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LINEAR REPEATER DESIGN FOR THE GSFC MARK 1 TRACKING AND DATA RELAY SATELLITE

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TRACKING AND DATA RELAY SATELLITE

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I. INTRODUCTION

The concept of using tracking and data relay satellites (TDRS) to supplement and/or replace ground stations in supporting low-altitude earth-orbiting spacecraft has been given considerable study (Refs. 1-5) since the idea was first advanced in the early 1960's. Recently, the Goddard Space Flight Center (GSFC) has conducted a study of spacecraft and system concepts applicable to a TDRS flight program in the mid 1970's time frame (Ref. 6). Supported by a concurrent effort at the Jet Propulsion Laboratory (Ref. 7), the GSFC study noted apparently conflicting requirements in the matter of frequency selection for the TDRS system. Specifically, the low data rates and operational constraints associated with TDRS support of small unstabilized spacecraft and emergency support of manned vehicles pointed to a system implementation using broad-beam antennas at low frequencies, while the high data rates associated with TDRS support of advanced manned and automated spacecraft indicated a system configuration using narrow-beam antennas at high frequencies. An obvious solution, of course, would be to provide TDRS support on a multiple frequency basis. Thus, low data rate support services such as command, tracking, housekeeping telemetry and emergency voice might be implemented between gain-limited antennas in the 100 to 200 MHz region of the spectrum and high data rate links implemented between aperture-limited antennas at frequencies well above 1 GHz.

This paper discusses a single aspect of the general TDRS telecommunications design problem, namely use of synchronous relay satellites to collect low data rate telemetry from multiple small unstabilized spacecraft and transmit the multiple signals to a central ground data processing facility. The proposed approach is to configure the TDRS as a two-channel linear frequency translation repeater with each channel sensitive to one of two orthogonal linear signal polarizations, thus permitting optimal polarization diversity reception on a per user basis. Classical load rating theory is used to size repeater gain and dynamic range requirements for linear operations in the presence of an anticipated worst-case RFI environment. A sample design based on user/TDRS signaling in the existing VHF telemetry band suggests that the two-channel linear repeater approach can be implemented with acceptable penalties in spacecraft weight and prime power relative to alternate approaches such as hard-limiting repeaters.

II. BASIS FOR REPEATER DESIGN

The rationale for providing a two-channel TDRS/ground transmission link is based on NASA's experience with polarization diversity reception of VHF telemetry from unstabilized earth-orbiting spacecraft (Ref. 8). These spacecraft use nondirective antennas which, while radiating near-omnidirectional energy, have polarization characteristics which are strongly orientation-dependent. Received signals from such spacecraft will thus exhibit time-varying polarizations which in general will range over all extremes from right-hand circular to left-hand circular. In polarization diversity reception, independent signal samples from orthogonal linear polarized antennas are combined in phase so as to maximize the received signal/noise ratio. Since such combining must generally be done on a per signal basis, a logical approach to implementation of diversity reception in the multiple-access TDRS case is to receive the user signals on orthogonal linear antennas and relay the pair of resultant multi-channel signals to the ground independently for reception and processing in multiple polarization diversity receivers. This is the scheme proposed for the GSFC Mark 1 TDRS system (Ref. 6).

An extensive literature (Refs. 9-15) exists on the question of communications satellite repeaters handling multiple signals in the presence of thermal noise and RFI. The repeater configuration usually assumed in these treatments is the so-called average power-limited hard-limiting frequency translating repeater. This type of repeater has a fixed constant output power under all conditions of repeater input signal, noise, and RFI power levels; depending on these conditions, the constant available output power is divided among useful retransmitted signal power, retransmitted noise and RFI, and intermodulation products produced by the interaction of signals, noise, and RFI in the repeater's bandpass limiter.

In the multiple-user VHF TDRS application under consideration, use of a limiting repeater does not appear to be consistent with a general objective of minimizing degradation in the retransmission of user signals to the ground. For example, RFI conditions at the input to the repeater may be so severe that bandpass limiting of the composite signal, noise, and RFI process may produce co-channel intermodulation products of unacceptable magnitudes. Also, the baseline channel capacity of the TDRS/ground link may, without undue penalty, be made so much greater than that of the typical user/TDRS link that the increased ground receiver thermal noise floor due to reduced power linear operation of the TDRS repeater need not lead to appreciable degradation of the signal/noise conditions which existed at the spacecraft repeater input port(s).

