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PART I FINAL REPORT

TRACKING & DATA RELAY SATELLITE SYSTEM CONFIGURATION & TRADEOFF STUDY

VOLUME VII TELECOMMUNICATIONS SYSTEM SUMMARY

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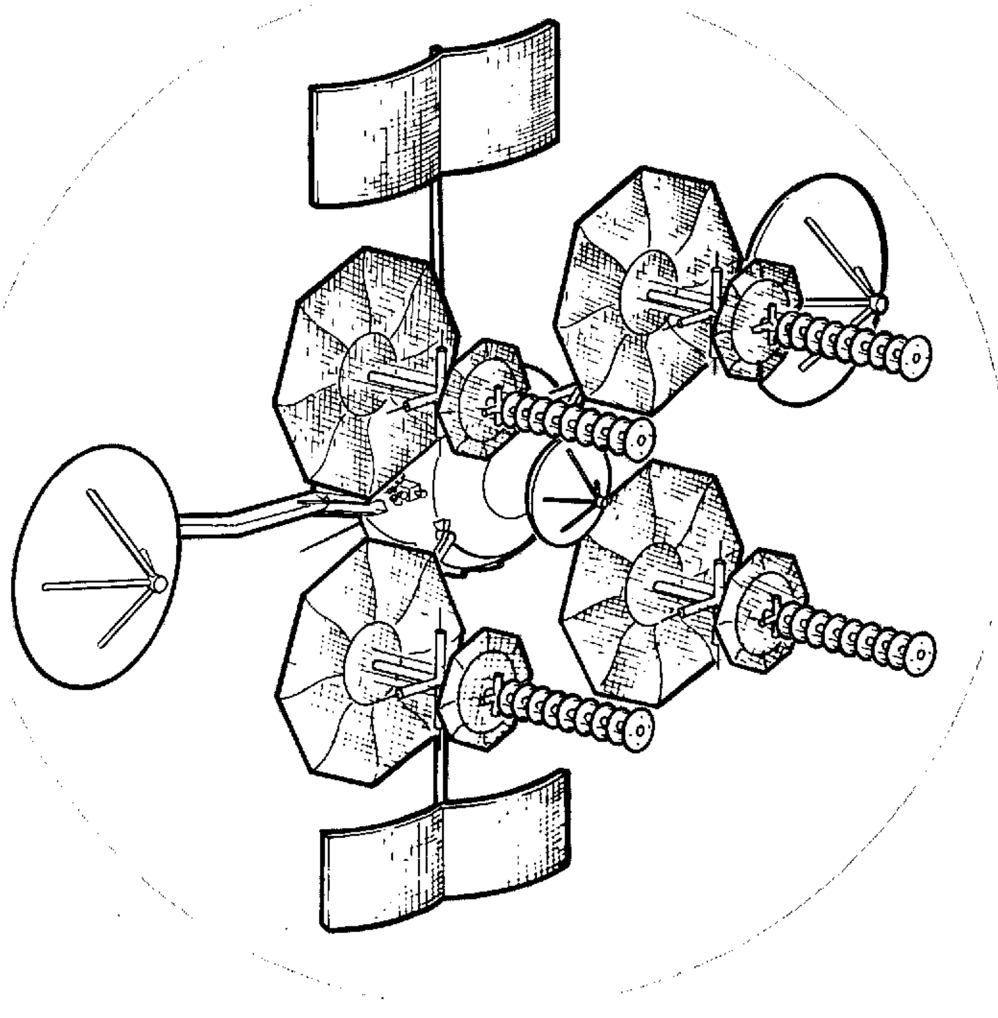

OCTOBER 1972

SUBMITTED TO
GODDARD SPACE FLIGHT CENTER
NATIONAL AERONAUTICS & SPACE ADMINISTRATION

Space Division
North American Rockwell

12214 Lakewood Boulevard, Downey, California 90241

IN ACCORDANCE WITH
CONTRACT NAS5-21705

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PART I FINAL REPORT

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VOLUME VII

TELECOMMUNICATIONS SYSTEM SUMMARY

T. E. Hill
TDRS STUDY MANAGER

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FOREWORD

This report summarizes the results of Part I of the study conducted under Contract NAS5-2107, Tracking and Data Relay Satellite Configuration and Systems Trade-off Study - 3-Axis Stabilized Configuration. The study was conducted by the Space Division of North American Rockwell Corporation for the Goddard Space Flight Center of the National Aeronautics and Space Administration.

The study is in two parts. Part I of the study considered all elements of the TDRS system but emphasized the design of a 3-axis stabilized satellite and a telecommunications system optimized for support of low and medium data rate user spacecraft constrained to be launched on a Delta 2914. Part II will emphasize upgrading the spacecraft design to provide telecommunications support to low and high, or low, medium and high data rate users, considering launches with the Atlas/Centaur and the Space Shuttle.

The report consists of the following seven volumes.

1.	Summary	SD 72-SA-0133-1
2.	System Engineering	SD 72-SA-0133-2
3.	Telecommunications Service System	SD 72-SA-0133-3
4.	Spacecraft and Subsystem Design	SD 72-SA-0133-4
5.	User Impact and Ground Station Design	SD 72-SA-0133-5
6.	Cost Estimates	SD 72-SA-0133-6
7.	Telecommunications System Summary	SD 72-SA-0133-7

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R.H. French	"	Operations Analysis
G. Shaushanian	"	User Transponder Design

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TABLE OF CONTENTS

VOLUME I

VOLUME II

VOLUME III

Section | Page

Section Page

VOLUME IV

Section | Page

VOLUME VI

VOLUME VII

ILLUSTRATIONS

TABLES

14.0 SUMMARY OF THE TDRS TELECOMMUNICATION SYSTEM

14.1 INTRODUCTION

This volume summarizes the baseline TDRSS Telecommunication System including the TDR Satellite Telecommunication Subsystem, User Spacecraft Terminal, and the Ground Based Terminal as illustrated in Figure 14-1. Detailed analysis and description of the Telecommunication Subsystem is included in Volume III, and User Spacecraft Impact and the Ground Station are combined in Volume V of this Part I Final Report. The topics covered are:

- System Service and Performance Summary showing the link support, modes of operation, and link performance to the Low Data Rate and Medium Data Rate User Spacecraft.
- Link Budget Calculation to show a typical computation for each space-to-space and space-to-ground link including the assumptions used in each calculation.
- Summary of subsystem terminal characteristics including the Spaceborne Telecommunication System, User Spacecraft Terminal, and Ground Station.

The overall telecommunications service requirements are shown in Table 14-1, and the overall working frequency plan is shown in Table 14-2.

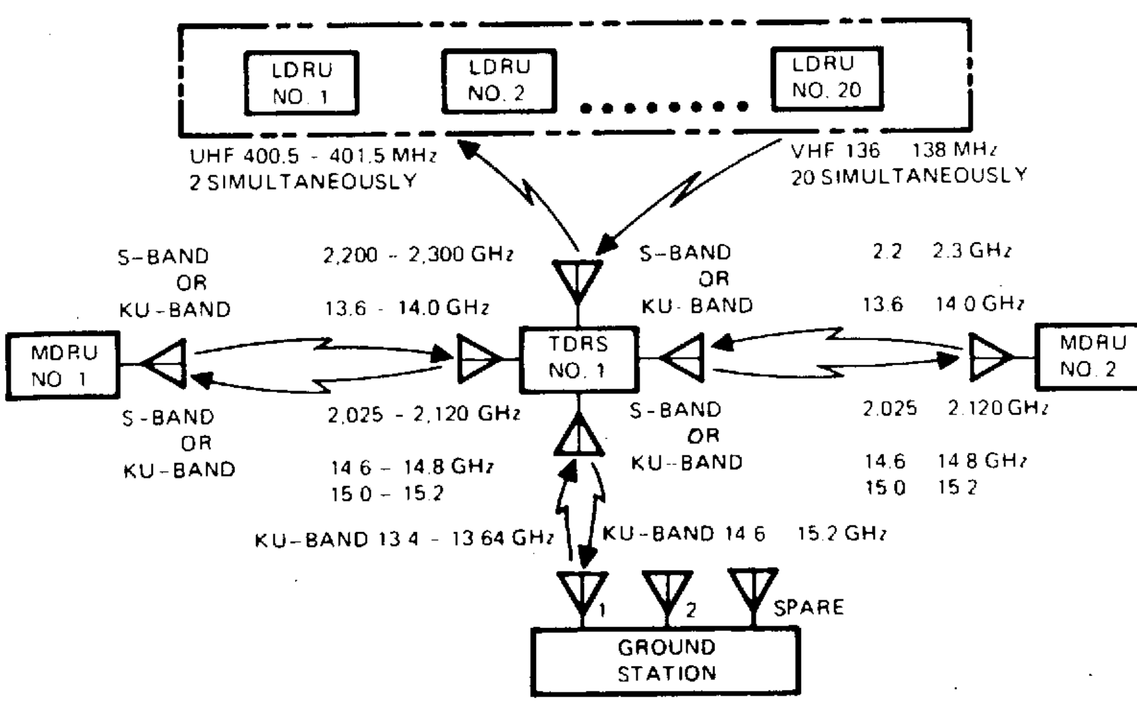

Figure 14-1. Components of the TDRS Telecommunication System (Typical = One TDRS Satellite)

Table 14-1. Telecommunications Service Requirements
(as per SOW)

Description	LDR User	MDR User	Manned User (Shuttle)
Number of users	Forward: Minimum of 1 Return: 20	Minimum of 1	Minimum of 1
Frequency	Forward: VHF, UHF, S-band Return: VHF	S- or X- or Ku-band	S-band, VHF-band
Communications requirement	Forward: 100 to 1000 bps Return: 1 to 10 kbps	Forward: 100 to 1000 bps Return: 10 to 1000 kbps	Forward: 2 kbps 1 or 2 voice at 19.2 kbps Return: 76.8 kbps 1 or 2 voice at 19.2 kbps
Constraints	·Linear transponder in return link ·High RFI ·Flux density (IRAC): VHF $\leq$ -144 dBw/m^2/4 khz UHF $\leq$ -150 dBw/m^2/4 khz S-band $\leq$ -154 dBw/m^2/4 khz ·EIRP = +30 dBw/channel (VHF, UHF) = +41 dBw/channel(S) .BER = 10^{-5}	·Linear TDRS transponder return link ·Variable frequency ·Flux density (IRAC): S-band $\leq$ -154 dBw/m^2/4 khz X-band $\leq$ -150 dBw/m^2/4 khz Ku-band $\leq$ -152 dBw/m^2/4 khz ·BER = 10^{-5}	·User antenna gain = +3 dB ·BER Voice: 10^{-3} Data: 10^{-4} ·User transmit power = 16 dBw

