

FINAL SUMMARY REPORT MULTIPATH SIGNAL MODEL DEVELOPMENT

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FINAL SUMMARY REPORT

MULTIPATH SIGNAL MODEL DEVELOPMENT

November 1970

By

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Contract No. NAS5-10797

For

National Aeronautics and Space Administration
Goddard Space Flight Center
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By

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MULTIPATH SIGNAL MODEL DEVELOPMENT

1. INTRODUCTION

1.1 Scope

This report comprises the Final Summary (Type III) Report covering studies performed under Contract NAS5-10797 for NASA Goddard Space Flight Center, Greenbelt, Maryland. The objective of this study is to develop and use mathematical models of signals received through the multipath environment of a TDRS-to-User spacecraft link and vice-versa. The TDRS (tracking and data relay satellite) will be in synchronous orbit. The User spacecraft will be in a low-altitude orbit between 200 and 4000 km. The scope of the study is defined in the contract work statement which is reproduced below for reference.

1.2 Statement of Work

According to Article I of the contract schedule, with minor editing, the scope of the work is as follows:

Teledyne ADCOM shall furnish all manpower, equipment and technical services necessary to study, develop and use mathematical models of the multipath environment of a TDRS-to-User spacecraft link and vice-versa in accordance with the following Work Statement.

Item I - Mathematical Models

Produce a mathematical model which completely characterizes a radio link in the multipath environment.

Item II- Influence of Signals

Investigate the characteristic behavior of the model developed in Item I for S-band systems using sidetone or pseudo-noise ranging; investigate the characteristic range and range rate behavior of the model when the ground equipment is specifically that of the S-band modified ATS-R system; investigate the

characteristic range rate behavior for conditions when a phase locked or coherent S-band transponder is employed on the user spacecraft; investigate the characteristic behavior of the model when it is used to represent a communication link with sinusoidal FM signals for the transmission of data at VHF; and finally, investigate the characteristic behavior of the model when it is used to represent the VHF ranging link with signals typical of unmodified GRARR.

Item III - Simulation

Based on the mathematical model derived in Item I, the means by which the link characteristics can be best simulated in the laboratory shall be determined.

Item IV - Experiment Design

Recommendations shall be made as to the most appropriate means for using the model to test TDRS signal processing techniques and equipment and to qualify the final system as it is developed.

1.3 Outline of the Report

As various elements of the study program were completed, the results were reported to GSFC in the form of detailed Technical Memoranda. These included logical development of mathematical formulas, analysis, and other data necessary for a complete description of the work performed, with the results, conclusions and recommendations derived therefrom. In all, twelve Technical Memoranda were submitted, a listing of which is presented in Section 1.4 below. They constitute a detailed record of all the studies conducted under the contract. Consequently, the purpose of this Final Report is to summarize the results of the study program, and to draw final conclusions and recommendations.

Section 2 is devoted to a discussion of the multipath channel modeling effort that underlies all the other elements of the study. Emphasis in the development of the various models was placed on the use to which the model will be put; hence several modeling techniques

were developed for different signal types and analytical purposes. Laboratory simulation techniques were evolved based on some of these models, and are reviewed in Sec. 3. A satellite flight experiment proposed for measuring some of the important channel parameters is then summarized in Sec. 4.

The multipath channel models were applied to the performance analysis of a variety of existing systems as they would be employed in a TDRS configuration. Performance of the Apollo Unified S-Band System (which uses a pseudo-noise technique) in the presence of multipath interference was analyzed, and is summarized in Sec. 5. Performance of the GRARR system was also evaluated, for the S-Band case using a coherent transponder in Sec. 6, and for the VHF case in Sec. 7.

The models were also employed in the conceptual design and performance evaluation of a promising TDRS system employing wide-band FM signals. This is a form of spread-spectrum multiple-access system employing wide-deviation sinusoidal subcarriers to achieve the desired spectrum spreading. Evolution of this system concept is reviewed in Sec. 8, and analyses of its performance are discussed in Sec. 9. The report concludes with final recommendations in Sec. 10.

1.4 Technical Memoranda

The following Technical Memoranda were submitted to GSFC as a detailed record of all the studies conducted under the contract.

<u>Tech. Memo.</u>	<u>Date</u>	<u>Title</u>	<u>Authors</u>
G-161-1	12/26/69	TDRS System Configurations Employing Wideband FM VHF Signals	Southard Lippincott & Ahmas F. Ghais
G-161-2	12/26/69	Multipath Performance of a TDRS System Employing Wideband FM VHF Signals	Sung J. Sohn and Ahmas F. Ghais

<u>Tech. Memo.</u>	<u>Date</u>	<u>Title</u>	<u>Authors</u>
G-161-3	2/10/70	Effects of Multipath on Range-Rate Errors for an Apollo USB Link Utilizing a Data-Relay Satellite	Richard H. Wachsman and Sung J. Sohn
G-161-4	7/70	Multipath Error in Range Rate Measurement by PLL-Transponder/GRARR/TDRS	Sung J. Sohn
G-161-5	7/70	Multipath Errors in Range Rate Measurement by a TDRS/VHF - GRARR	Sung J. Sohn
G-161-6	7/70	Mathematical Models of TDRS Multipath Environment	Elie J. Baghdady and Richard H. Wachsman
G-161-7	3/20/70	Uplink Performance of a Wideband FM TDRS System in an Interference Environment	Richard H. Wachsman
G-161-8	3/20/70	Downlink Performance of a Wideband FM TDRS System in a Multiple User Interference Environment	Richard H. Wachsman
G-161-9	4/23/70	Modifications of the Wideband FM TDRS System	Richard H. Wachsman
G-161-10	12/70	Simulation of the TDRS Multipath Environment	E. J. Baghdady A. F. Ghais R. H. Wachsman
G-161-11	12/70	Experimental Determination of the Multipath Characteristics of the TDRS/Satellite Link	R. H. Wachsman
G-161-12	12/70	Effects of Diffuse Multipath Interference in a Wideband FM TDRS VHF Link	R. H. Wachsman

2. MATHEMATICAL MODELS OF TDRS MULTIPATH ENVIRONMENT

Development of mathematical models of a TDRS radio link in a multipath environment is discussed in this section. The process is shown to consist of four interrelated steps which involve modeling of the various aspects of the problem, viz. the received signal, the radio link, system performance criteria, and the propagation physics. A variety of mathematical models are shown to be necessitated by factors such as the frequency band employed, the modulation techniques and communications functions performed, and the engineering emphasis underlying the mathematical analysis.