III. REPEATER SIZING - SINGLE USER CASE

The problem of repeater sizing for the general case of multiple user signals, noise, and RFI will be formulated on the basis of the simplified TDRS system model shown in Fig. 1 (only one of two diversity channels is shown for clarity).

A user signal is received at the TDRS at a power level P_1 against a background of white gaussian receiver thermal noise of density KT_1 (refer to the Glossary for definition of symbols). The composite signal plus noise process is amplified in the TDRS repeater and transmitted to the ground via an RF link of rated channel capacity[1] $G_2 P_{tr}/KT_2$. With reference to the tandem link shown in Fig. 1, the actual user/TDRS/ground channel capacity is given by the expression $G_1 G_2 P_1/[G_1 G_2 KT_1 + KT_2]$. When written in the form of an overall noise density to signal ratio,

$$KT_{total}/G_1 G_2 P_1 = KT_1/P_1 + KT_2/G_1 G_2 P_1 \qquad \text{(Eq. 1.)}$$

the tandem link capacity is very near to being in terms of the individual link capacities P_1/KT_1 and $G_2 P_{tr}/KT_2$. Defining the parameter α as the ratio of retransmitted user power to available rated TDRS transmit power, i.e.

$$\alpha = G_1 P_1/P_{tr}, \qquad \text{(Eq. 2)}$$

we have that the tandem link channel capacity can be written in terms of the individual link capacities as

$$G_1 G_2 P_1/KT_{overall} = [KT_1/P_1 + KT_2/\alpha G_2 P_{tr}]^{-1}. \qquad \text{(Eq. 3)}$$

The problem of sizing the repeater is now essentially that of determining the maximum value of gain G_1 consistent with class A linear operation given specified input signal and noise conditions. The approach taken here is as follows. The repeater is taken to have a maximum power rating for linear operations of γP_{tr}. The bandpass gaussian noise process of average power $KT_1 B$ at the repeater input port is taken to have an effective peak/rms ratio X_1. Maximum linear drive conditions obtain when the repeater gain G_1 is adjusted to satisfy the amplitude constraint relationship

$$\sqrt{2\gamma P_{tr}} = \sqrt{G_1}\left[\sqrt{2P_1} + X_1\sqrt{KT_1 B}\right]. \qquad \text{(Eq. 4)}$$

This is illustrated in Fig. 2. On the basis of this relationship, we have that α can be expressed in terms of the power back-off factor γ and the input signal and noise conditions as

$$\alpha = \gamma P_1/\left[\sqrt{P_1} + \sqrt{\tfrac{1}{2}X_1^2 KT_1 B}\right]^2. \qquad \text{(Eq. 5)}$$

For engineering purposes, the peak/rms ratio of gaussian noise may be taken to be 12.0 db or 3.98 numeric (Ref. 16). Using this value for X_1 and values of 0, 1, 2, and 3 db for the power back-off factor γ, the parameter α is plotted as a family of curves in the upper area of Fig. 3 vs. TDRS repeater input signal/noise ratio $P_1/KT_1 B$ in db on the upper abcissa.

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[1] In terms of available average signal power relative to available noise density - an "infinite bandwidth" channel capacity in the Shannon sense.

Limiting cases of particular interest are:

- Case A: $P_1 >> KT_1B$ - In this case, $\alpha \cong \gamma$ because virtually 100% of the TDRS transmit power is useful user signal power G_1P_1.

- Case B: $P_1 << KT_1B$ - In this case, $\alpha = \gamma + 10\log_{10}[P_1/KT_1B]$ - 9.0 db. Virtually all of the TDRS transmit power is retransmitted receiver noise of average power G_1KT_1B with peak power 12.0 db above the mean, corresponding to peak TDRS transmit power of $10\log_{10}P_{tr} + 3.0 - \gamma$ dbw, the designed for maximum linear drive level.

