,

signal-to-noise ratio per channel is limited to about +9dB.

This is easily developed from heuristic reasoning as follows: The well-known result of Davenport that the signal-to-noise ratio out of a limiter is about 1 dB below that of the input for signal-to-noise ratios much less than unity. Viewed from the output, this degradation may be attributed to the creation of intermodulation products that fall in-band. If there are N watts for each channel's signal at the output, and there are M signals with input powers of W watts, the input ratio of a "desired" single channel to the entire input signal is 10 log (1/M). The output signal-to-noise ratio is thus about 0.8/M for the channel, or:

$$0.8/M = 1/1.26M = 1/(M + 0.26M) = 1/(\text{original noise} + 0.26\text{x original noise}) = 1/(\text{original noise} + \text{I.M. noise}).$$

The I.M. noise is thus about 5.85 dB below the channel. However, the channel will be detected on a voltage basis rather than power and will thus receive a 3dB improvement, yielding about a +9 dB ratio over the I.M. noise in that channel.

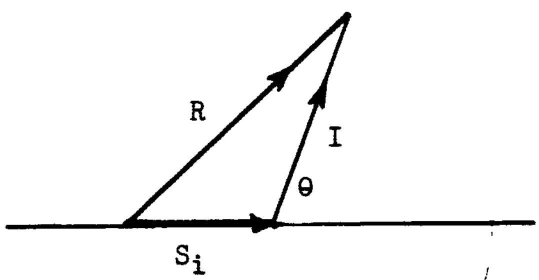
The conditions for the validity of this result are seen to be that the spectrum can be fully loaded with Gaussian signals of equal intensity.

Channelized signals in the TDRS environment using ABC would not satisfy the Gaussian requirements unless there were a very large number of them present since (1) the burst format with a 20% duty cycle reduces the effective occupance by that ratio (for the TDRS signals only) and (2) the channel allocation of 30 kHz and the channel utilization of 20 kHz mean that the TDRS signals will leave one-third of the spectrum absolutely clear, on the average.

Even with sixty users, a 20% duty-cycle format will result in the effective number of users being only 12, for purposes of repeater input loading calculations. The bandwidth ratio alone accounts for about 1.7 dB additional margin (10 log 30/20 = 1.7). The analysis assumes also that the degradation is due to uniformly dense I.M. products and such is not the case with non-contiguous signals such as the channelized signals to be used with the ABC system. For the actual ABC case, additional analysis is required to pinpoint the actual I.M. penalties.

C-2. COHERENT SIGNAL LOSS DUE TO CW INTERFERENCE

Consider the case of just two narrowband CW signals at the input of a hard limiter. At the output there will be a mutual suppression effect of each signal on the other even in the absence of noise or other signals. The following analysis treats this signal loss in the coherent carriers.



S_i = input signal

I = interfering signal

θ = phase between S_o and I

R = vector resultant of S_o and I

The effect of a "perfect" limiter is taken to be a constant magnitude resultant, |R|, with only the phase preserved. This is computed by taking the resultant vector and normalizing to the length |R|. A coherent receiver will respond only to the component of R that is cophase with S_i, the input signal. The coherent component is the desired output, S_o. It is given by

$$S_o = \frac{S_i + I \cos \theta}{+\sqrt{S_i^2 + I^2 + 2S_i I \cos \theta}}$$

$$= \frac{a + \cos \theta}{+\sqrt{1 + a^2 + 2a \cos \theta}}$$

where $a = S_i / I$

Since the keying or pulsing is taken to be a worst case of full overlap and since the frequency separation is taken to be an integral multiple of the bit rate, the excursion of Θ is a whole number of full revolutions; i.e., multiples of 2 radians. The average signal voltage is then

$$\overline{S_o} = \frac{1}{2\pi} \int_0^{2\pi} \frac{a + \cos\Theta}{\sqrt{1 + a^2 + 2a\cos\Theta}} \, d\Theta$$