Received signal models were developed and documented in detail in Technical Memorandum G-161-6, along with sufficient consideration of the propagation physics to obtain quantitative information on the various parameters characterizing the models. The influence of these received signals on the various systems under consideration was then analyzed in Technical Memoranda G-161-2, 3, 4, 5, 7, 8, 9, and 12.

2.1 Development of a Mathematical Model

Mathematical models of a TDRS radio link in a multipath environment which are useful from a communications engineering standpoint were developed through consideration of the following interrelated steps:

a) Multipath Signal Model

A general model of the received uplink and downlink RF signals (direct-path and reflected paths) is derived from elementary considerations of the multipath geometry and the anticipated sources of significant multipath interference;

b) Radio Link System Model

The transmitter, transponder, relay and receiver signal processing functions are modeled, and the above multipath signal model is traced through the system to the measurement or user output;

c) Performance Criteria

Appropriate system performance criteria are developed and evaluated in terms of the parameters of the multipath signal model and the system model, and

d) Multipath Physics Model

Finally, a model of the physics of the multipath scattering is developed which may be used to estimate the magnitudes of the pertinent parameters of the multipath signal model. Such a model must of necessity be a compromise between physical reality and mathematical tractability, its usefulness being determined by the extent to which it realistically represents a typical multipath environment.

The important point in the above is the realization that the suitability of the mathematical model involves its ability to predict realistically the performance limitations of the particular system in question in the presence of the given multipath environment. The total mathematical model therefore involves four interrelated steps. Inadequacy of any of these four modeling steps may result in an inability of the total mathematical model to characterize all the significant effects of the multipath interference on system performance. Likewise, over-refinements of the models in any one of these four steps may lead to needless complication and loss of an intuitive insight into the dominant effects of the multipath interference.

The above modeling procedure was used earlier¹ to develop a mathematical model of a TDRS/GRARR S-Band range rate measurement link in a multipath environment.

1. ADCOM, Multipath Effects on GRARR Tracking Utilizing a Data Relay Satellite, Final Report on Contract NAS5-10780, for NASA/GSFC, September 15, 1969.

Simplifying assumptions were made, that

- a) the link between the TDRS and the ground station was ideal, so that the system could be modeled as if the GRARR receiver were on board the TDRS,
- b) the GRARR signal was fully acquired by the receiver, and
- c) tracking errors were small.

The last two assumptions recognized the fact that of primary interest is the additional range rate measurement errors which are caused by the presence of small multipath interference. This approach enabled use of linear equivalent models of the GRARR carrier and subcarrier tracking phase locked loops, and permitted neglecting all but the lowest order effects of the multipath interference.

Following previous noise analyses of the GRARR system, a convenient performance criterion of the range rate measurement system was taken to be the rms range rate error. This rms error was expressed in terms of certain GRARR system parameters and the variances of the carrier and subcarrier tracking loop phase errors. Consequently, in view of the assumed linearity of the equivalent models of the carrier and subcarrier tracking loops, it was only necessary to determine the contribution to these loop phase error variances from the uplink and downlink multipath interference.

From elementary considerations of the multipath geometry, in which it was assumed that the multipath arose from reflections (or scattering) off the ocean, signal models of the received uplink and downlink RF direct-path and reflected paths were postulated. Both a specular and a diffuse multipath component were assumed to be present in the received RF multipath signal. When these signal models were traced through the transponder and the GRARR receiver models, it was found that the multipath contribution to the variances of the phase errors

of carrier and subcarrier tracking phase locked loops consisted of a specular and diffuse component.

The worst case situation was seen to be the case where the relative specular multipath doppler frequency offset was small enough so that the largest spectral components of the multipath interference lay inside the loop noise bandwidths. In this case, the multipath parameters which entered into the evaluation of the rms range rate error were the relative rms specular multipath amplitude and the maximum value of the diffuse multipath spectral power density. These parameters were evaluated with the aid of a scattering model which attempted to take into account all the significant features of the physics of the scattering while keeping the mathematics in a tractable form. Approximations were made which tended to overestimate the detrimental effects of the multipath interference.

This approach was justified on an engineering basis in that the primary concern was whether or not the system would be able to meet certain minimum performance specifications in the presence of small multipath interference, and whether or not additional antenna directivity would be required at the mission spacecraft to discriminate against the multipath. Consequently, if the estimated upper bounds on the detrimental effects of the multipath still permit these specifications to be met, this approach is justified. On the other hand, if the upper bounds are too loose, and predict that the system would not meet the required specifications in the presence of multipath, then further refinements in the scattering model would be called for.

The electromagnetic scattering model used assumed that the sea was a perfect reflector, in the sense that the magnitude of the reflection coefficient was taken to be unity. The surface undulations were assumed to be distributed at random with a two-dimensional

isotropic Gaussian distribution. In addition, the autocorrelation function of the surface heights was assumed to be Gaussian. With the additional assumption that the slopes of the surface undulations are small and that the scattering is primarily diffuse (with a small specular component still present), the required multipath parameters were estimated in terms of the sea surface height variance, the wavelength of the incident radiation, the grazing angle of the incident radiation, and the rms sea surface slope. This scattering model was based on models developed by Beckmann and Spizzichino², and Durrani and Staras³.

The GRARR system parameters, such as the required loop noise bandwidths and the doppler count number, were determined from considerations of the direct-path doppler dynamics, and the worst-case rms range rate errors were evaluated. These values were found to be within the required system specifications, so that no additional antenna directivity was felt to be necessary. In addition, the results appeared to lend support to various approximations and assumptions made in the development of the model. Modifications and extensions of this mathematical model for a more general TDRS-to-User Spacecraft radio link in a multipath environment are discussed below.

2.2 Extensions to more General TDRS Links

For a more general radio link involving a TDRS satellite in a multipath environment, some of the approximations and assumptions made in the development of the mathematical model for the TDRS/GRARR S-Band range rate measurement link must be re-examined.

2. Beckmann & Spizzichino, The Scattering of Electromagnetic Waves from Rough Surfaces, Pergamon Press, 1963.
3. Durrani & Staras, "Multipath Problems in Communications between Low-Altitude Spacecraft and Stationary Satellites," RCA Review, March, 1968.