Table 14-2. System Frequency Plan

	Links	Frequency	Channel Bandwidth
Forward Link	• LDR	400.5 to 401.5 MHz	1 MHz 4 - 250 Khz channels
	• MDR S-band Ku-band	 2025 to 2120 MHz 14.6 to 15.2 GHz	 95 MHz channel 4 - 100 MHz channels
	• TDRS/GS Ku-band VHF S-band	 13.4 to 13.64 GHz 148.26 MHz 2200 to 2290 MHz	 240 MHz 90 MHz
	• Tracking/Order Wire	2066 MHz	
	• Ku Beacon	15.0 GHz	
Return Link	• LDR	136 to 138 MHz	2 MHz (20 users multiple accessed/TDRS)
	• MDR S-band	 2200 to 2300 MHz	 20-10 MHz slots in 5 MHz steps or 100 MHz wide open
	• Ku-band	13.6 to 14.0 GHz	4-100 MHz channels
	• TDRS/GS Ku-band VHF S-band	 14.6 to 15.2 GHz 136.11 MHz 2025 to 2110 MHz	 200 or 600 MHz channel 85 MHz
	• Tracking/Order Wire	2249 MHz	

14.2 SYSTEM SERVICÉ AND PERFORMANCE

14.2.1 LDR Return Link

The Adaptive Ground Implemented Phased Array (AGIPA) is the primary mode with F-FOV approach as a back-up for LDR return link functions. This approach provides multiple access support to twenty simultaneous LDR users per TDR satellite. The service characteristics are:

Function		AGIPA Mode	F-FOV Mode
• Telemetry Data			
No RFI		13.7 - 20 kbps	4.8 kbps
-160 dBm/Hz		5.61 - 16 kbps	0.9 kbps
• Voice			
No RFI		Yes	Yes
-160 dBm/Hz		Yes	No
• Range Error			
No RFI	meter	0.91 - 0.76	1.2
-160 dBm/Hz	meter	1.45 - 0.909	
• Range Error			
No RFI	cm/sec	0.99 - 0.623	0.8
-160 dBm/Hz	cm/sec	0.56 - 0.47	1.2

Figure 14-2 presents the LDR return link performance as a function of RFI level. The assumptions used in calculating the curves are:

Item	AGIPA Mode	F-FOV Mode
Modulation	Δ PSK	Δ PSK
User EIRP, dBw	4.0	4.0
Losses-Space & Scan	-169.3	-173.1
-Polarization	-0.5	-0.5
TDRS Antenna Gain, dB	16.8	16.8
Syst Noise Temp, dB	30.2	30.2
Δ CNR Degradation, dB	-1.0	-1.0
FEC Coding Gain, dB	4.7	4.7
E_b/N_o for data, dB	9.9	9.9
C/N_o for voice, dB-Hz	48.8	48.8
Δ SIR(1) dB	5 -18	

Note: 1. Improvement in signal-to-interference ratio as compared to F-FOV was determined in a RFI model analysis in study.

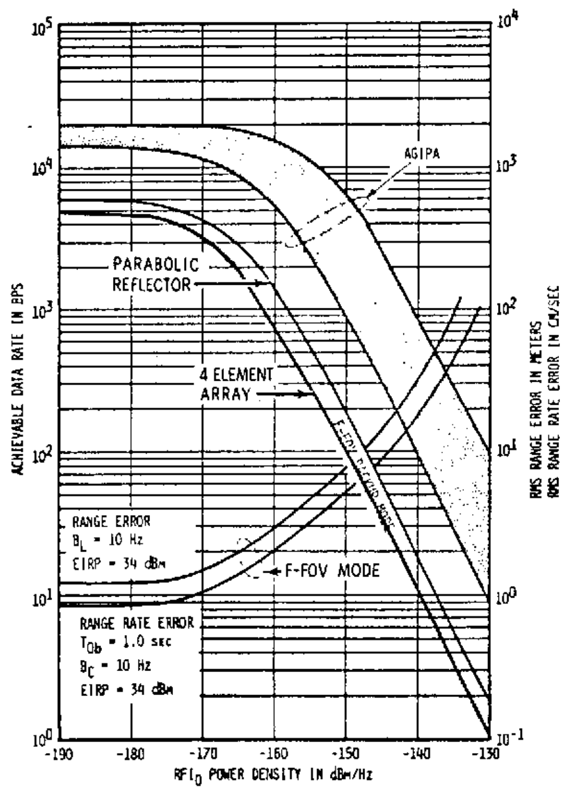

Figure 14-2. LDR Return Link Performance Achievable Bit Rate, Range Error, and Range Rate Error

14.2.2 LDR Forward Link

An electronically steered array provides a high gain beam for each of two channels. Alternatively one element can be used to provide a beam covering the entire thirty-one degrees (0.54 rad) field of view (F-FOV mode). The configuration supports: (1) two simultaneous users in steered array mode, or (2) one user in steered array mode and one user in F-FOV mode. The service characteristics are:

Function		Steered Array Mode (+30 dBw)	F-FOV Mode (+24 dBw)
Command Data			
No RFI		2100 bps	650 bps
-160 dBm/Hz		179 bps	42 bps
Voice			
No RFI		Yes	Yes
-160 dBm/Hz		Yes	Yes
Range Error			
No RFI	meter	4.2	7.5
-160 dBm/Hz	meter	13.2	26.1
Range Rate Error			
No RFI	cm/sec	0.4	0.72
-160 dBm/Hz	cm/sec	0.6	1.13

Figure 14-3 presents the LDR forward link performance as a function of RFI. The assumptions used in calculating the curves are:

	Steered Array Mode	F-FOV Mode
Modulation	Δ PSK	Δ PSK
EIRP at 31°(.54 rad) FOV, dBw		
Data	30	24
Voice	36	24
Losses-Space & Scan, dB	-178.1	-178.1
-Polarization, dB	-3.0	-3.0
User Antenna Gain, dBi		
Unmanned	-3.0	-3.0
Manned	0	0
System Noise Temp., dB	26.8	26.8
Δ CNR Degradation, dB	-0.25	-0.25
Design Margin, dB		
Data	3.0	3.0
Voice	11.2	1.1
E_b/N_o for data, dB	9.9	9.9
C/N_o for voice, dB/Hz	48.8	48.8

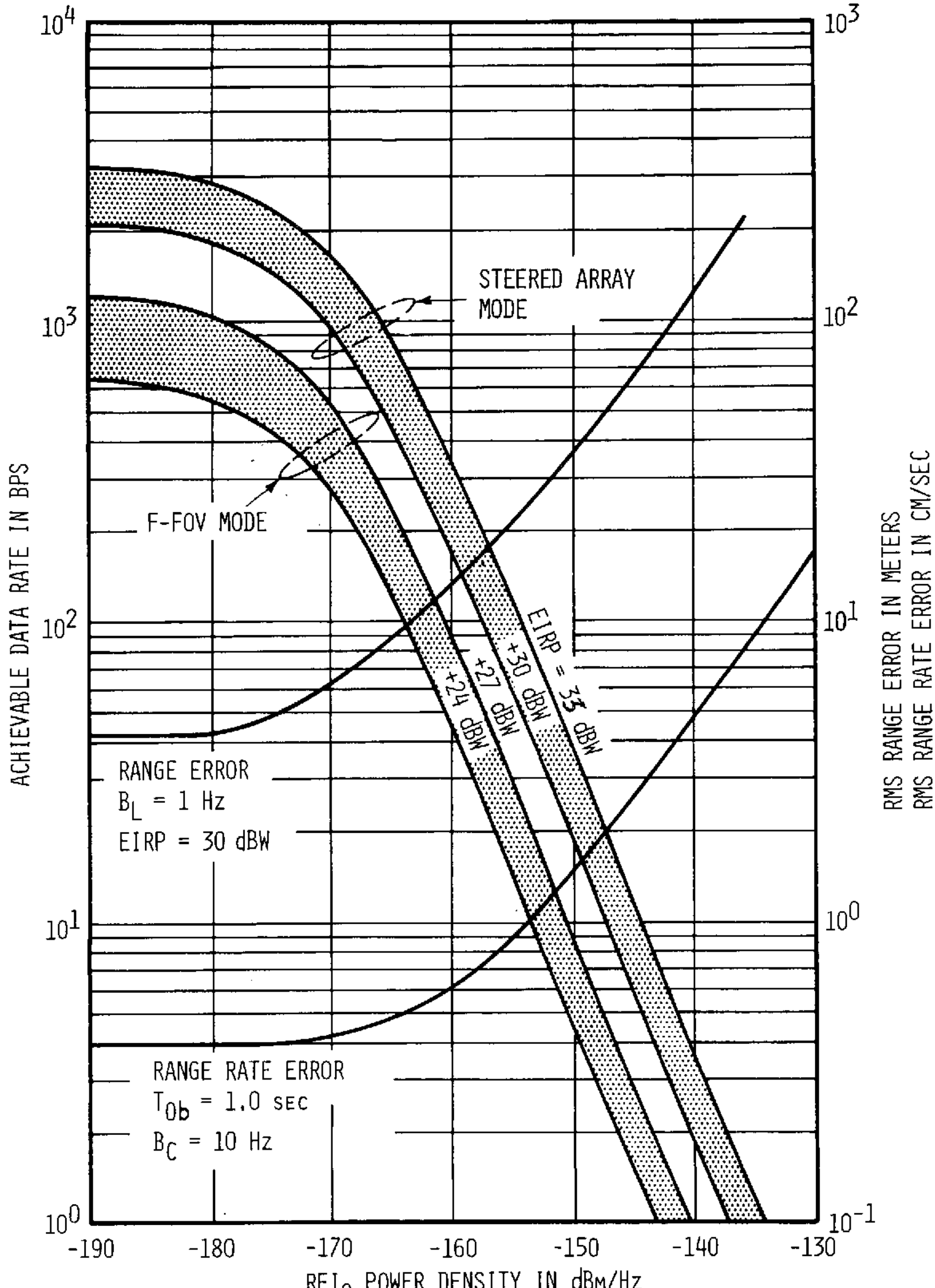

Figure 14-3. LDR Forward Link Performance Achievable Data Rate, Range Error, and Range Rate Error

14.2.3 MDR Link Performance

The MDR transponder on the TDRS provides dual frequency operation in both the forward and return links. S-band is provided to support current users with minimum impact. Ku-band is provided to support future high performance users. The RF interface with the MDR users is provided by two 6.5 feet (2 m) dishes to simultaneously support two S-band users, two Ku-band users, or S-band and one Ku-band user.