Determination of the repeater gain for the postulated condition of maximum linear drive level follows immediately from the relationship $G_1 = \alpha P_{tr}/P_1$. Computation of the tandem link channel capacity is facilitated by use of the curve in the lower area of Fig. 3. One determines the magnitude of the difference between the user/TDRS channel capacity and the adjusted TDRS/ground channel capacity in db, locates a point on the lower abcissa, and reads on the left ordinate the number of db to be subtracted from the smaller of the two. This represents the degradation due to the finite noise floor of the ground receiver.

IV. REPEATER SIZING - GENERAL CASE

The system model for the single user case is extended to include multiple users plus RFI as follows. Assume there are N constant envelope user signals and M RFI sources. Let the received power of the i'th user be P_i and the worst-case received power of the j'th RFI signal be Q_j. The amplitude constraint relationship of Eq. 4. is extended to read

$$\sqrt{\gamma P_{tr}} = \sqrt{G_1}\left[X_1[\tfrac{1}{2}KT_1B]^{\frac{1}{2}} + X_2[\sum^{N} P_i]^{\frac{1}{2}} + X_3[\sum^{M} Q_j]^{\frac{1}{2}}\right] \quad \text{(Eq. 6)}$$

where X_1 has been defined above and X_2 and X_3 are the peak/rms ratios of the signal and RFI processes respectively.

For N less than ten, X_2 (in decibel form) should be computed from the defining relationship

$$10\log_{10}X_2 = 20\log_{10}\sum^{N}\sqrt{2P_i} - 10\log_{10}\sum^{N} P_i \quad \text{(Eq. 7)}$$

with a similar relation applicable to computation of X_3 for small numbers of RFI signals. For cases in which both N and M are large, the central limit theorem may be invoked to bless both the signal and RFI processes with gaussian amplitude statistics. In this situation, the constraint relationship may be written

$$\sqrt{2\gamma P_{tr}} = \sqrt{G_1}\left[\sqrt{2P_1} + X_1\left[\sqrt{KT_1 B} + \sum_{2}^{N} P_i + \sum^{M} Q_j\right]\right]. \qquad \text{(Eq. 8)}$$

The complex of thermal noise, competing users, and RFI can now be considered an equivalent bandpass gaussian process of mean power KTB_{eq} and we have that the ratio of retransmitted single user power $G_1 P_1$ to the rated TDRS transmit power is in a form similar to Eq. 5., i.e.

$$\alpha = \gamma P_1 / [\sqrt{P_1} + \sqrt{\tfrac{1}{2} X_1^2 KTB_{eq}}\,]^2 . \qquad \text{(Eq. 9)}$$

This permits immediate use of the curves of Fig. 3 derived for the case of a single user signal plus additive gaussian noise. This general formulation may be recognized as a more-or-less elementary application of classical load-rating theory for multi-channel amplifiers (Ref. 16).

V. APPLICATION TO THE GSFC MARK 1 TDRS

The use of the relationships developed in the above is best appreciated by a specific design example. The VHF receive/retransmit subsystem of the GSFC Mark 1 TDRS system has the basic parameters shown in Table 1 (details of implementation are given in Ref. 6). On the basis of a compilation of some seventy-two potential sources of in band RFI (Ref. 17), the worst-case mean RFI power which would be seen by either channel of the VHF receiving system has been estimated to be -95.0 dbm in either channel. Assuming ten equal power simultaneous users, the mean power developed by the nine competing signals would be -116.5 dbw in either channel. The thermal noise power in either channel is -105.6 dbm. The equivalent gaussian bandpass noise process is then computed to have a mean level of -94.5 dbm in either channel. Thus, the per channel P_1/KTB_{eq} ratio is -32.5 db.

The estimated Mark 1 TDRS/ground $G_2 P_{tr}/KT_2$ channel capacity is nominally +95.3 db-Hz per channel. To determine the degradation in user/TDRS channel capacity which will be incurred by operating the two-channel repeater in a linear manner under the postulated conditions of multiple users and RFI, we assume a power back-off factor γ of 1.0 db and use Case B in lieu of Fig. 3 to determine a value of the α parameter of -42.5 db. The adjusted TDRS/ground channel capacity for the single user is +95.3 - 42.5 = +52.8 db-Hz. The difference between the adjusted TDRS/ground channel capacity and the user/TDRS channel capacity is +52.8 - 42.6 = 10.2 db. Using the curve in the lower area of Fig. 3, we find that the user/TDRS channel capacity is degraded 0.4 db to +42.2 db-Hz. Optimal polarization combining at the ground will effect a 3.0 db improvement, so that the overall user/TDRS/ground channel capacity is +45.2 db-Hz. This is to be contrasted with a value of +45.6 db-Hz which would obtain if diversity combining were done at the TDRS and the TDRS/ground link had infinite channel capacity.