Modifications in the mathematical model were necessitated by such factors as: significant changes in RF frequency; different types of modulating signals and communications functions (with corresponding changes in system designs and performance criteria); and finally, changes in engineering emphasis. The modified and extended models were documented in Technical Memorandum G-161-6. Such changes included:

a) RF Frequency:

The models were modified to apply to RF frequencies other than at S-Band. For an RF frequency in the VHF region, specular multipath is more pronounced than at S-Band. Consequently, it was necessary to refine both the model of the receiver signal processing to include stronger specular multipath interference, and the scattering model to permit more accurate calculation of the rms relative specular multipath amplitude. Models appropriate to VHF were presented in Technical Memorandum G-161-6, and summarized in Technical Memorandum G-161-5.

b) Modulating Signals and Communications Functions:

For different classes of modulating signals, the presence of multipath interference may cause different types of disruptive effects. In the range rate measurement system discussed above, the desired doppler information is extracted by narrowband carrier and subcarrier tracking phase-locked loops. Only multipath components which fall inside these loop noise bandwidths contribute to range rate errors. Consequently, the propagation model used was only required to yield reasonable estimates of the relative multipath magnitudes and dopplers. For other types of communications functions, such as

sidetone or pseudo-noise ranging, data, voice or television transmission, the multipath causes different effects, and different multipath parameters become important. This requires refinements in the scattering model in order to permit accurate estimates of these different parameters. Models appropriate to more general modulating signals and communications functions, such as spread-spectrum multiple-access signals, were developed in Technical Memorandum G-161-6. Then they were applied in Technical Memoranda G-161-2 and G-161-7 to the wideband FM spread-spectrum multiple-access system, in Technical Memorandum G-161-3 to the Apollo USB TDRS system, in Technical Memo. G-161-4 to the PLL transponder GRARR/TDRS system, and finally, in Technical Memo. G-161-5 to the VHF GRARR/TDRS system.

c) Engineering Emphasis:

A change in engineering emphasis may require additional refinements in the model of the multipath channel. For example, somewhat different approaches might be taken in each of the problems given below:

- i. The effects of multipath interference on a given system in a given multipath environment are to be determined. The work recorded in Technical Memos. G-161-3, 4, and 5 falls under this category.
- ii. A system is to be designed with specific communications requirements which will be able to effectively combat multipath interference in a given multipath environment. It is this type of problem which led to the development of a concept of wideband sinusoidal FM as a technique for combatting multipath interference. This is recorded in Technical Memos. G-161-1, 2, 7, 8, 9 and 12.
- iii. The properties of a scattering model are to be verified by reflecting specially designed signals off the scattering surface and measuring appropriate properties of the reflected signal. Such an experiment design for model verification is described in Tech. Memo. G-161-11.

- iv. A communications link is to be established in which the desired signals are transmitted via a bounce off a scattering surface. Examples of this are ionospheric and tropospheric scatter communications. Here the problem is to design the signal and the system so that required communications performance specifications of the link will be met. This type of problem is listed for the sake of completeness. We have not treated this problem in this work. That is, we treat the earth-reflected multipath as an undesired interference and not as a part of the signal.

In problem (i) the use of worst-case bounds on the multipath interference may be quite acceptable in the estimation of the effects of the multipath interference on a given system, since what is usually desired in this case is assurance that the system will meet its specifications in the presence of the multipath interference. In problem (ii) certain significant differences between the direct-path and reflected-path signals may be utilized in the design of a signal/system format to permit discrimination against the multipath interference. In this case it may only be necessary to accurately model those aspects of the multipath interference which will be utilized in the discrimination process. In problem (iii) more accurate characterization of the reflected received signals and the scattering surface and scattering physics may be required if properties of the scattering mode are to be verified or deduced from measurements on signals scattered off the surface. Finally, in problem (iv) properties of the multipath channel such as the coherence bandwidth and the fading margin requirements are important. In conclusion then, the degree of sophistication and refinement in modeling a radio link in a multipath environment principally depends on the engineering emphasis or purpose of the model.

2.3 Types of Models

The propagation of electromagnetic waves between satellites in synchronous and low orbits and to and from earth-stations as well as airborne terminals is subject to the effects of a number of phenomena associated with the presence of the atmosphere, the ionosphere and the earth's surface, and with the relative motions of the various communication nodes. Atmospheric effects are of significance at frequencies in excess of 100 MHz, and become progressively more severe at frequencies of several GHz and above, especially at frequencies corresponding to millimetric and submillimetric wavelengths. Ionospheric effects, especially scintillations, are pronounced at frequencies in the 100 MHz region, but decline at higher frequencies. In this report, the discussion is focused on the aspects of multipath propagation effects that influence the design and the communication capacity of links utilizing frequencies on the order of 100 MHz and above. Atmospheric and ionospheric effects are discussed only in passing.

There are two general approaches to the study of propagation disturbances: the physiogeometric approach and the system-function approach. Both of these approaches are essential to a complete understanding of the transmission medium and its limitations. A third approach, the performance-index approach, applies only to systems utilizing specific equipment, and lumps the effects of all disturbances and the equipment performance characteristics inseparably.

In the physiogeometric approach, principal attention is on the "causal forces" at work -- the propagation mechanisms (including their time and frequency characteristics), physical processes and geometries -- that shape the channel response. Physical laws and geometrical relationships are applied to the analysis of propagation

between separate locations and to the determination of techniques for efficient coupling into and out of the propagation medium, for understanding the causes of the multipath disturbances, and for proper modeling of the received signal.

In the system-function approach, the medium is viewed as a "black box" accessible only through input and output pairs of terminals determined by the access terminals of the transmitting and receiving antennas. The behavior of the channel response, or the terminally observable effects of whatever causal propagation mechanisms are at work in the channel, is then analyzed using techniques and concepts for relating response and excitation at the terminals of a "black box". The channel is thus represented by one of a set of randomly time-variant system functions, each defined as the characteristic response to a specified elementary excitation. This approach is essential for yielding the type of parametric representation of the channel that the system designer needs and requires for evaluating the achievable performance with specific signal designs and performance achievement techniques. For given modes or techniques of coupling to the medium, this approach yields guides for counteraction of channel disturbances by appropriate signal design, signal processing, signal combining and detection operations, etc., and hence for the selection of terminal equipment or modems.

In the light of the above categorization of approaches to the characterization of a communication medium, the first objective of work reported in Tech. Memo. G-161-6 is to establish a complete phenomenological characterization of the radio propagation mechanisms for representative TDRS geometrical configurations. Accordingly, the presentation starts in Sec. 2 of that Memo. with a discussion of the various scintillation effects and multipath mechanisms associated with propagation

through the earth's atmosphere, with emphasis on phenomena that have thus far been extensively studied and measured in the troposphere and near the earth's surface. The material presented in Sec. 2 is important in the selection of operating frequencies on the satellite to ground links for systems utilizing satellites as communication and data relays or as navigation aids. The data presented are also useful in estimating tracking errors due to atmospheric refractive effects, and in formulating mathematical models of signals that have traversed some part of the atmosphere.