Space Shuttle support is provided by the MDR transponders with the following capabilities:

Forward link	One data link at 2 kbps
	One data link at 2 kpbs plus one voice link at 19.2 kbps
	One data link at 2 kbps plus two voice links each at 19.2 kbps
Return link	One data link at 76.8 kbps
	One data link at 76.8 kbps plus one voice link at 19.2 kbps
	One data link at 76.8 kbps plus two voice links each at 19.2 kbps

The capability for scientific user support (Spec MDR) is:

Forward link data rate	1000 bps (S or Ku-band)
Return link data rate	10 kbps with 7 dBw EIRP at S- or Ku-band 1 MBps with 27 dBw EIRP at S- or Ku-band

Figures 14-4 and 14-5 present the MDR return and forward link performance as a function of user S/C ERP and antenna gain respectively. The assumptions used in calculating the curves are:

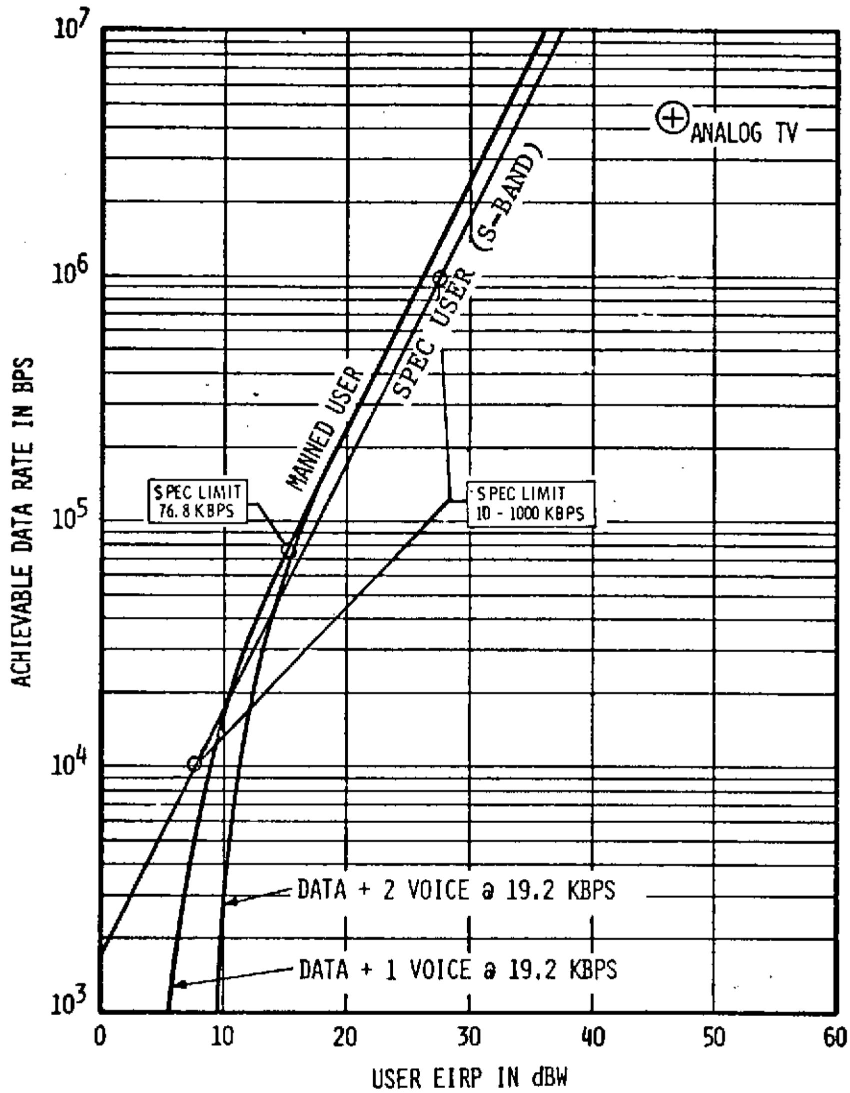

Figure 14-4. MDR Return Link Performance

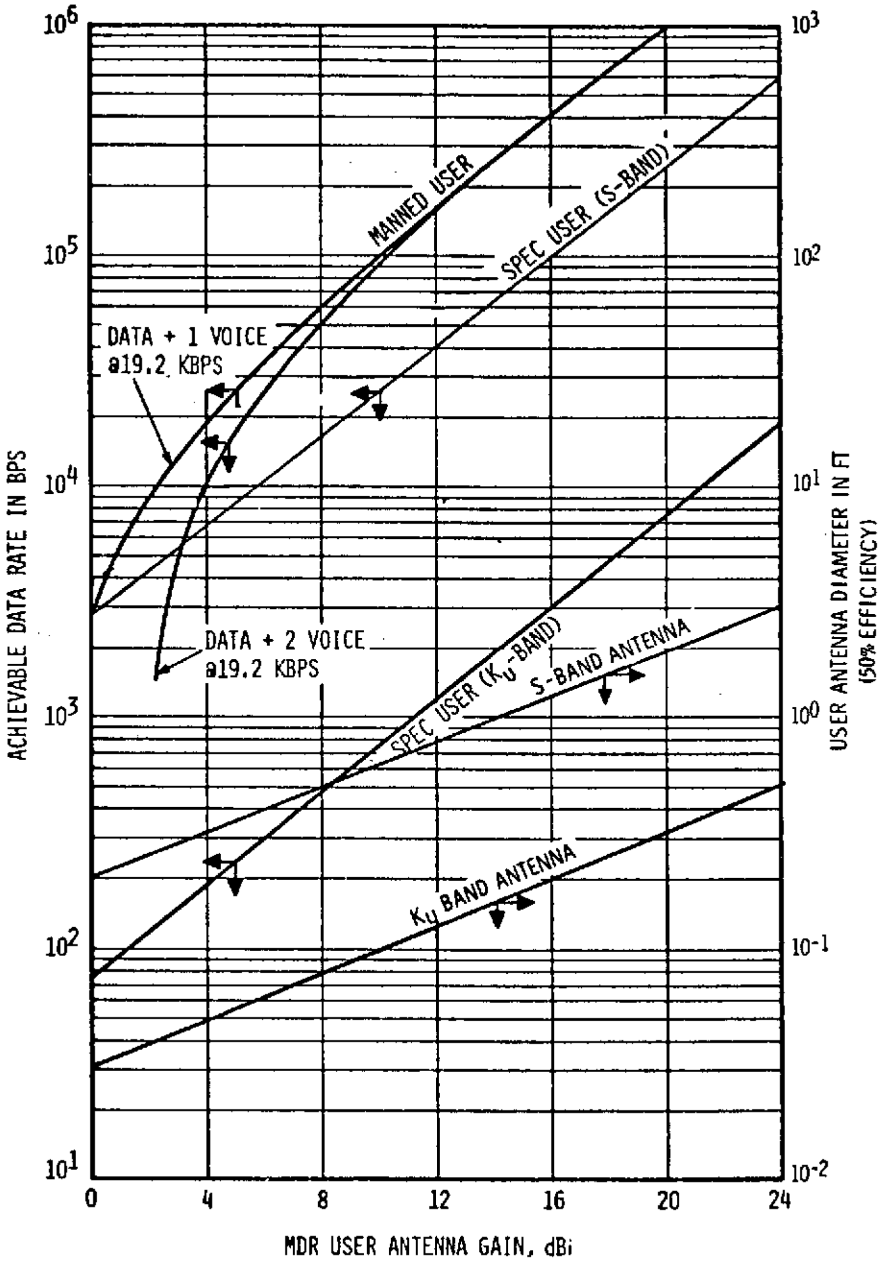

Figure 14-5. MDR Forward Link Performance

	Item	Spec S-Band MDR User	Manned MDR User	Spec Ku-Band MDR User
FORWARD LINK	TDRS EIRP, dBw	41.0	41.0/47.0(4)	45.8
	Space loss, dB	192.0	192.0	208.1
	Other losses (1) dB	1.1	1.1	1.1
	User antenna gain, dBi	G_u	3.0	G_u
	User system noise temp., dB	29.1	27.3 (2)	33.5 (3)
	Design margin, dB	3.0	3.0	3.0
	C/N_o available dB/Hz	$44.4+G_u$	49.2/55.2	$28.7 + G_u$
RETURN LINK	TDRS system noise temp. (5), dB	26.2	26.2	26.2
	Space loss (5) dB	191.1	191.1	191.1
	Other losses (1) dB	1.6	1.1	1.1
	FEC coding gain (6)	4.7	4.7	4.7
	Design margin, dB	3.0	3.0	3.0
	TDRS antenna gain, dBi	30.9	30.9	30.9

(1) Combined polarization, pointing and Δ CNR degradation

(2) Uncoded paramp

(3) Tunnel diode amplifier

(4) 6 dB increased EIRP for voice mode

(5) Values selected at a point where the product of loss and system temperature maximizes.

(6) Forward error control (R = 1/2, K = 7 convolutional code; Viterbi decoder).

14.3 LINK BUDGET

14.3.1 LDR Return Link Budget

The LDR return link operates in the 136-138 MHz VHF band, and uses an adaptive process called AGIPA in its primary mode, and F-FOV as a backup mode. The link performance was calculated as shown in Table 14-3 using the following expression to compute the achievable data rate (H):

$$H = \frac{P_u \text{ (FEC)}}{\text{CNR} \left[N_i + \frac{1}{\Delta \text{SIR}} \left(\text{RFI}_o + M_o + D_o \right) \right]} \qquad (1)$$

Where:

CNR = required CNR

N_i = input thermal noise density at TDRS

P_u = $(\text{EIRP})_{\text{User}} \times G_{\text{TDRS}} \times L_T$ = received user power at TDRS

L_t = all losses including space, polarization, and scan

FEC = forward error control

Δ SIR = improvement in signal-to-interference ratio provided by AGIPA

RFI_o = unintentional interference signal power density

M_o = intentional multipath interference signal from desired and other in-band LDR users

$= \frac{1}{CR} \left\{ K \left[\frac{4 P_u}{\propto} + \frac{n-1}{20} \times R \times P_u \right] \right\}$

CR = PN chip rate

K = an attenuation factor proportional to the reflection coefficient = 1.0

n = the number of users/channel = 20

R = the ratio of average multipath contribution of other users to the desired signal power ($\approx$7 dB for the 1976 user s/c distribution)

= 2h/300; h = user altitude = 300 km (worst case for multipath)

D_o = intentional direct interference signal from other in-band LDR users

= $(n-1) \, P_u / CR$

The sample link calculation was computed for an RFI_o of - 160 dBm/Hz, and user EIRP of + 4 dBw. The Δ SIR improvement is a minimum value based on results of an RFI model analysis conducted during the study.

