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EVALUATION OF S-BAND FM DIRECT LINK SIGNAL AND SYSTEM DESIGN

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FINAL REPORT

PREPARED FOR

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1.0 INTRODUCTION

The Shuttle Orbiter will have several communications links, depending on the particular type of mission involved and depending on the mission phase. The primary support network for NASA missions will be the Space Tracking and Data Network (STDN), which will include the Tracking and Data Relay Satellite System (TDRSS) and a few (ultimately 3 to 5) ground stations (G-STDN). The primary support network for DoD missions will probably also be the NASA STDN, although there is a definite requirement for direct communications with the USAF Satellite Control Facility (SCF). The Shuttle communications links and services may be categorized as shown below:

A. S-Band Direct Links (G-STDN or SCF)
  - PM Uplink (voice, commands and ranging)
  - PM Downlink (voice, telemetry, and ranging)
  - FM Downlink (television, recorder playback, main engine data, and payload data)

B. S-Band Relay Links (TDRSS)
  - PM Uplink (voice and commands)
  - PM Downlink (voice and telemetry)

C. S-Band Payload Links
  - Orbiter-to-Payload (commands)
  - Payload-to-Orbiter (telemetry)

D. Ku-Band Relay Links (TDRSS)
  - Uplink (voice, commands, and text/graphics)
  - Downlink (voice, telemetry, television, payload data, and recorder playback)

E. UHF Direct Links
  - ATC voice
  - EVA voice/telemetry.

The purpose of this report is to assess the adequacy of the S-Band FM Downlink to satisfy all known requirements during all mission phases. Some potential performance problems are described in subsequent sections of the report and corrective actions are recommended when appropriate.

2.0 DESCRIPTION OF CURRENT (BASELINE) S-BAND FM LINK DESIGN

2.1 Functional Requirements - NASA Missions

A general requirement for Shuttle RF communications is that services be required as specified during the following mission phases:

- Prelaunch
- Liftoff (SSO/ET/SRB mated ascent)
- Ascent (SSO/ET)
- On-Orbit Operations
- Reentry
- Landing
- Post-Landing

The specific functional requirements which have been imposed on the S-Band FM direct downlink for NASA missions (whenever direct Orbiter-to-G-STDN line-of-sight exists) are for transmission of one (at a time) of the following:

- Three independent 60 kbps digital real-time main engine data channels
- Real-time television composite video
- Real-time attached payload data (analog up to 4 MHz or digital up to 5 Mbps)
- Playback digital data from the Operational Instrumentation (OI) recorder, consisting of one at a time of the following:
  (1) Playback of any one recorded 60 kbps main engine data channel at any one of four playback data bit rates from 60 kbps (1:1 playback) to 960 kbps (16:1 playback) as

60 kbps (1:1 playback) to 960 kbps (16:1 playback) as established prior to each mission.*

(2) Playback of recorded 128-kbps PCM telemetry data at any one of three playback data bit rates from 128 kbps (1:1 playback) to 1024 kbps (8:1 playback) as established prior to each mission.*

(3) Playback of recorded 192-kbps time-division-multiplexed (TDM) data (128-kbps PCM telemetry plus two 32-kbps digital voice channels) at any one of two playback data bit rates—192 kbps (1:1 playback) and 960 kbps (5:1 playback)—as established prior to each mission.*

- Playback digital data from the Mission Specialist Station (MSS) recorder at a playback data bit rate up to 1024 kbps.

Figure 1 shows the functional interface configuration for this link. In the Orbiter FM signal processor, the three real-time main engine data channels (at 60 kbps each) phase-shift-key (PSK) three subcarriers at 576 kHz, 768 kHz, and 1024 kHz, respectively, which are then frequency-division-multiplexed into a single analog main engine data signal. The FM signal processor accepts one of its input analog or digital data signals or the FDM main engine data signal to frequency modulate (FM) the link carrier (2250.0 MHz). At the ground station, the carrier modulating signal is recovered by an FM wideband receiver and demodulator. The ground station signal processor routes the postdetection signal as required.

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*Each of the three 60-kbps main engine data channels is recorded by one of the two Orbiter recorders, and either the 128-kbps PCM telemetry data or the 192-kbps TDM data (one at a time) is recorded by either of the two Orbiter recorders. The playback data bit rate is the real-time data bit rate multiplied by the ratio of the playback to the recording tape speed. Each recorder has four selectable tape speeds during a mission which are pre-mission wired from 14 possible tape speeds. The possible tape speeds for recording 60-kbps main engine data are 15, 19, 24, and 30 inches/second, and for recording 192-kbps TDM data are 24, 30, or 38 inches/second. The other possible tape speeds are 6, 48, 60, 76, 96, and 120 inches/second.