On the basis of the phenomenological characteristics of TDRS multipath transmission, mathematical models of signals received through various propagation mechanisms are formulated in Sec. 3. These models are essential for performing analyses of the propagation effects upon TDRS link performance with any particular design of signals and detection techniques. Such analyses may then be carried out by standard analytical processes (including the use of computational machine aids) or by computer and/or laboratory simulation of the terminal equipment and the propagation mechanisms. The equivalent-filter models of the channel, presented in Sec. 3.2, are also invaluable for analyzing the communication and tracking performance of a link, as well as for computer or analog laboratory simulation of the medium.

Finally, detailed analyses of representative TDRS channel geometries are presented in Sec. 4 in order to determine numerical estimates and ranges of values of the critical parameters in the mathematical models of the channel.

The applicability of the derived models to ionospheric effects expected in a TDRS system deserves special comment. All the models are applicable to any time-varying linear channel, which may include ionospheric disturbances such as scintillations, fading and dispersive

effects. Any of these effects may be encountered in a TDRS mission under certain geometrical and physical conditions. For example, it is known that significant ion densities often extend to altitudes of many hundreds of miles at the equator and the polar regions, so that the signal from a low altitude spacecraft may traverse part of the ionosphere on its way to the TDRS. Unfortunately, very little empirical knowledge is available about the resulting fluctuations in signal parameters. Consequently, while the mathematical models are capable in principle, of describing the ionospheric effects, the various parameters characterizing each model cannot be quantified for lack of measurements. This may pose a potentially serious problem for the TDRS system, if the effects such as fade depths actually exceed the margins allowed in the link designs. It definitely represents a serious problem for aeronautical relay satellite systems since the propagation paths can always be expected to traverse the full depth of the ionosphere.

3. SIMULATION OF THE TDRS MULTIPATH ENVIRONMENT

The problem of the laboratory simulation of the TDRS multipath environment was treated in Tech. Memo. G-161-10.

Techniques for the simulation of both the received direct path signal and the earth-reflected specular and diffuse multipath components were presented. The simulation of the received LOS signal included direct-path carrier doppler and ionospheric scintillation and multipath effects. Simulation of the earth reflected multipath components included multipath time delay and carrier doppler for the specular and diffuse components, and time delay spread and doppler spread for the diffuse component.

Although a simulator which processes the RF input might appear to be the most desirable simulation approach, problems of achieving the required time delays and time delay spreads for the multipath components at RF (or IF) preclude this technique. An alternative approach is preferred in which the modulation is first delayed, either jointly or one modulation signal component at a time, and then modulated on doppler shifted carriers which may then be doppler spread. Techniques for delaying various types of baseband modulating signals were presented along with techniques for simulating doppler shifted carriers and doppler spread carriers with AM and FM or PM modulation on them. These various simulation techniques were then arranged to configure a typical complete simulator design.

Finally, a special purpose technique for simulating a wideband FM diffuse multipath component was presented. The wideband FM

signal in question consists of a carrier which is simultaneously PM modulated by a narrowband data signal and wideband FM modulated by a sinusoidal subcarrier. The assumption is made that the time delay spread is much less than the data bit period but significantly greater than the subcarrier period. In this case the various sidebands fade independently, and this fact may be used to simulate the diffuse multipath component. This independently fading sideband model was described in Tech. Memo. G-161-6 and in Sec. 2 of this report.

4. EXPERIMENTAL DETERMINATION OF THE MULTIPATH CHARACTERISTICS OF THE TDRS/SATELLITE LINK

Several possible experimental techniques for measuring some of the more important multipath characteristics of the TDRS/satellite link were presented in Tech. Memo. G-161-11.

A low-orbit satellite, in an orbit chosen so as to enable a variety of multipath geometries and scattering surface conditions to be encountered, transmits a signal in the VHF down-link frequency band. This signal, which is relayed to the ground by the TDRS, consists of a carrier FM modulated by a sinusoidal subcarrier. A modulation index of approximately 3.2 produces a spectrum in which most of the power resides in the carrier and in sidebands up to fourth order. The sub-carrier frequency is made greater than the fading bandwidth, yet less than the coherence bandwidth of the earth-reflected diffuse-scattered received signal. This is necessary if the coherence bandwidth of the diffuse multipath is to be measured.

The total signal received by the ground station, after the coherent removal of one-way X-band doppler in the TDRS-to-ground link, consists of a direct-path VHF signal and an earth-reflected VHF interference. Receiver processing serves to mix this total signal down to a bias frequency whose value is approximately twice as large as the wideband FM bandwidth. The signal is then recorded on a tape recorder for further processing.

In post-flight processing, the recorded signal is fed into a bank of sideband filters which isolate the different sidebands so that

the output of each filter consists of the direct-path and earth-reflected path sideband. The outputs of the sideband filters are then mixed down to a common frequency by mixing the output of each filter by the appropriate multiple of the subcarrier frequency. The power density spectrum of these signals may be measured and added to produce an "average" power density spectrum. The purpose of measuring the power density spectrum of a segment of the received signal sidebands is to permit identification of the earth-reflected signal through its spectral properties and to permit a determination of the spectral spread or fading bandwidth of the diffuse-scattered multipath interference.

For the case where the earth-reflection is primarily specular, envelope detection of any of the sidebands can yield a measurement of the ratio of the amplitudes of the specular to direct-path received signals. This is obtained by measuring the maximum and minimum of the fading envelope and computing the ratio.

If the coherence bandwidth of the earth-scattered diffuse multipath is greater than the subcarrier frequency, it may be possible to estimate it by measuring the correlation in the fluctuations of the squares of the envelopes of the different sidebands. The correlation efficiencies are the actual quantities measured, and a plot of these as a function of the frequency separation of the sidebands involved yields information about the coherence bandwidth.

There are a number of problems which must be resolved if the above measurements are to produce meaningful results. In particular, the earth-reflected multipath interference must be larger than any other sources of noise, interference, or errors. Exact details of the power density spectrum and correlation efficiency measurements must also be worked out.