The average signal power is

$$\overline{P_{s_o}} = \frac{1}{2\pi} \int_0^{2\pi} \frac{(a + \cos\Theta)^2}{1 + a^2 + 2a\cos\Theta} \, d\Theta$$

For the average voltage, $\overline{S_o}$, the case where a = 1 gives

$$\overline{S_o}\,(a=1) = \frac{1}{2\pi} \int_0^{2\pi} \frac{1 + \cos\Theta}{\sqrt{2(1 + \cos\Theta)}} \, d\Theta$$

$$= \frac{1}{\sqrt{2}\,\pi} \int_0^{2\pi} \sqrt{1 + \cos\Theta} \, d\Theta$$

$$= \frac{1}{\pi} \int_0^{\pi} \cos(\Theta/2) \, d\Theta$$

$$= 2/\pi \, .$$

Since the maximum value is for $a \rightarrow \infty$ and is obviously 1, [in formal fashion, since:

$$\overline{S_o}\,(a \rightarrow \infty) \rightarrow \frac{1}{2\pi} \int_0^{2\pi} d\Theta = 1.$$

]

this is a 3.92 db loss of signal.

For large interference, a $\longrightarrow$ 0 and we have

$$\overline{S_o} \text{ (a small) } (=) \frac{1}{2\pi}\int_0^{2\pi} \frac{a + \cos\theta}{1 + (a \;\; + 2a\cos\theta)/2}\, d\theta$$

$$(=) \frac{1}{2\pi}\int_0^{2\pi}\left(1 - \frac{a \;\; + 2a\cos\theta}{2}\right)\left(a + \cos\theta\right) d\theta$$

$$(=) \frac{1}{2\pi}\int_0^{2\pi}\left[\cos\theta + a\sin^2\theta - \frac{3}{2}a^2\cos\theta - \frac{a^3}{2}\right] d\theta$$

$$(=) \frac{1}{2\pi}\left(I_1 + I_2 + I_3 + I_4 \right)$$

where

$$I_1 = \int_0^{2\pi} \cos\theta \; d\theta = 0$$

$$I_2 = \int_0^{2\pi} a\sin^2\theta \; d\theta = \pi a$$

$$I_3 = \int_0^{2\pi} -\frac{3}{2}a^2\cos\theta \; d\theta = 0$$

$$I_4 = \int_0^{2\pi} -\frac{a^3}{2}\, d\theta = \pi a^3$$

This is a 50% loss of voltage or approximately 6 db when S_o is small since:

$$\overline{S_o} \text{ (a small) } (=) (a - a^3)/2 \;\; (=) \;\; a/2.$$

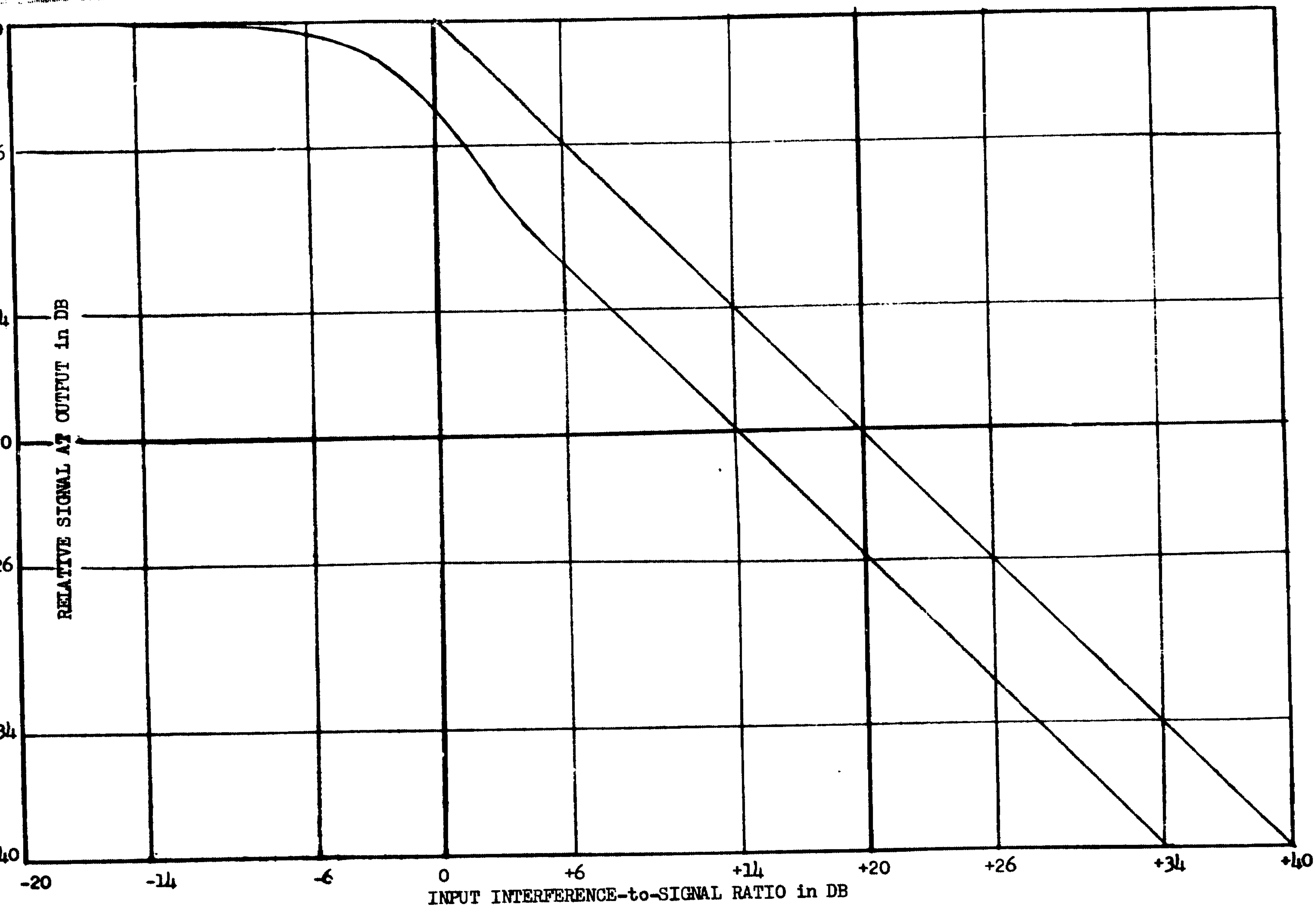


Figure C-1 Mean Loss of Coherent Signal Due To CW Interference

APPENDIX D

CALCULATION OF THE EFFECT OF FINITE TRANSPONDER S/N RATIO

P_r = relay transmitter power per user

G_r = relay antenna gain

N_r = relay noise power

P_u = user transmitter power

G_u = user antenna gain

N_u = user noise power

G_p = propagation path gain

For simplicity, let $G = G_r G_u G_p$.

Received power at user = $P_r G + N_u$

$$\text{User transmitter power} = \left(\left[\frac{P_r G}{P_r G + N_u} \right] P_u + \left[\frac{N_u}{P_r G + N_u} \right] P_u \right)$$

$$\text{Received power at relay} = \left(\text{User transmitted power} \right) G + N_r$$

Therefore the round-trip signal-to-noise ratio back at the relay will be:

$$S/N = \frac{P_r G P_u G}{N_u P_u G + N_r (P_r G + N_u)}$$

If $N_r = N_u = N$, it follows that:

$$S/N = \frac{\left(\frac{P_r G}{N}\right)\left(\frac{P_u G}{N}\right)}{\left(\frac{P_r G}{N}\right) + \left(\frac{P_u G}{N}\right) + 1} = \frac{(S/N)_r (S/N)_u}{(S/N)_r + (S/N)_u + 1}$$

where $(S/N)_r$ and $(S/N)_u$ are the signal-to-noise ratios at the relay and user.