The calculation shows that even in the relatively large RFI environment of -160 dBm/Hz that AGIPA (with minimum adaptive processing gain) provides over 5 kbps of data, and/or voice with considerable margin. The F-FOV mode can support approximately 1 kbps of data but requires higher EIRP to support voice.

Table 14-3. LDR - Return Link Budget

		AGIPA Mode		F-FOV Mode	
		Data	Voice[1]	Data	Voice[1]
Modulation		ΔPSK	ΔPSK	ΔPSK	ΔPSK
User EIRP	dBw	4.0	7.0[2]	4.0	7.0[2]
TDRS antenna gain (peak)	dBi	16.8	16.8	16.8	16.8
Losses - space + scan[7]	dB	-169.3	-169.3	-173.1	-173.1
- polarization	dB	- 0.5	- 0.5	- 0.5	- 0.5
Received power	dBw	-149.0	-146.0	-152.8	-149.8
System noise temperature	dB	30.2	30.2	30.2	30.2
Noise density - thermal	dBw/Hz	-198.4	-198.4	-198.4	-198.4
multipath	dBw/Hz	-200.7	-200.7	-200.7	-200.7
Other direct signal	dBw/Hz	-196.7	-196.7	-196.7	-196.7
RFI_o	dBw/Hz	-190.0	-190.0	-190.0	-190.0
Total noise density	dBw/Hz	-188.4	-188.4	-188.4	-188.4
TDRS ΔCNR degradation[3]	dB	-1.0	-1.0	-1.0	-1.0
C/N_o	dB-Hz	38.4	41.4	34.6	37.6
FEC coding gain[5]	dB	4.7	4.7	4.7	4.7
Available C/N_o (w/o AGIPA process gain)	dB-Hz	43.1	46.1	39.3	42.3
E_b/N_o[6]		9.9	--	9.9	--
AGIPA process gain[4]	dB	4.3[9]	4.3[9]	--	--
Achievable bit rate	dB	37.5	--	--	--
	bps	5610	--	871	--
Required C/N_o for voice	dB-Hz	--	48.8	--	48.8
Design margin	dB	--	1.6	--	-6.5[10]

NOTES

1. Voice is delta modulated, 19.2 kbps at $P_e = 10^{-3}$ and requires a C/N_o of 48.8 dB-Hz.
2. Manned user assumed to have directional antenna with 0 dBi gain.
3. A CNR degradation (ΔCNR) of 1.0 dB assumed for the TDRS transponder.
4. Worst case AGIPA processing gain included. Actual AGIPA performance in RFI model has shown 5 to 18 dB signal-to-interference ratio improvement over F-FOV approach.
5. Coding gain achieved with Forward Error Control (FEC) using Rate 1/2 constraint length 7 with a Viterbi decoder.
6. E_b/N_o = 9.9 for ΔPSK at $P_e = 10^{-5}$.
7. Worst case combination of space and scan losses since they do not maximize at the same spacecraft aspect angle.
8. Chip rate (CR) = 10^6 bps.
9. AGIPA processing gain of 6.5 dB as compared to F-FOV approach, or 4.3 dB is compared to nonadaptive AGIPA.
10. For equivalent performance as AGIPA, the EIRP must be increased (7.0 + 6.5 + 1.6) to 15.1 dBw or 32.4 watts.

14.3.2 LDR Forward Link Budget

The LDR Forward Link operates in the 400.5 - 401.5 MHz UHF band, and provides two forward channels for voice and/or data. Both channels can operate in a high gain steerable beam mode, or one channel can be operated in a low gain F-FOV mode. Sample link calculations have been made, as shown in Table 14-4, for both data and voice transmissions in both steerable beam and F-FOV modes, using the following expression for command data rate (H):

$$H = \frac{P_u}{CNR \left\{ N_i + RFI_o + \frac{1}{CR} \left[\frac{4 P_u}{\propto} \right] \right\}} \qquad (2)$$

where the parameters are as defined for equation (1).

In the calculation, the worst case combination of the space loss and scan loss have been used, since the individual worst cases do not occur simultaneously.

The link calculation shows that in the presence of -160 dBm/Hz RFI environment that peak command data of 272 bps and 76.8 bps can be supported in the steerable beam and F-FOV modes, respectively. Voice can be supported in the AGIPA mode with over 10 dB margin, but will require forward error control coding gain of 4.4 dB in the F-FOV mode to provide a margin of 3 dB.

14.3.3 MDR Return Link Budgets

The MDR return link power budgets for S-band (spec user and manned user) and Ku-band are presented in Tables 14-5 and 14-6, respectively. The objective here is to develop an estimate for the required user EIRP for various levels of mission support. To compute the EIRP required, the following equation was used:

$EIRP_{required} = \left(\frac{C}{N_o} \right)_{required}$ + Boltzmanns Const. $\left(-228.6 \frac{dBw}{^oK\text{-}Hz}\right)$ + TDRS System Noise Temperature + Path Loss + Other Losses - TDRS Antenna Gain + Forward Error Control + Design Margin.

The required $\left(\frac{C}{N_o}\right)$ is based on the type of service and performance desired over the link. The values for TDRS system temperature and path loss were chosen for the point where their combined effect is maximum. Other losses referred to are the combination of pointing, polarization and TDRS Δ CNR degradation. A forward error control coding gain of 4.7 dB was added to the link budget so that the system will have maximum return link performance with minimum impact on the user EIRP requirements.

With the exception of the manned user the transmit power P_T required is expressed in terms of dBw-G_u, where G_u is the user antenna gain. The required P_T then will decrease as the user antenna gain increases. For example, the 1 Mbps link requires a P_T of 27.6 dBw-G_u; if the user antenna gain is on the order of 20.7 dBi then P_T is on the order of 7 dBw or 5 watts. For the manned user G_u is fixed at 3 dBi, thereby fixing the shuttle required P_T somewhere between 11.79 and 46.44 dBw depending on the service required.

Table 14-4. LDR - Forward Link Budget at UHF

	Steerable Beam Mode		F-FOV Mode	
	Data	Voice (1)	Data	Voice
Modulation	△ PSK	△ PSK	△ PSK	△ PSK
Transmitter Power, dBw	13.0	19.0	13.0	13.0
TDRS Antenna Gain (peak) dBi	21.0	21.0	15.0	15.0
Transmit Line Losses (2), dB	1.0	1.0	1.0	1.0
EIRP (peak), dBw	33.0	39.0	27.0	27.0
Losses - Space & Scan (3), dB	-178.1	-178.1	-178.1	-178.1
- Polarization, dB	-3.0	-3.0	-3.0	-3.0
User Antenna Gain, dBi	-3.0	+0.0(4)	-3.0	0.0(4)
Received Power, dBw	-151.1	-142.1	-157.1	-154.1
System Noise Temp., dB	26.8	26.8	26.8	26.8
Noise Density - Thermal, dBw/Hz	-201.8	-201.8	-201.8	-201.8
- Multipath	-197.8	-(4)	-197.8	- (4)
- RFI, dBw/Hz	-190.0	-(4)	-190.0	- (4)
Total Noise Density, dBw/Hz	-189.1	-201.8	-189.1	-201.8
TDRS △ CNR Degradation (5), dB	-0.25	-0.25	-0.25	-0.25
Available C/N_o, dB	37.25	59.45	31.75	47.45
E_b/N_o (6), dB	9.9		9.9	
Design Margin, dB	3.0	10.65	3.0	-1.35(8)
Achievable Bit Rate, dB	24.35		18.85	
bps	272.0		76.8	
Required C/N_o for voice		48.8		48.8

Notes:
(1) Voice is delta modulated, 19.2 kpbs at $Pe = 10^{-3}$ and requires a C/N_o of 48.8 db-Hz.
(2) No diplexer required in dual VHF-UHF antenna design.
(3) Worst case combination of the space loss and scan loss since they do not maximize at the same spacecraft aspect angle.
(4) For the manned user, a directional antenna providing 0 dBi gain toward the TDRS satellite has been assumed, and rejecting all interference signals.
(5) A CNR degradation (△CNR) of 0.25 dB assumed for the TDRS transponder.
(6) $E_b/N_o = 9.9$ for PSK at $Pe = 10^{-5}$.
(7) CR = (Chip Rate) = 167 kcps.
(8) Total margin must include +1.35 dB plus the desired design margin.

Table 14-5. MDR Return Link Budget (S-Band)

Item	MDR User 10 kbps[1]	MDR User 1000 kbps[1]	MDR User Analog TV[2]	Manned User (Space Shuttle) Data[3] (76.8 kbps)	Manned User (Space Shuttle) Data + 1 Voice[4]	Manned User (Space Shuttle) Data + 2 Voice	Manned User (Space Shuttle) Analog TV
C/N_0 required, dB-Hz	49.9	69.9	87.54	57.59	58.17[5]	58.50[6]	87.54
FEC coding gain, dB	4.70	4.70		4.70	4.70	4.70	
Effective C/N_0, dB-Hz	45.2	65.2	87.54	52.89	53.47	53.80	87.54
Path loss[7], dB	191.1	191.1	191.1	191.1	191.1	191.1	191.1
System temperature[7], dB	26.2	26.2	26.2	26.2	26.2	26.2	26.2
Boltzmann's const, dBW/°K-Hz	-228.6	-228.6	-228.6	-288.6	-228.6	-228.6	-228.6
Pointing loss, dB	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Polarization loss, dB	0.5	0.5	0.5	0.5	0.5	0.5	0.5
G_{user}, dBi	G_u	G_u	G_u	3.0	3.0	3.0	3.0
G_{TDRS}, dBi	30.9	30.9	30.9	30.9	30.9	30.9	30.9
ΔCNR degradation, dB	1.0	1.0	1.0	0.5	0.5	0.5	0.5
System margin, dB	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Required EIRP, dBw	7.6	27.6	49.94	14.79	15.37	15.70	49.44
Transmit power[8], dBw	$7.6 - G_u$	$27.6 - G_u$	$49.94 - G_u$	11.79	12.37	12.7	46.44

NOTES
1 ΔPSK; BER = 10^{-5} (E_b/N_0 = 9.9 dB)
2 Commercial quality $(S/N)_o$ = 40 dB; BW = 4.5 MHz
3 ΔPSK; BER = 10^{-4} (E_b/N_0 = 8.7 dB)
4 Voice is delta modulated at 19.2 kbps; carrier modulation is ΔPSK (BER = 10^{-3}; C/N_0 = 48.8 dB-Hz)
5 Combine value of data (C/N_0 = 57.59) and one voice (C/N_0 = 48.8)
6 Combine value of data (C/N_0 = 57.59) and two voice (C/N_0 = 51.8)
7 This value is selected at the point where the product of the path loss and system temperature is maximum
8 Transmit power into antenna

Table 14-6. MDR Return Link Budget (Ku-Band)

Item	10 kbps[1]	1000 kbps[1]	Analog TV[2]
C/N_0 required, dB - Hz	49.9	69.9	87.54
FEC coding gain, dB	4.7	4.7	-
Effective C/N_0, dB - Hz	45.2	65.2	87.54
Path loss[3], dB	208.1	208.1	208.1
System temperature[3], dB	26.7	26.7	26.7
Boltzmann's const., dBw/°K - Hz	-228.6	-228.6	-228.6
Pointing loss, dB	0.1	0.1	0.1
G_{user}, dB	G_u	G_u	G_u
G_{TDRS}, dB	47.1	47.1	47.1
ΔCNR degradation, dB	0.5	0.5	0.5
System margin	3.0	3.0	3.0
Required EIRP, dBw	7.9	27.9	50.2

1 ΔPSK; BER = 10^{-5} (E_b/N_0 = 9.9 dB)
2 Commercial quality $(S/N)_0$ = 40 dB; BW = 4.5 MHz
3 This value is selected at the point where the product of path loss and system temperature is maximum.