5. EFFECTS OF MULTIPATH ON RANGE-RATE ERRORS FOR AN APOLLO USB LINK UTILIZING TDRS

Worst-case range rate errors arising from earth-reflected multipath interference were computed in Tech. Memo. G-161-3 for an Apollo USB communications link which utilizes a data-relay satellite.

First, the Apollo USB range rate measurement system was modeled so that the rms range rate error was expressed as a function of the rms phase error of the sum channel receiver carrier tracking loop. The contribution to this error from multipath interference on both the up-link and the down-link was then computed. This involved modeling the received multipath interference on both the up-link and the down-link, and tracing this multipath interference through the Apollo USB transponder and sum channel carrier tracking loops. The multipath contribution to the sum channel receiver carrier-tracking loop phase error variance was expressed in terms of multipath parameters and phase-locked-loop parameters. These multipath parameters were then expressed in terms of the multipath geometry, the wavelength of the transmitted radiation, and the roughness parameters of the scattering surface. A worst-case example yielded an rms range rate error of approximately 1.4 cm/sec., which is a tolerably small error for most purposes.

6. MULTIPATH ERROR IN RANGE RATE MEASUREMENT BY PLL-TRANSPONDER/GRARR/TDRS

Range rate errors in a TDRS/Modified S-Band GRARR system which utilizes a PLL transponder were calculated in Tech. Memo. G-161-4.

The results of a worst-case range-rate error analysis were presented in the form of curves in Fig. 2 of Tech. Memo. G-161-4, reproduced below for reference. The low orbit spacecraft was assumed to be in a circular orbit nearly perpendicular to the earth-TDRS axis. The earth scattering was assumed to occur off the surface of the sea with an rms roughness of 0.1 meter. At very low grazing angles, specular scattering predominated over diffuse scattering as expected. However, for grazing angles greater than approximately 15° , the diffuse multipath predominated. The range rate errors at different low-orbit altitudes peaked between 5° and 10° .

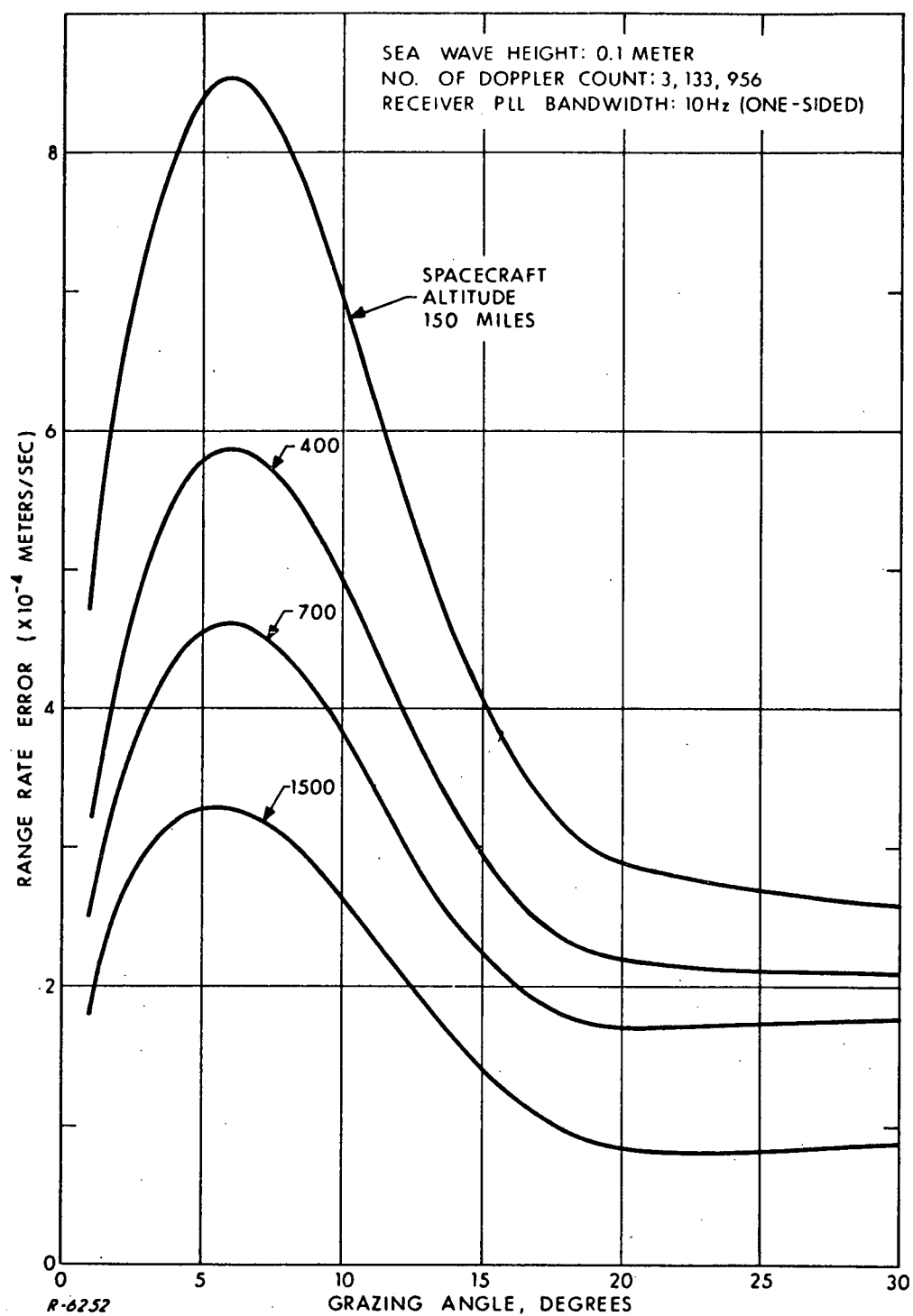


Fig. 1 Worst Case Range-rate Error as a Function of the Grazing Angle (same as Fig. 2 of Tech. Memo. G-161-4).

7. MULTIPATH ERRORS IN RANGE RATE MEASUREMENT BY A TDRS/VHF-GRARR

The contribution of multipath interference to errors in range rate measurement in a TDRS/VHF-GRARR system was computed in Tech. Memo. G-161-5.

In this computation specular multipath was assumed to be the dominant multipath interference at low grazing angles at VHF. A worst-case orbital configuration was considered in which there was very little relative specular multipath doppler. This meant that the specular multipath interference was not attenuated by the carrier and subcarrier PLL transfer functions. Curves of rms range rate error for various orbital altitudes and scattering surface roughnesses were plotted in Fig. 3 of Tech. Memo. G-161-5, reproduced below for reference.