Using the data from Table 7-1, we have the following results:

For Tracking:

$(S/N)_r$ = 33.3 dB, $(S/N)_u$ = 23.3 dB, Hence from the derived formula on the preceeding page,

$$S/N = \frac{(2140)(214)}{2140 + 214 + 1} = 194.5, \text{ or } +22.8 \text{ dB.}$$

For Telemetry:

$(S/N)_r$ = 26.3 dB, $(S/N)_u$ = 16.3 dB, Hence:

$$S/N = \frac{(426)(42.6)}{426 + 42.6 + 1} = 38.6, \text{ or } + 15.9 \text{ dB.}$$

APPENDIX E

ELLIPTICAL ORBIT COMMUNICATION PARAMETERS

It is desired to determine the Doppler shift, rate-of-change of Doppler shift, and the path length time difference between direct and reflected propagation paths for the configuration involving a stationary relay satellite and a spacecraft having an elliptical orbit. Solutions for circular spacecraft orbits have been obtained by Golden[1], and his terminology will be employed whenever possible.

The elliptical orbits of primary interest are those which result in maximum rates-of-change of Doppler shift, therefore the relay satellite will be assumed to lie in the orbital plane. The configuration geometry is illustrated in Figure B1.

Reference to Brouwer[2] yields the following equations involving orbital parameters:

$$t = \frac{a^{3/2}}{(GM)^{1/2}} \left[2 \tan^{-1}\left(\left[\frac{1-e}{1+e}\right]^{1/2} \tan\left[\emptyset/2\right] \right) - \frac{e(1-e^2)^{1/2}\sin(\emptyset)}{1 + e \cos(\emptyset)} \right]$$

$$\alpha = \tan^{-1}\left[2\, e \sin(\emptyset/2) \,/\, (1 + e \cos\emptyset)\right]$$

$$r = a\,(1-e^2)^{1/2} / (1 + e \cos\emptyset)$$

$$V = (GM/a)^{1/2} \left[\frac{1 + 2\, e(\cos\emptyset) + e^2}{(1 - e^2)} \right]^{1/2}$$

where:

t = time in seconds required for the spacecraft to travel from perigee to a point ϕ degrees from the major axis of the ellipse

a = length of semi-major axis of the ellipse

G = gravitational constant $= 6.695 \times 10^{-11}$ Newton meter^2 kg^{-2}

M = mass of the earth $= 5.977 \times 10^{24}$ kg

e = eccentricity of the orbit

ϕ = angle from the major axis to the spacecraft position

r = distance from center of earth to spacecraft

α = angle between direction of motion and direction perpendicular to r

V = spacecraft velocity

ϕ_0 = angle from major axis to relay position

Inspection of Figure B1 yields:

$$\begin{pmatrix} \text{radial velocity between} \\ \text{relay and spacecraft} \end{pmatrix} = V\cos(B)$$

$$\text{Spacecraft altitude} = r - A$$

where A = radius of earth=6378166 meters [Golden[19]]

The Doppler shift, DS, at a frequency of 140 MHz is determined using:

$$DS = \left[140 \times 10^6 \; V \cos(B)\right] / \left[299.7925 \times 10^6\right].$$

The path length time difference, PLTD, is easily determined using Golden's results for each value of $(\phi - \phi_0)$ and $(r-A)$.

Using the above equations and assuming an elliptical orbit with 100 nautical mile perigee and 2,000 nautical mile apogee, DS, (r-A), and (t) were calculated for values of ϕ in one degree steps from zero to 180 degrees and values of $\emptyset_o$ in 45-degree steps from zero to 315 degrees. The Doppler shift, rate-of-change of Doppler shift, and path length time difference as functions of time from perigee, (t), were calculated for each value of $\emptyset$ and the results are illustrated in the Interim Report.

Extrapolation of the results for Doppler shift and Doppler shift rate from VHF to UHF requires only proportional scaling.