The sensitivity of the system noise temperature (T_s) to the noise temperature (Te_1) of the parametric amplifier for the MDR S-Band Receiver was also computed and is shown in Figure 14-6. The expressions used for the curve are:

$$T_s = T_a + T_r$$

$$T_r = T_o\ (L_1-1) + Te_1\ (L_1) + Te_2\ (L_1)/G_1 + \ldots\ldots.. \qquad (3)$$

$$= 116 + 1.4\ Te_1 + 12.6 = 128.6 + 1.4\ Te_1$$

Where the parameters used in the equation are defined in the block diagram in the same figure. The antenna temperature (T_a) of 234° K is the worst case temperature as seen by the MDR receiver. For the predicted device temperature of 50° K for the 1974 time period, the resultant system noise temperature is 26.15dB or 410° K. On the other hand if a conservative design employing existing (1972) technology of 100° K is used, the system noise temperature increases by only 0.5 dB.

14.3.4 MDR Forward Link Budgets

The forward link power budgets for the Medium Data Rate user is presented in Table 14-7 for three generic user types; namely, the spec (or scientific) MDR user operating at S-band, the Manned user (Space Shuttle), and the Spec-MDR user operating at K_u-band. In the table, the available carrier-to-noise density ratio (C/N_o) was computed to assess the overall performance of each. The expression used to compute (C/N_o) is as follows:

$$\left(\frac{C}{N_o}\right)_{Available} = \text{EIRP - Free Space Loss + User Antenna Gain - (Other Losses* + Boltzmanns Constant } \left(-228.6\ \frac{dBw}{0\ K\text{-}Hz}\right) \text{+ User System Noise Temperature)}$$

* Other losses comprise pointing, polarization, and TDRS Δ CNR degradation losses.

For the MDR S- and K_u-band Spec user, C/N_o is in terms of dB-Hz + G_u (the user antenna gain), implying that any addition of user gain produces a corresponding increase in C/N_o. For the Spec MDR S-band user, the required maximum forward link support of 1 Kbps can be achieved with a system margin of 8.7 dB + G_u (dB). Likewise, the Spec MDR K_u-band user can be provided with forward link support of 75 X G_u bps (i.e., if the MDR user spacecraft carries a K_u-band antenna having a gain of 20 db (100) the forward link data rate which can be supported is 7.5 kbps.)

The manned user link has a C/N_o of 53.4 db-Hz available. As can be seen from the table, forward error control coding is required to support 1 data link (2 kbps) and 2 voice links (each at 19.2 kbps).

14.3.5 TDRS-to-Ground Station Return Link Budget

The TDRS-to-Ground Station return link operates in the 14.6 to 15.2 GHz Ku-band, and must operate in the presence of rain in the earth's atmosphere. This link has a margin of 7.5 dB during normal, clear weather operation, and an additional 10 dB power amplification is provided for operation in rain.

Table 14-7. MDR Forward Link Budget

Item		MDR S-Band User	Manned User (Space Shuttle)	MDR Ku-Band User
Modulation		ΔPSK	ΔPSK	ΔPSK
Transmitter power	dBw	12.5	12.5/18.5	-2.0
TDRS antenna gain	dB	29.8	29.8	48.1
Transmit line losses	dB	1.3	1.3	1.0
EIRP	dBw	41.0	41.0/47.0[7]	45.1
Losses				
Space	dB	-192.0	-192.0	-208.1
Pointing	dB	-0.1	-0.1	-0.1
Polarization	dB	-0.5	-0.5	-0.5
User antenna gain	dBi	G_u	3.0	G_u
Received power	dBw	$-151.6 + G_u$	-148.6/-142.6	$-163.6 + G_u$
System noise temperature	dB	29.1	27.3[1]	33.5[5]
Thermal noise density	dBw/Hz	-199.5	-201.3	-195.1
TDRS ΔCNR degradation	dB	-0.25	-0.25	-0.25
Available C/N_0	dB-Hz	$47.65 + G_u$	52.45/58.45	$31.25 + G_u$[6]

Support Requirements		100 bps[2]	1000 bps	Data[3]	Data + 1 Voice[4]	Data + 2 Voice[4]	BER = 10^{-5} (ΔPSK)
C/N_0 required	dB-Hz	29.9	39.9	41.7	49.6	52.4	--
Data rate achievable	bps	--	--	--	--	--	$68.4 \times G_u$[6]
Design margin	dB	$17.75 + G_u$	$7.75 + G_u$	10.75	8.85	6.05	3.0

NOTES
1. Noise temperature with an uncooled paramp.
2. For ΔPSK with a BER = 10^{-5} (E_b/N_0 = 9.9 dB)
3. Data = 2 kbps ΔPSK with BER = 10^{-4} (E_b/N_0 = 8.7 dB)
4. Voice is delta modulated at 19.2 kbps; carrier modulation is ΔPSK (BER = 10^{-3}; (C/N_0 = 48.8 dB-Hz)
5. Tunnel diode amplifier
6. A 1.0 ft (.3 m) antenna at Ku-band provides about 28.5 dB gain (i.e., a factor of about 800) providing an achievable bit rate of about 55 kbps
7. Increased EIRP used for voice mode only

Space Division
North American Rockwell

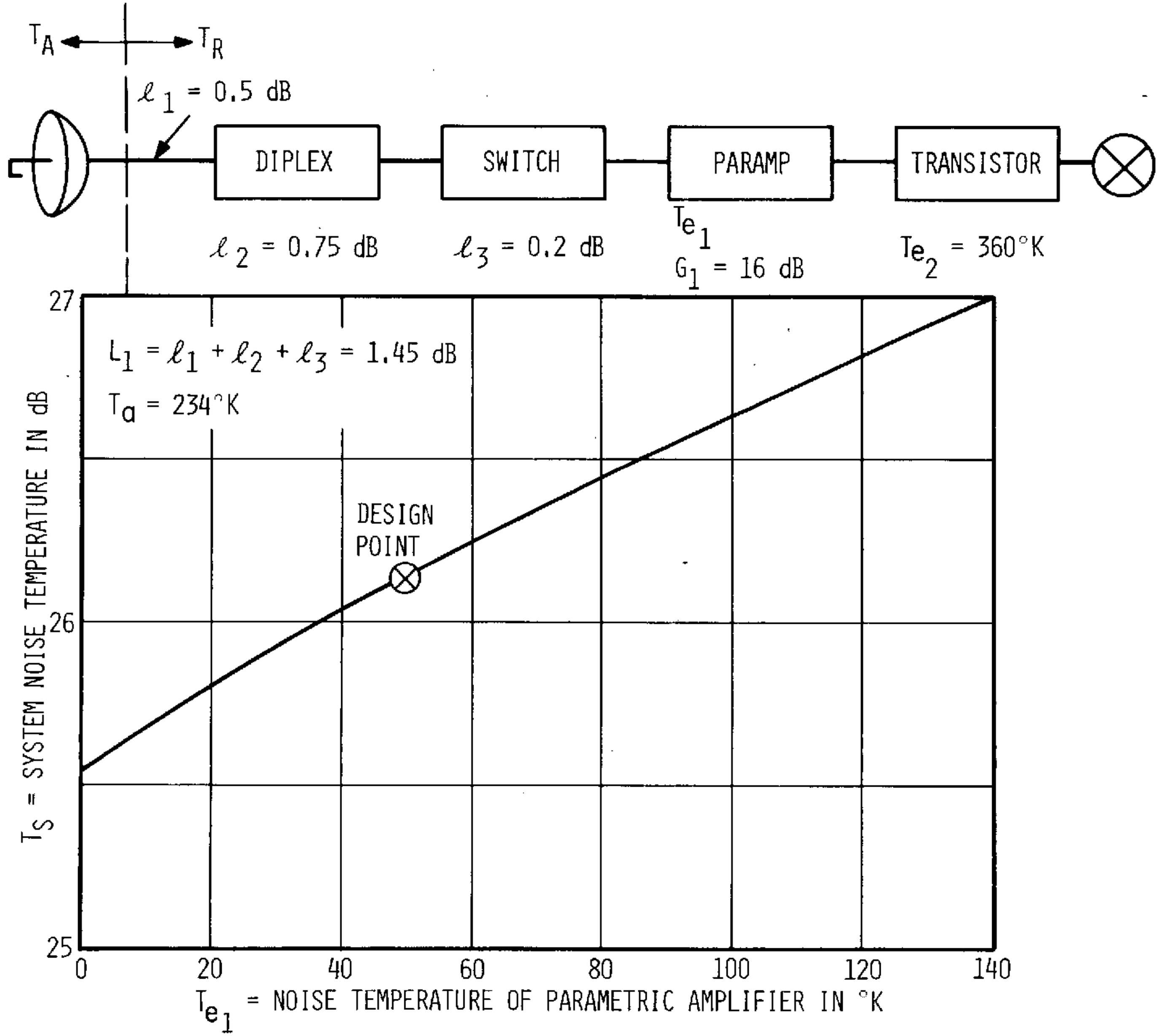

Figure 14-6. System Noise Temperature Vs Noise Temperature of Parametric Amplifier

This link is sized for the worst case of transmitting TV to the GS, using FDM/FM. The index of modulation is 0.94 using a phased locked demodulator at the GS.