The repeater gain per channel is computed to be +124.5 db. This is comparable to that of the quasi-linear VHF repeater flown in the ATS Program. The repeater dynamic range must provide for handling of input full load sinusoidal test tones of -86.0 dbm without distortion. This is not considered a significant design problem using high performance solid-state components in the repeater proper and state of the art TWT's for the final output power amplifier.

VI. CONCLUSIONS

A technique for sizing multiple-access TDRS repeaters for linear operations in a severe RFI environment was described. Using the parameters of a proposed TDRS system and a worst-case estimate of the in-band RFI environment, linear repeater gain and dynamic range requirements were determined on the basis of maximizing the overall user/TDRS/ground channel capacity. The results of the analysis provide confidence that the two-channel linear repeater is an attractive and feasible implementation of the VHF TDRS concept.

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GLOSSARY OF MAJOR SYMBOLS

B.......TDRS repeater equivalent noise bandwidth, Hz.
G_1......Power gain of TDRS repeater, input port to output port.
G_2......Power gain of TDRS/ground link, from TDRS output port to ground receiver input port.
$n_1(t)$....TDRS repeater input noise process.
$n_2(t)$....Ground receiver input noise process.
K.......Boltzmann constant, -228.6 dbw/$^{\circ}$K-Hz.
P_i......Power of i'th constant envelope user signal at TDRS input port.
Q_j......Worst-case constant envelope power of j'th RFI signal.
T_1......TDRS repeater equivalent noise temperature.
T_2......Ground receiver equivalent noise temperature.
X_i......Peak/rms ratio of i'th signal or RFI process.
P_{tr}.....TDRS rated repeater transmit power, watts.
γ.......Power back-off factor for linear operation of TDRS repeater.
α.......Parameter relating rated transmit power P_{tr} to useful signal retransmitted signal power $G_1 P_1$.
N......Number of simultaneous user signals.
M......Number of simultaneous RFI sources.

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TABLE 1

SUMMARY OF MARK 1 TDRS SYSTEM PARAMETERS

Repeater Type	Two-channel linear frequency translation
Receive frequency band	136.0 - 138.0 MHz
Receive antenna beamwidth	~26° (provides coverage of all earth-orbiting spacecraft out to 3000 miles)
Receive antenna gain	~16 db, either channel
Repeater receiving system temperature	1000° K
Transmit frequency band	X-band (~7.3 GHz)
Transmit rated power per channel	10 watts
Transmit antenna gain per channel	~20 db
Ground antenna diameter	85 feet
Ground receiving system temperature	~100° K

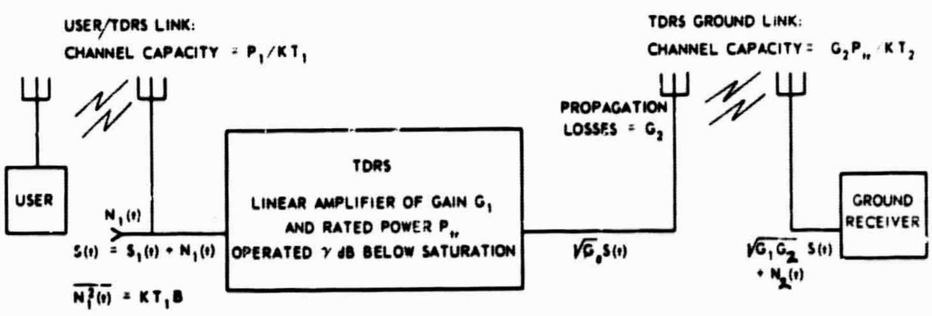

Figure 1. Illustrating the tandem link concept for the single user case.