References

1. Golden, T., Range And Velocity Components of TDRS Multipath Signals, NASA/GSFC document X-520-69-38, February 1969.

2. Brouwer and Clemence, Methods of Clestial Mechanics, Academic Press, New York, 1961.

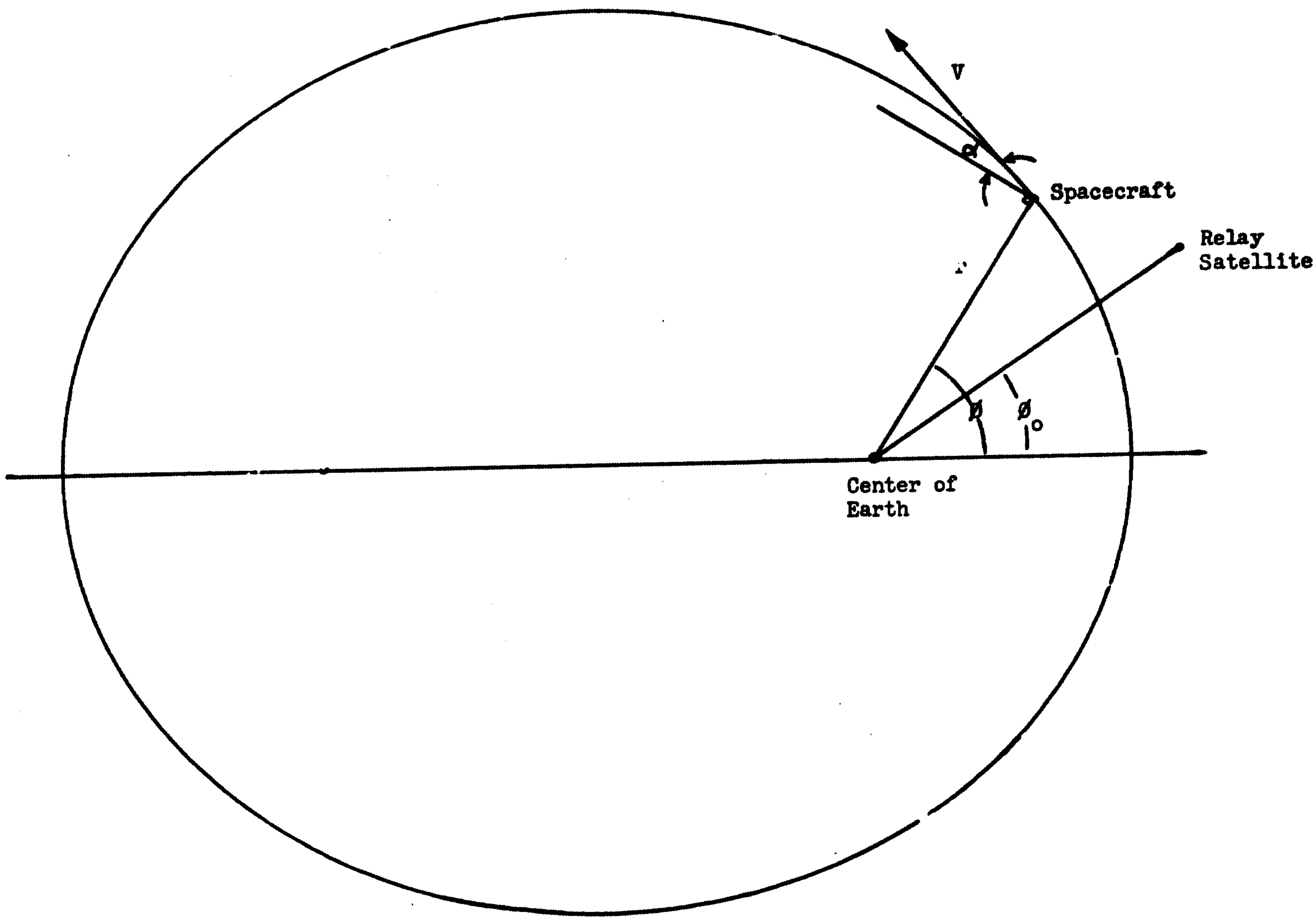


Figure E-1 Elliptical Orbit Geometry