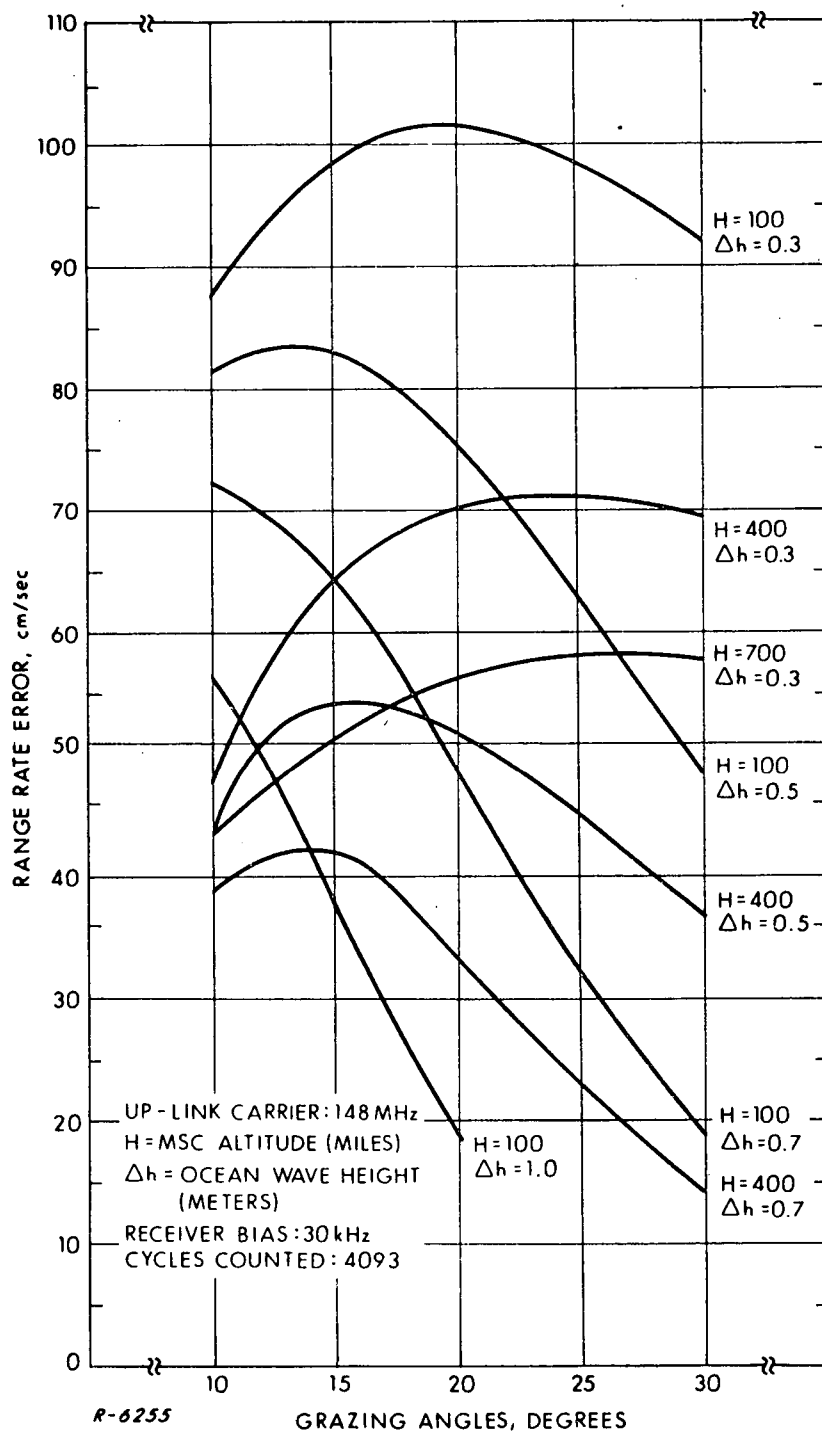


Fig. 2. Range-Rate Errors as a Function of Grazing Angle (same as Fig. 3 of Tech. Memo. G-161-5).

8. THE WIDEBAND FM/TDRS SYSTEM CONCEPT

8.1 Modulation Techniques for Spread-Spectrum Multiple-Access

Radio communications links between the TDRS and the user spacecraft will suffer from multipath and radio frequency interferences. To combat these interferences it has been suggested that spread-spectrum signals be utilized on both the uplink and downlink. Spread-spectrum signals have the further benefit of enabling spread-spectrum multiple-access operation of the tracking and data relay system. Thus, the increased spectrum occupancy requirements of such signals would be at least partly offset by the ability to communicate simultaneously with several user spacecrafts over the same wideband channel.

Of the three most common types of spread-spectrum signals, namely:

- Pseudo-noise phase modulated carrier,
- Frequency-hopping signal,
- Wideband frequency-modulated carrier,

the latter has seen the least use in multiple-access applications.

Under the present contract, Teledyne ADCOM has evolved several forms of a multiple-access system concept utilizing wideband FM signals for the TDRS application. These have been documented in Tech. Memo. G-161-1, and refined and modified in Tech. Memos. 2, 7, 8, 9 and 12. The present section serves to identify and describe the most promising form of this system concept, while the next section summarizes the performance analyses conducted for this system.

8.2 Wideband FM Multiple-Access Technique

The basic signal format used in this system concept, both on the uplink and downlink is as follows:

- a) Ranging information is carried in a cluster of range tones designed to yield the desired range measurement accuracy and ambiguity resolution.
- b) Data, viz., commands on the uplink and telemetry on the downlink, is carried by a split-phase signal added to the range-tone cluster.
- c) Identification of the particular transmitting spacecraft, whether it be a TDRS on the uplink or a user spacecraft on the downlink, is by means of a sinusoidal subcarrier and carrier having a unique combination of frequencies.
- d) Spectrum-spreading is accomplished by frequency modulating the VHF carrier by the sinusoidal subcarrier using a wide frequency deviation (modulation index ≈ 6).
- e) The range tone cluster plus the split-phase data signal are made to phase modulate the wideband FM VHF signal using a small phase deviation (in the order of a radian).

Straightforward means for accomplishing these modulation operations have been evolved, but their discussion is left to the Tech. Memos.