The link power budget is computed using the following equation:

$$P_{TDRS} = \frac{(CNR_o)\ (KT_S\ B) \propto_T}{G_{TDRS} G_{GS}}$$

where:

T_S = system noise temperature, including the antenna and receive thermal temperaturs

KT_SB = system noise power

G_{TDRS} = three foot (0.91m) aperture at TDRS

G_{GS} = sixty foot (18.3m) aperture at GS

$\propto_T$ = total losses including space, pointing, polarization, transmit line (component losses)

B = RF bandwidth

CNR_o = CNR required for FM

The resultant link budget is shown in Table 14-8, and shows that a TDRS transmitter power of 2.75 watts is required for operation in rain, and 0.275 watt for clear weather operation.

14.3.6 Ground Station-to-TDRS Forward Link Budget

The CNR required for the GS-to-TDRS-to-User link was computed using the tandem link equation to determine the required CNR for the GS-to-TDRS portion of the tandem link using the following equation:

$$CNR_F = \left(CNR_{TDRS} \times CNR_{GS}\right) \Big/ \left(CNR_{TDRS} + CNR_{GS} + 1\right)$$

where:

CNR_F = final CNR required

CNR_{TDRS} = CNR required in the space-to-space link

CNR_{GS} = CNR required in the ground-to-space link

The results of the CNR's computation are shown in Figure 14-7 for the LDR and typical MDR modes, and are used in Table 14-9 to compute the TDRS transmit power requirement for this link. Since the MDR-TV requires the largest transmit power, it has been used to size the transmitter using the following link equation:

$$P_{TDRS} = \frac{(CNR_F)\ (KT_SB) \propto_T}{G_{TDRS}\ G_{GS}}$$

Table 14-8. TDRS-to-Ground Station Return Link Budget

Modulation	FDM/FM
CNR Required	0dB (1)
RF Bandwidth	600. MHz (2)
GS System Noise Temperature	25.2 dB (3)
Thermal Noise Power	-115.6 dBw
GS Antenna Gain	67.9 dBi (4)
Losses - Space	-208.1 dB
- Pointing	-1.0 dB
- Polarization	-0.5 dB
- Transmit Line/Others	-1.0 dB
Rain Margin	17.5 dB (5)
EIRP Required at TDRS	44.6 dBw
TDRS Antenna Gain	40.3 dBi
TDRS Transmit Power Req'd.	4.3 dBw
	2.75 watt - for rain
	0.275 watt - for clear weather

Notes:
(1) FM modulation with modulation index of 0.94 with phase locked demodulator.
(2) For TV transmission.
(3) Two uncooled paramps in cascade each with Te of 130°K.
$T_s = T_a + (L_1 - 1)\ T_o + L_1\ Te_1 + (L_1\ Te_2/G_1) + \ldots..$
$= 18 + (0.43)\ 290 + 1.43 \times 130 + (1.43 \times 130/100) = 329°K = 25.2$ dB
(4) 18.3 m aperture with 75% efficiency
(5) Rain margin provides operation in 25 mm/hr rainfall rate.

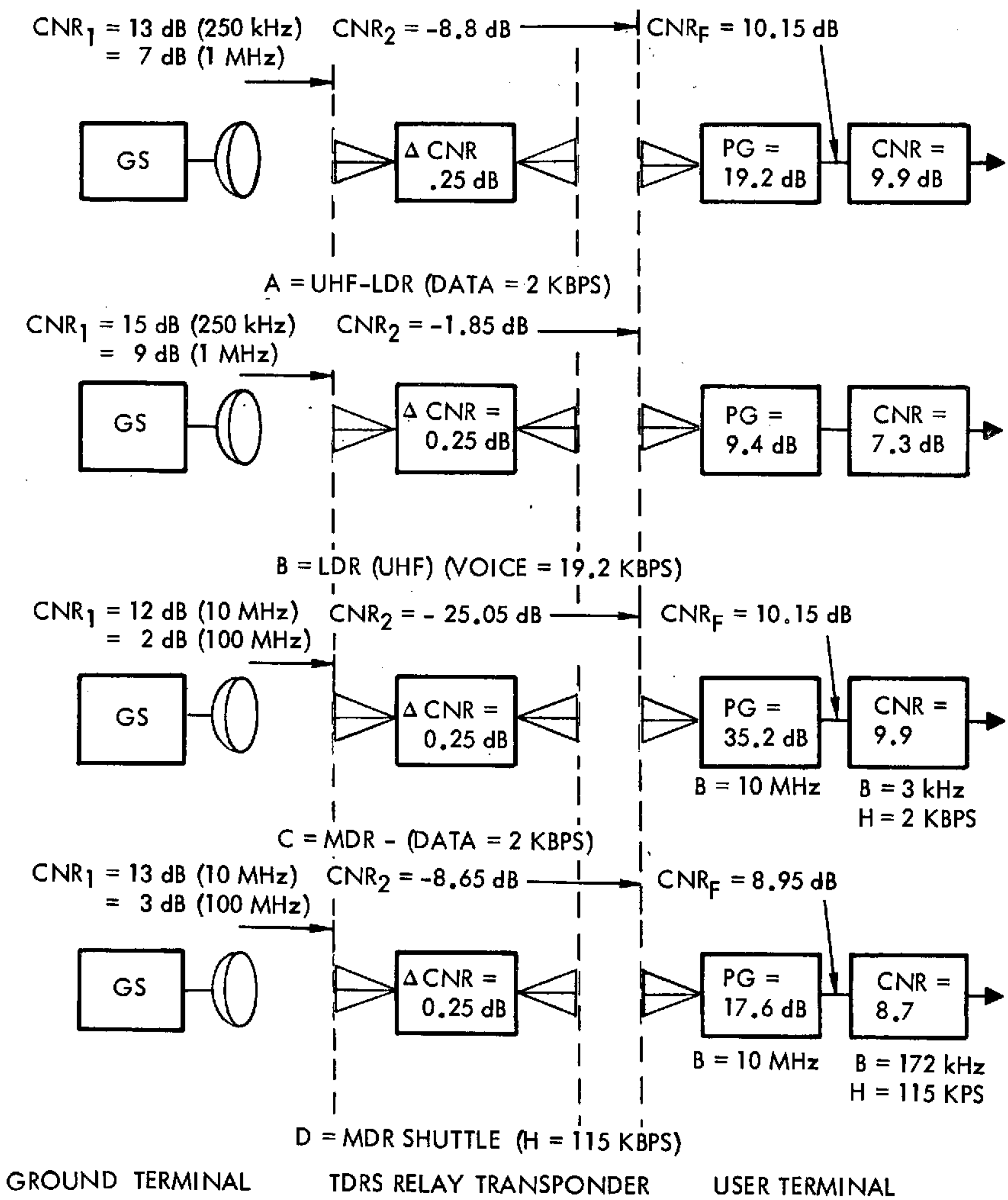

Figure 14-7. CNR Calculation in TDRS/GS Forward Link

Table 14-9. Ground Station-to-TDRS Forward Link Budget

Parameter	LDR Data	LDR Voice	MDR Data	MDR - Shuttle Data + 2 Voice
Modulation	ΔPSK	ΔPSK	ΔPSK	ΔPSK
Data Rate, kbps	1.0	19.2	2.0	115.0
CNR Required (1), dB	7.0	9.0	2.0	3.0
RF Bandwidth, MHz	1.0	1.0	100.0	100.0
System Noise Temperature (2), dB	33.6	33.6	33.6	33.6
Thermal Noise Power, dBw	-135.0	-135.0	-115.0	-115.0
TDRS Antenna Gain, dBi	39.6	39.6	39.6	39.6
Losses: Space, dB	-207.2	-207.2	-207.2	-207.2
Pointing, dB	-1.0	-1.0	-1.0	-1.0
Polarization, dB	-0.5	-0.5	-0.5	-0.5
Atmospheric, dB	-0.4	-0.4	-0.4	-0.4
Transmit Line/Others, dB	-5.9	-5.9	-5.9	-5.9
Rain Margin (3), db	17.5	17.5	17.5	17.5
EIRP Required, dBw	64.9	66.9	79.9	80.9
GS Antenna Gain (4), dBi	67.0	67.0	67.0	67.0
GS Transmit Power Required, dBw	-2.0	-0.1	12.9	13.9
GS Transmit Power Required, watts	0.63	1.0	19.5	24.5

NOTES:
(1) See Figure A-7 for the required CNR for the GS/TDRS link.
(2) Uses mixer front end.
(3) Rain margin provides operation in 25mm/hr rainfall rate.
(4) Sixty feet (18.3m) aperture with seventy-five percent efficiency

where:

T_S = system noise temperature, including antenna and receive thermal temperature

KT_SB = system noise power

G_{TDRS} = three foot (0.91m) aperture at TDRS

G_{GS} = sixty foot (18.3m) aperture at GS

α_T = total losses including space, pointing, polarization, transmit line (component losses)

B = RF bandwidth

14.3.7 Tracking/Order Wire Link Budget

The Tracking/Order Wire Transponder operates in the S-band spectrum and provides three associated telecommunication functions, viz:

- Tracking and position location of the TDR satellite using trilateration ranging with two remote GS and the TDRS GS.
- Order wire receiver to establish order of priority access to the S-band MDR channel.
- S-band beacon for S-band MDR users employing steerable antenna

Typical link calculations were made for both forward and return link operations as shown in Table 14-10.

14.3.8 Ku-Band Beacon Link Budget

The Ku-band beacon is used as a source by Ku-band MDR users with steerable antennas to acquire and track the TDRS satellite. This beacon can also be used by the GS as a pilot signal to coherently lock its frequency source, in the event the normal mode where the TDRS locks-on to the GS pilot signal cannot be established. The sample link calculation is shown in Table 14-10 for the TDRS to user case to size the transmitter requirements.