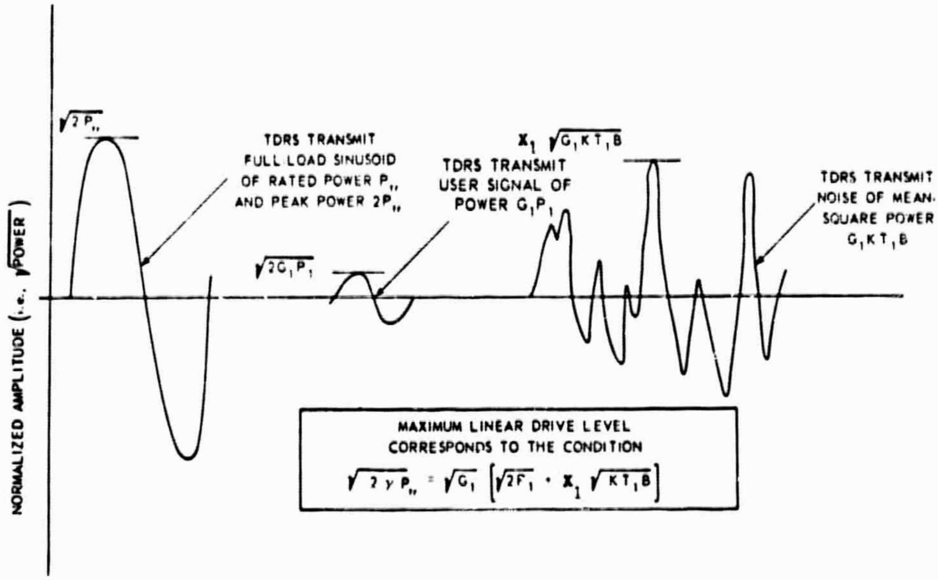

Figure 2. Illustrating the amplitude constraint relationship of Eq. 4; single user case plus additive noise.

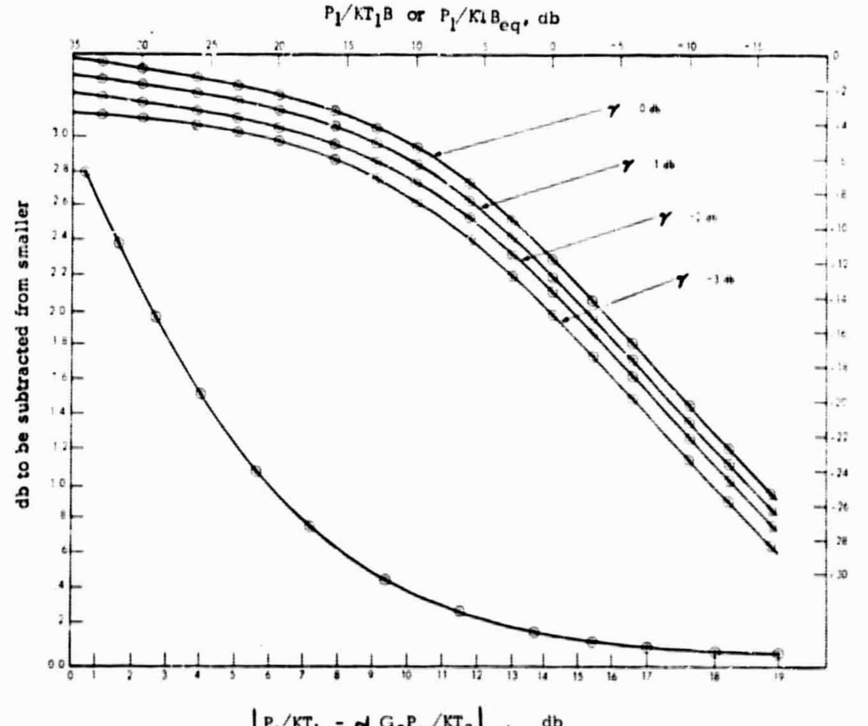

Figure 3. Composite nomograph: upper curves show α vs. P_1/KT_1B or P_1/KTB_{eq}; lower curve relates difference in P_1/KT_1 and $\alpha G_2 P_{tr}/KT_2$ to db degradation in P_1/KT_1 due to finite channel capacity of the TDRS/ground link.