Now, each transmitting spacecraft is identified by a unique combination of carrier and subcarrier frequencies. On the uplink, all TDRS's transmit wideband FM signals, centered on the same carrier frequency, so their spectra completely overlap in the 2 MHz bandwidth. On the downlink, a user spacecraft transmits at one of three carrier frequencies. The frequencies of the two outer carriers are offset from the nominal turned-around carrier by 25.6 kHz. Three rather than one downlink carrier frequencies were selected in order to increase the available number of unique carrier and subcarrier frequency combinations. Since each downlink signal occupies most of the 2 MHz bandwidth, the downlink spectra substantially overlap.

Reception and separation of a desired signal in the presence of other multiple-access signals is based on utilizing the unique combination of carrier and subcarrier frequencies characterizing it. A compound phase-locked loop receiver locks onto both the carrier and subcarrier frequencies by fully compressing the subcarrier modulation on the desired signal. Undesired multiple-access signals, as well as any multipath or RFI disturbances that may be present, are further spread in spectrum by this compression operation, reducing their effects on receiver performance. In this manner, the spread-spectrum multiple-access advantage is realized in achieving disturbance-resistant communications with several spacecrafts over the same frequency band.

8.3 System Configuration

The system configuration is described first for the simplified situation of a single user and a single TDRS. Figure 3 illustrates this situation. At the ground station data acquisition facility (DAF), the VHF signal is generated, modulated with the command data, then translated up to X-band for transmission to the TDRS. All frequencies, including the range tones, are obtained from the station master clock and frequency synthesizer. The TDRS operates on the received X-band signal according to the bent-pipe principle, coherently translating it back down to VHF for relay to the user spacecraft.

At the user transponder receiver, the compound phase-locked loop locks onto the carrier and the subcarrier, and yields the split-phase command signal for detection in the command extractor. The extracted uplink carrier frequency is multiplied in the transponder transmitter by turnaround ratio (23/25) to generate the coherent downlink carrier. A new subcarrier for the downlink signal is generated by the transponder clock and frequency synthesizer. Thus the downlink subcarrier

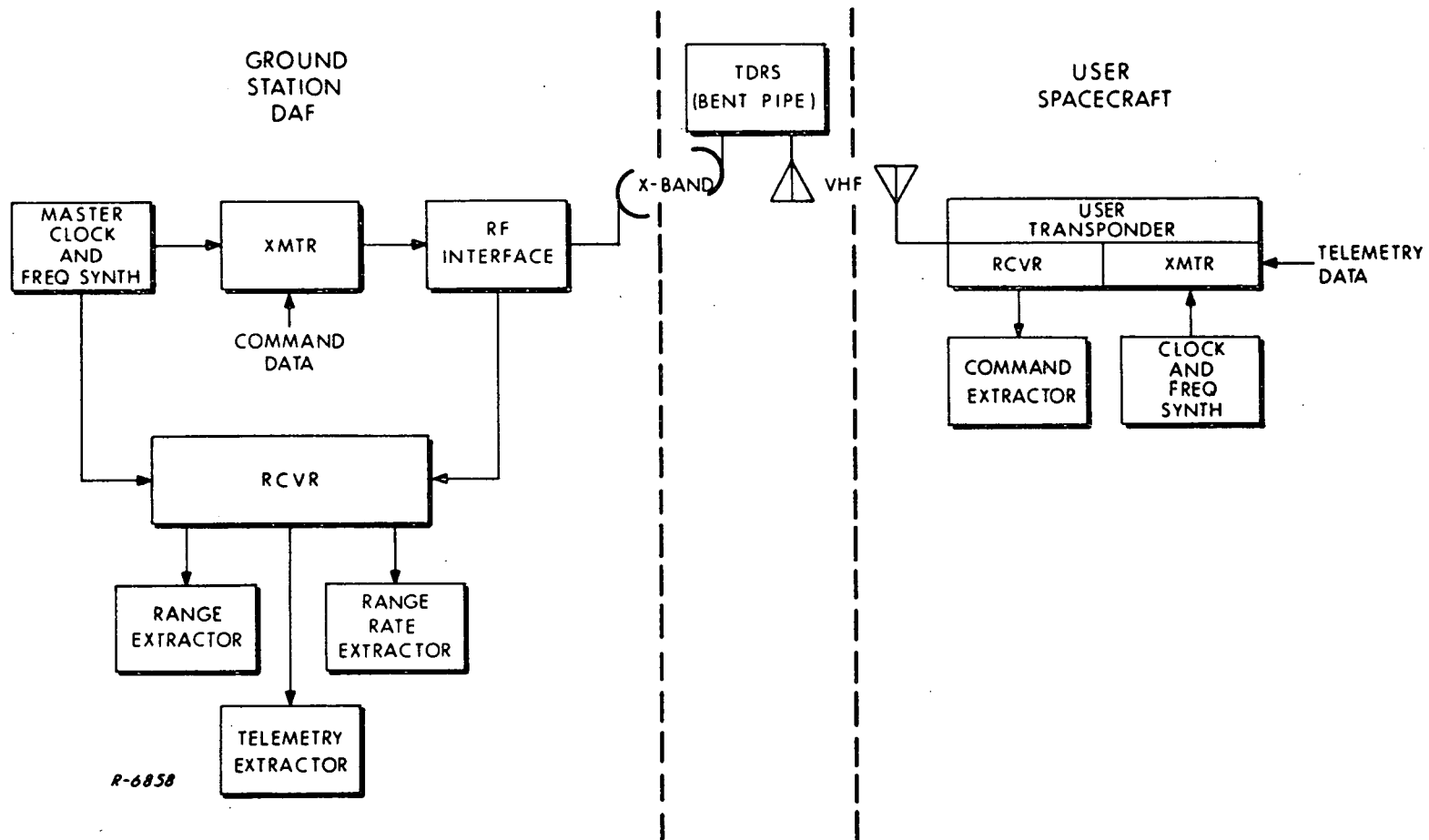


Fig. 3 System Configuration, Single User and Single TDRS

is not maintained coherent with the uplink subcarrier. The uplink range-tone cluster is filtered prior to remodulation on the downlink signal. The transponder transmitter combines the telemetry data, filtered range tones, subcarrier and turnaround carrier to generate the downlink VHF signal.

On the downlink the TDRS again operates on the bent-pipe principle to coherently translate the received VHF signal up to X-band for relay to the DAF. At the DAF the received X-band signal is translated back down to VHF for processing in the VHF receiver. A compound phase-locked loop locks onto the carrier and subcarrier, yielding

- a) the carrier frequency to the range rate extractor which measures the round-trip doppler,
- b) the range tone cluster to the range extractor which measures the phase shifts on the various range tones, and
- c) the split-phase telemetry signal to the telemetry extractor for data detection.