14.4 SUBSYSTEM TERMINAL CHARACTERISTICS

14.4.1 TDRS Telecommunication Subsystem

The TDRS Telecommunication System includes the Telecommunication Service System, and the Tracking, Telemetry and Command (TT&C) System. A functional block diagram of the Telecommunication System is shown in Figure 14-8 and includes:

- LDR Transponder
- MDR #1 Transponder
- MDR #2 Transponder

Table 14-10. TDRS Tracking/Order Wire Transponder and Ku-Band Beacon Link Budgets

	Tracking/Order Wire Transponder		Ku-Band Beacon
	Forward	Return	
Transmitter Power, dBw	3.0	16.0 (1)	1.5
Transmit Antenna Gain, dBi	14.5	3.0 (1)	12.0
Transmit Losses, dB	-3.0	-3.0	-0.5
EIRP, dBw	14.5	16.0 (1)	13.0
Losses: Space, dB	-191.0	-192.4	-208.1
Polarization, dB	-1.0	-1.0	-1.0
Receive Antenna Gain, dBi	43.0	12.0	30.0 (5)
Received Power, dBw	-135.0	-165.4	-166.1
Thermal Noise Density, dBw/Hz	-206.8	-201.1	-203.8
System Noise Temperature, dB	21.8	27.5 (2)	24.8
TDRS ΔCNR Degradation, dB	-0.5	-0.5	-
Available C/N_o, dB-Hz	(3) 71.8	35.2	37.7
E_b/N_o, dB-Hz		9.9	
Design Margin, dB		5.0	5.0
Achievable data rate, dB		20.3	32.7
Achievable data rate, bps		≈100.0	

Notes:
(1) Assumed Space Shuttle as user.
(2) Transistor with Te = 360 K
(3) For C/N_o = 71.8 dB-Hz and a chip duration of 2×10^{-6} sec the one way ranging error (ΔR) for the TDRS/GS link is 7×10^{-2} meters.
(4) This is more than adequate to provide order wire service.
(5) Assumes that a high performance Ku-Band MDR user will have at least 30 dBi antenna gain.

- TDRS/GS Transponder
- Frequency Source
- Tracking/Order Wire Transponder
- Ku-Band Beacon
- TT&C

The major characteristics of the Telecommunication System are shown in Table 14-11, and a size, weight, power summary is shown in Table 14-12.

14.4.2 User Transponder Design

14.4.2.1 LDR Transponder on User S/C

A simplified schematic block diagram of the LDR transponder is shown in Figure 14-9. The receiver is designed to tune to any one of four UHF carrier frequencies used by the two TDRSs. The carrier in the forward link is phase modulated by a 167 Kchip/sec pseudonoise (PN) sequence to discriminate against multipath and to distribute the signal energy radiated from the TDRS to conform to the IRAC requirements. A 1 Mchip/sec PN sequence is used in the return link to permit code division multiple access of 20 LDR users through a common channel in the TDRS with sufficient process gain to achieve a specific level of performance for any one user in the face of nineteen interfering users. The use of PN sequences in both the forward and return links provides a vehicle for deriving range information.

The data is delta PSK modulated with convolutional encoding to save power through error control. The demodulation process in the receiver is rather straightforward. The transmitter, except for the PN modulation, is a standard transmitter configuration.

A preliminary estimate of the size and prime power requirements of the user LDR transmitter and receiver are: transmitter - power, 16 watts; size, 225 in^3 (3700cc); and receiver - power, 12 watts; size, 195 in^3 (3200cc).

The characteristics of the LDR user terminal are summarized in the following:

LDR User Terminal Characteristics

Forward Link

•Data Rate	100 bps to 1000 bps
•Carrier frequency	400.5 to 401.5 MHz (4 - 250 KHz channels)
•PN Modulation	167 Kchips/sec
•Code Length	Short - 2047 chips Long - Eleven 2047
•One PN Code Sequence To All Users	

FOLDOUT FRAME

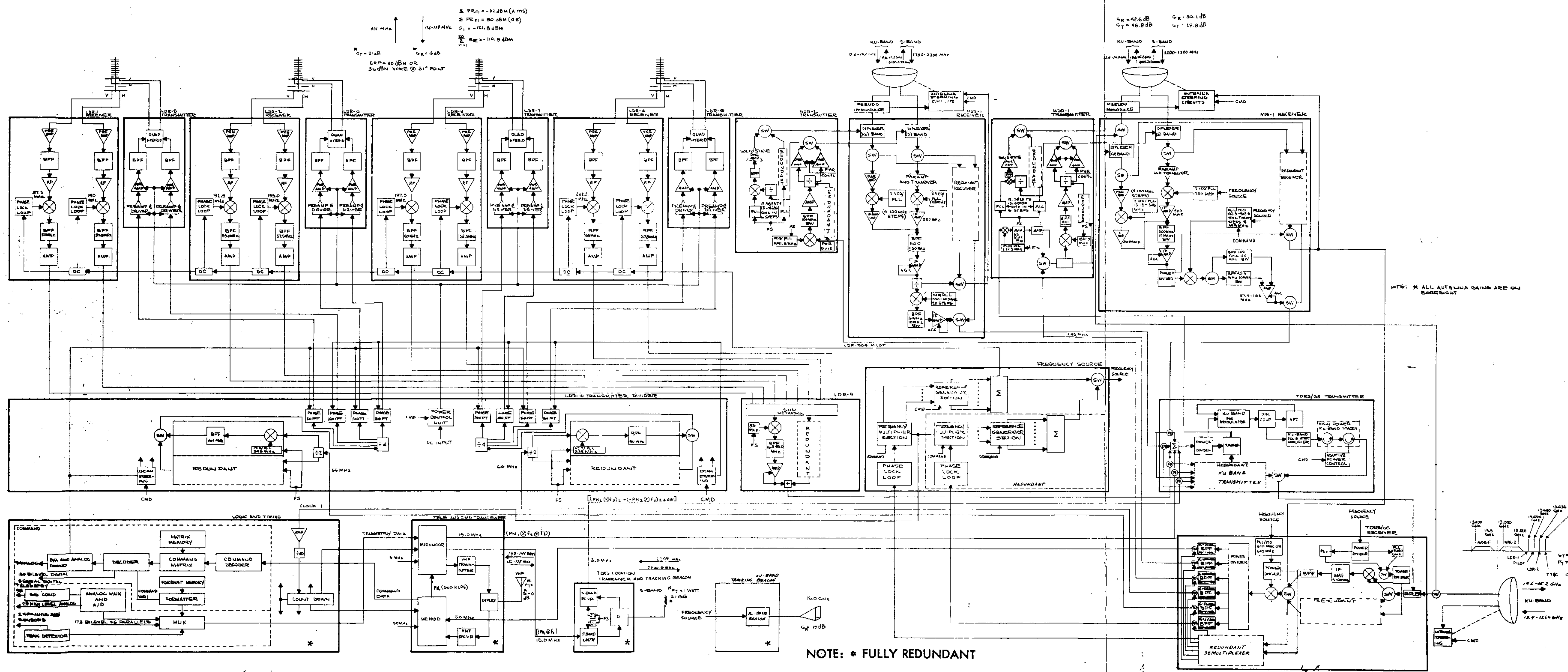

Figure 14-8 Telecommunications Subsystem Block Diagram

Table 14-11. Telecommunication Transponder Characteristics

Parameter	LDR Transponder	MDR #1 & #2 Transponder	TDRS/GS Transponder
Antenna	• Dual Freq. (VHF/UHF) Quad-Array • Gain: 15 dBi (VHF) 21 dBi (UHF)	• Dual Freq. 2 meter dish - Cassegrain for Ku-band - Prime Focus for S-band • Gain: $\approx$30.2 dBi (S) $\approx$48.3 dBi (Ku)	• Ku-band 0.9 meter dish • Gain: $\approx$40 dBi
Receiver • Frequency • Type • Bandwidth	• 136 - 148 MHz • Linear • 2 MHz/channel x 8 channels	• 2.2-2.3 or 13.6-14.00 GHz • Linear • 20-10 MHz tuneable in 5 MHz steps or 100 MHz wide band at S-band; and 4-100 MHz at Ku-band • S-band paramp (T_e = 50 K) + transistor (T_e = 360 K) Ku-band paramp (T_e = 100 K)	• 2.2-2.3 or 13.4-13.6 GHz • Linear • 240 MHz • Mixer (NF = 6 dB)
Transmitter • Frequency • Bandwidth • Transmitter RF Power	• 400.5-401.5 MHz • 1 MHz • 5 or 20 watts/channel x 8 channel (4 channels per each forward link	• 2.025-2.12 or 14.6-14.8 and 15.0-15.2 GHz • 95 MHz at S and 4 selectable 100 MHz at Ku • S-band: 14 or 56 watts Ku-band: 0.56 watts	• 2.025-2.11 or 14.6-15.2 GHz • 200 or 600 MHz • 2.75 or 0.275 watts

Table 14-12. Telecommunications Subsystem Size, Weight, and Power Summary

Subsystem	Size		Weight		Power	
	in.	cm	lb	kg	Peak	Average
LDR						
Receiver (4)	8x7x.5	20.2x17.8x1.27	7.6	3.5		7.93
I.F. Summing Network	4x7x0.5	10.2x17.8x1.27	1.3	0.6		1.14
Transmitter (4)	10x2.62x1.12	25.4x6.7x2.84	4.5	2.0	137.6	34.40
Trans. Divider Network	10x7.5x2.25	25.4x19.0x5.7	5.1	2.31		11.40
Antenna, incl stem unit and support link			31.6	14.35		
MDR NO. 1						
Receiver	12x8x4	30.5x20.4x10.2	8.8	4.0	6.2	6.2
Transmitter	6x4.50x10	15.3x11.4x25.4	13.0	5.9		
S-band					190.0[1]	47.5
Ku-band						14.5
Antenna, incl. support strut			33.96	15.4	24.0	7.0
MDR NO. 2						
Receiver	12x8x4	30.5x20.4x10.2	8.8	4.0		6.2
Transmitter	6x3.75x10	15.3x9.5x25.4	11.0	5.0		
S-band					180.4[1]	45.1
Ku-band						13.2
Antenna, incl. support strut			33.96	15.4	24.0	7.0
TDRS/GS						
Receiver	9x5x4	22.9x12.7x10.2	4.7	2.14		5.25
Transmitter	7x6.5x4	17.8x16.5x10.2	6.0	2.73	49.0[2]	11.0
Antenna			14.85	6.75	9.5	
FREQUENCY SOURCE	10x10x2	25.4x25.4x5.1	5.6	2.5		4.8
TT&C						
Processor	6.2x4.5x5.4	15.7x11.4x13.7	9.6	4.4	10.0	10.0
Transceiver	5.5x5.5x2.63	14x14x6.7	4.0	1.8	4.5[3]	0.5
Antenna			3.0	1.36		
TDRS TRACK'G/ORDER WIRE						
Transponder	8x4x0.5	20.3x10.2x1.3	5.4	2.5		7.9
Antenna			0.3	0.1		
Ku-BAND BEACON						
Beacon	4x3x3	10.2x7.62x7.62	3.6	1.6		8.3
Antenna			0.3	0.1		
DC CABLING			13.3	6.04		
RF CABLING	75 feet	(22.9 meters)	4.9	2.2		
WAVEGUIDE			5.0	2.3		
Totals			240.17	109.4		
Two MDR's in S-band						256.0
One MDR in Ku-band, one in S-band						224.1
Two MDR's in Ku-band						191.1

NOTES
1 For voice operation
2 During rain at ground station, add 10 dB to transmitter power
3 Transmitter (4 watts) not used "on station"

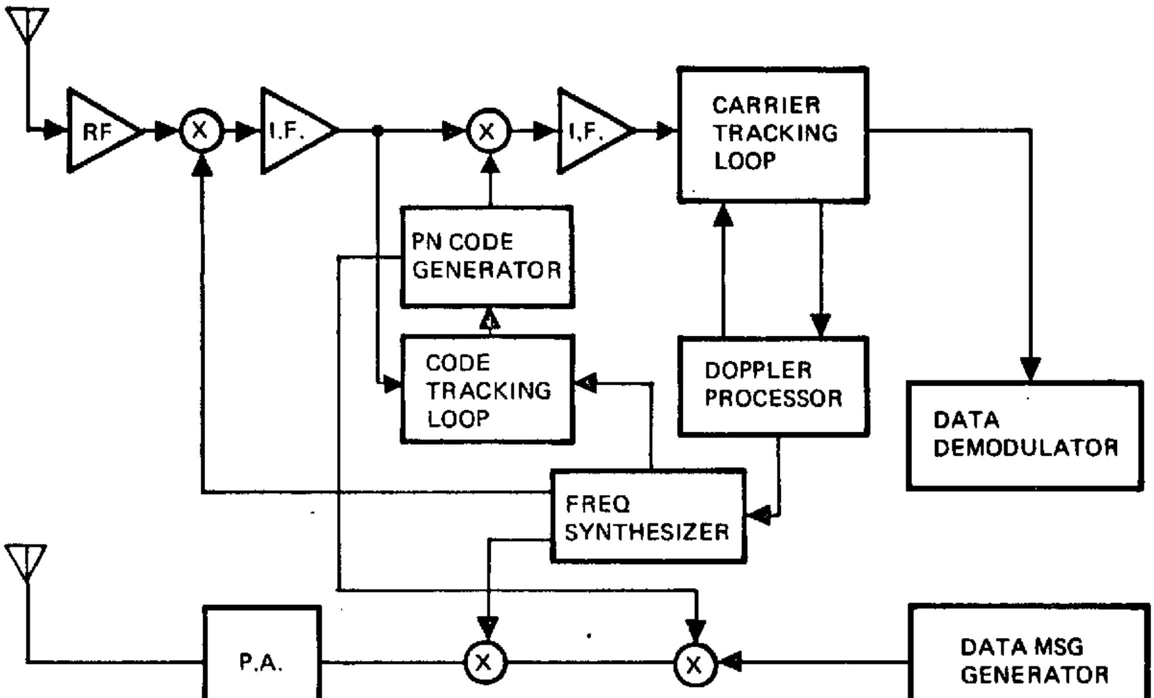

Figure 14-9. LDR Transponder

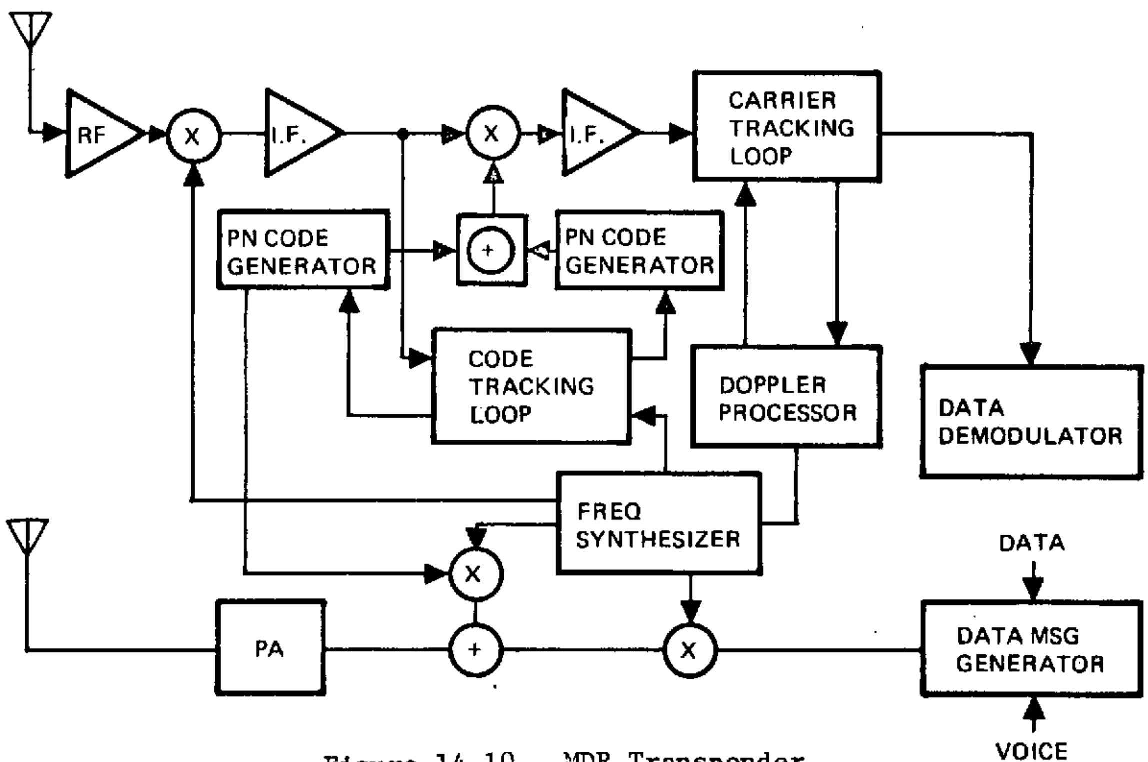

Figure 14-10. MDR Transponder

Return Link

• Data Rate	100 bps to 10,000 bps
• Carrier Frequency	136 MHz (1 channel)
• PN Modulation	1 mchip/sec
• Code Length	Short - 2047 chips (gold sequence) Long - Sixty-six 2047 (gold sequences in serial)
• Unique Code Sequence For Each User (TDRS Access is CDMA)	

- The 167 Kchip/sec PN chip rate in the forward link is necessary to distribute the signal energy to conform to IRAC requirements.
- A short PN code is used during the code acquisition phase to limit the maximum acquisition time to 40 sec.
- A long code is switched in after code acquisition to provide unambiguous ranging over a two-way range uncertainty of 40,000 Km.
- A 1 Mchip/sec PN chip rate in the return link is necessary to provide multiple access of 20 users per TDRS with sufficient process gain to meet the required level of performance.
- The return link code configuration is designed to maintain code synchronization with operating at different data rates.

14.4.2.2 MDR Transponder on User S/C

The MDR terminal receiver is a single channel S-band receiver. The carrier in the forward link is modulated by a single 5 Mchip/sec PN sequence during the code acquisition phase to distribute the signal energy radiated from the TDRS to conform to IRAC requirements. During the ranging phase a second PN sequence of 500 Kchip/sec rate is module-2 added to the first. A 500-Kchip/sec PN code generator synchronized to the uplink 500-Kchip/sec code is used to modulate the downlink carrier.

In both manned and unmanned users the data is delta PSK with convolutional encoding for error control. In the manned user case, the data and delta modulated voice can be time division multiplexed to quadraphase multiplexed to form a serial data stream. A simplified schematic diagram of the MDR transponder is shown in Figure 14-10.

A preliminary estimate of the size and prime power requirements for the user MDR transmitter and receiver are: transmitter - power, 33 watts; size, 240 in^3 (4000cc) and receiver - power, 12 watts, size 205 in^3 (3400cc).

The following is a summary of the characteristics of the MDRU terminal.

MDR User Terminal Characteristics

Forward link

. Data rate(1)	100 bps to 1000 bps
. Carrier frequency(1)	2025 to 2120 MHz (2 channels)
. PN modulation	5M chips/sec
. Code length	Short: 16,383 chips (gold sequence) Long: Forty 16,383 gold sequences in serial
. PN code sequence common to both users	
. Ranging code	Rate: 500 Kchips/sec; length: 65,535 chips

Return link

. Data rate(1)	10 kbps to 1000 kbps
. Carrier frequency(1)	2200 to 2300 MHz
. PN modulation is transponded 500 Kchip/sec PN modulation	
. Unique frequency channel for each of 2 users	

(1) Ku-band service operates at a carrier frequency of 14.6 to 15.2 and 13.6 to 14.0 GHz for the forward and return link, respectively; the forward link PN chip rate is on the order of 50 Mcps and the return link data rate is in excess of 1 Mbps.

- A 5 Mchip/sec PN chip rate in the forward link is required to distribute the signal energy to conform to the IRAC requirements.
- A short code is used during the code acquisition phase to limit the maximum acquisition time to 33 sec.
- A long code is switched in after code acquisition to provide unambiguous ranging over a two-way range uncertainty of 40,000 Km.
- The ranging code is used to limit the code for ranging purposes while still providing enough resolution to derive the required accuracy.
- A 65,535 code length is necessary to provide ambiguous ranging.
- The PN modulation in the return link is the 500 Kchip/sec PN code which can be transponded in the user for ranging purposes only.

14.4.3 Ground Station Terminal Characteristics

A functional block diagram of the TDRS Ground Station is shown in Figure 14-11. The components of the ground station telecommunication equipments are: RF front end, AGIPA processor, demodulator/tracking unit, and modulator. Its major characteristics are summarized in Table 14-13.

Table 4-13. Ground Station Telecommunications Characteristics

RF Front End	
• Antenna (2)	• 60 Feet (18.3m) parabolic dish, 75% efficient with >70 dB front-to-back ratio
• Receiver (2)	• 600 MHz front end with paramp (T_e = 100 K)
	• Demux - 40 LDR user; 4 MDR users, 2 Tracking and Telemetry, and 2 order wire
• Transmitter (2)	• Mux - 2 LDR, 2 MDR, TDRS Command, pilot
	• Transmit Power = 60 watts/TDRS
AGIPA Processor	• 1 processor/LDR user including a mini-computer for each processor
	• Uses PN Code to separate desired from interference signal
	• Uses adaptive spatial and polarization information to filter interference signals
Demodulator/Tracking Unit	• Extract NRZ-L bit stream from PN—ΔPSK input
	• Search and synchronize to desired PN code
	• Extract desired telemetry data
	• Extract range data
Modulator	• Convert NRZ-L data stream to Δ coded PCM, PN coded
	• Bi-phase modulate onto appropriate sub-carrier
	• Provide start pulse for the receiver tracking circuit

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