The system configuration for the general situation of several TDRS's and many user spacecrafts is illustrated in Fig. 4. Three TDRS's are shown, designated A, B and C, although extension to four is straightforward. A DAF is dedicated to each TDRS, with a separate X-band link up and down. Each TDRS radiates its VHF signal to all user spacecrafts in view, using the common uplink carrier frequency but identified by its unique subcarrier frequency. This is indicated in Fig. 4 by lines going to user No. 1 only to reduce pictorial clutter. Each user's transponder receiver locks onto the uplink signal containing the subcarrier to which it is tuned as soon as it comes into view of the appropriate TDRS, and commences to detect commands. Commands intended for a particular user are identified by an address

code unique to that user. Addressing of several users is accomplished by a time-division multiplexing scheme (TDM).

The user downlink identification, based on its carrier and subcarrier frequency combination, is either preset or is selectable on command from the DAF. The carrier frequency offset of 25.6 kHz, when used, is derived from the downlink subcarrier frequency, and is removed on the ground prior to doppler processing. On the downlink, each TDRS receives signals from all user spacecrafts in view, and relays the full downlink VHF band down to its DAF. Each DAF is equipped with a band of VHF receivers, one for each user addressed by the TDRS associated with that particular DAF.

9. WIDEBAND FM SYSTEM PERFORMANCE ANALYSES

The wideband FM system, as presently conceived, evolved from a series of performance analyses. These analyses were presented in Tech. Memos. G-161-2, 7, 8, 9 and 12. A first cut analysis of the wideband FM system was presented in Tech. Memo. G-161-2.

An analysis of transponder receiver signal processing in an interference environment was presented in Tech. Memo. G-161-7. The important results of this performance analysis which are incorporated into the present system are:

1. The command data should phase modulate the carrier rather than the subcarrier.
2. The modulation index of the wideband FM subcarrier should be on the order of 6 rather than 30.
3. A limiter should not be used in the carrier tracking loop.

An analysis of the performance of the ground receiver in a multiple-user interference environment was presented in Tech. Memo. G-161-8. The important results of this analysis which are valid for the present system are:

1. The telemetry data should phase modulate the carrier rather than the subcarrier.
2. The modulation index of the wideband FM subcarrier should be on the order of 6.
3. No limiter should be used in the carrier-tracking loop.
4. Different users should be identified on the downlink by a unique combination of carrier and subcarrier frequencies.

Additional modifications of the wideband FM system were presented in Tech. Memo. G-161-9. These modifications are utilized in the present system configuration and are:

1. Removal of the requirement that the subcarrier serve as a ranging signal. A separate range tone which phase modulates the uplink carrier is transmitted to all users. This tone is returned on the downlink as phase modulation of the downlink carrier. Ranging ambiguity resolution is accomplished by utilizing coherent ranging side-tones.
2. Generation of the downlink subcarrier by a subcarrier frequency synthesizer in the transponder. The subcarrier frequency may be selected on command from the ground.

The analysis conducted in Tech. Memo. G-161-7 considered specular rather than diffuse multipath interference. The effects of diffuse multipath interference in the wideband FM receiver were considered in Tech. Memo. G-161-12. The aim of that analysis was to develop an understanding of the manner in which the presence of diffuse multipath interference degrades performance. The model of the diffuse multipath interference assumed that the time delay spread was greater than the period of the subcarrier frequency but less than the bit period of the data. This meant that the various subcarrier sidebands faded independently. Consequently, an independently-fading sideband model was used in representing the diffuse multipath interference. Expressions were obtained for the contribution of the diffuse multipath to the carrier loop phase error variance, the subcarrier loop phase error variance, and the data demodulator "error" variance. This latter is the variance of the contribution of the diffuse multipath to the output of the data demodulator.

10. CONCLUSIONS AND RECOMMENDATIONS

Mathematical models of the multipath environment were formulated and used to evaluate the performance of several tracking and data systems operating in conjunction with a TDRS. Generally speaking, the effects of multipath on tracking functions were found to be small, and in fact could be made negligible by proper system design. The effects on data transmission are generally more serious because of the wider signal processing bandwidths required. Signal acquisition in the presence of multipath, while not directly addressed in this study, appears to be a problem for some of the systems under consideration.

The modeling effort has highlighted the need for more empirical knowledge of the magnitude of the various effects likely to be encountered in an operational TDRS system. This includes relative levels of diffuse and specular multipath, delay spread and doppler spread. The area of ionospheric effects, which was touched upon only lightly, deserves special attention. A great deal more information about observed fading properties, such as dispersive effects and statistics of fading depths, must be sought. Apart from an intensive search for any previously obtained observations, it seems necessary to perform flight experiments specially designed to measure propagation effects under realistic conditions.

In the process of performing this work we have evolved a promising concept for a Tracking and Data Relay Satellite (TDRS) system employing wideband frequency modulation (FM) signals. This is a form of spread-spectrum multiple-access system employing wide-deviation sinusoidal subcarriers to achieve the desired-spectrum

spreading. The concept encompasses the functions of tracking, command and telemetry, and is capable of accommodating many user spacecrafts and three or four relay satellites.

Analysis has indicated superior system performance in combating the expected sources of disturbance, including random noise, multipath, RF interference, and interferences from other user spacecrafts or other relay satellites. Furthermore, the system concept offers many deployment and operational advantages, such as flexibility in assignment of channels among different users, and ease of handover from one relay satellite to another. Wideband FM would be a highly effective and flexible approach to implementing the TDRS communications and tracking functions.

It is essential for GSFC to thoroughly evaluate the candidate TDRS system concepts prior to adoption of a specific approach for hardware implementation. Such evaluation includes paper design and performance evaluation of the concepts to meet practical requirements under the same ground rules.

However, we wish to emphasize that definitive evaluation and comparison of candidate system concepts must be based, not only on paper design and analytical predictions of performance, but also and more importantly on experimental evaluations. Only an experimental evaluation can uncover the practical advantages and limitations of a given system concept.

Consequently, we strongly recommend that GSFC initiate a combined analytical and experimental evaluation of the wideband FM system concept. Such a comprehensive program would yield, in a timely manner, sufficient information for a well-founded decision on the merits of the wideband FM system vis-a-vis other candidate concepts. Experimental as well as analytical evaluation of the wideband FM system is now urgently needed, in view of the on-going laboratory evaluation of other candidate concepts.