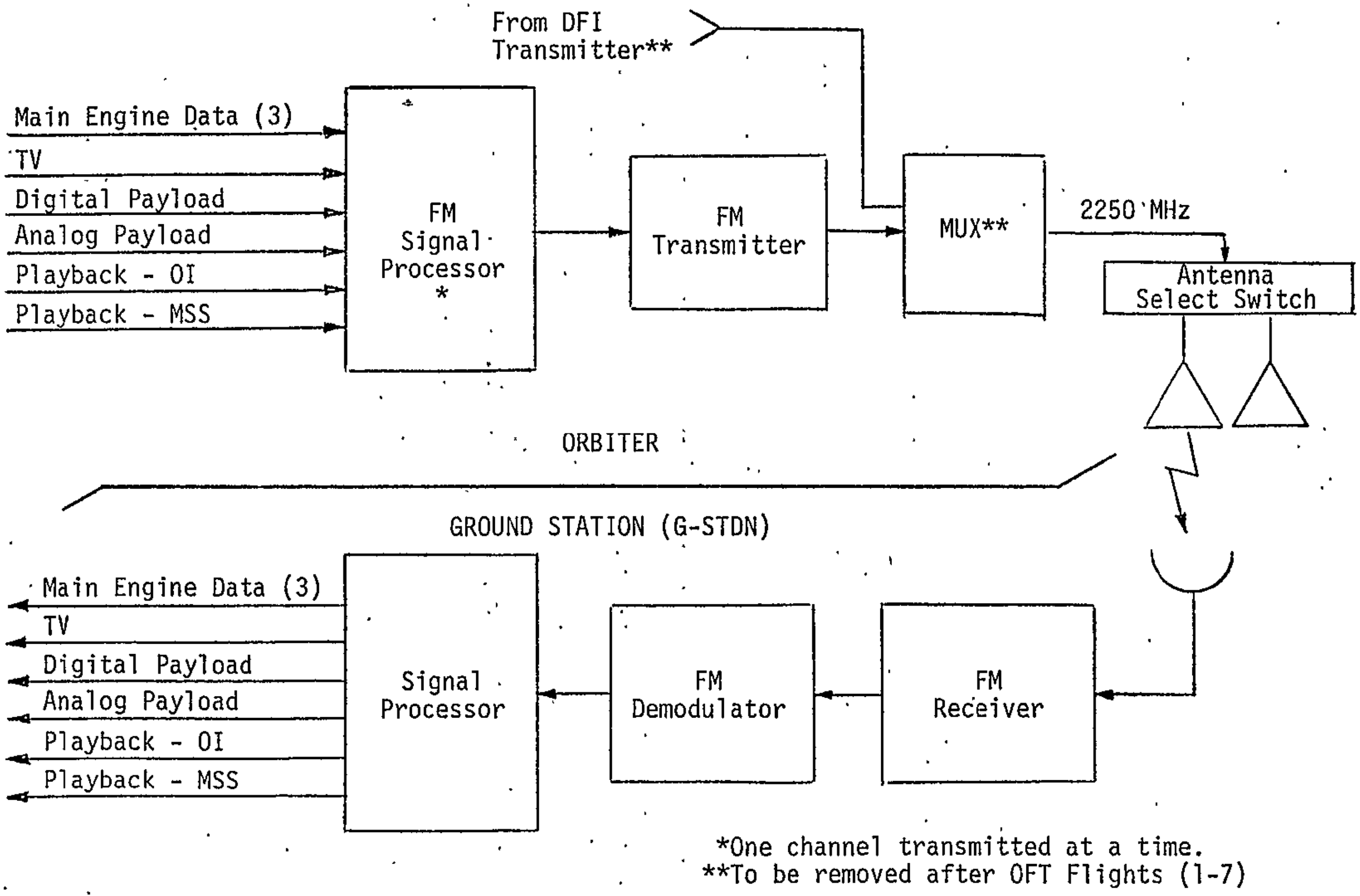


Figure 1. S-Band FM Direct Downlink Functional Configuration (Orbiter-to-G-STDN)

2.2 Functional Requirements - DoD Missions

For DoD missions, the S-Band FM downlink functional requirements are generally the same as for NASA missions, with the exception of a lack of requirement for television and that the maximum playback data bit rate of recorded data is 960 kbps. At this stage of the Shuttle program, however, plans for operation of DoD missions have not been firmly established, and it is very possible that requirements for other services (such as the main engine data channels) may disappear.

2.3 Performance Requirements

The maximum received information bit error probability at the STDN ground stations for any of the digital data channels described previously will be 10^{-4} for NASA missions and 10^{-5} for DoD missions in which data encryption is employed. The minimum received peak-to-peak television composite video signal to RMS noise ratio at the STDN ground stations will be 35 dB in a 3.0 MHz postdetection filter noise bandwidth. When the television composite video signal is replaced by a sinewave signal of the same peak-to-peak voltage and a frequency between 30 Hz and 3.0 MHz, the RMS sinewave signal to RMS noise ratio at the STDN ground stations will be 26 dB in a 3.0 MHz postdetection filter noise bandwidth.

2.4 Signal Characteristics

The characteristics of each of the required signals to be transmitted are detailed in this section.

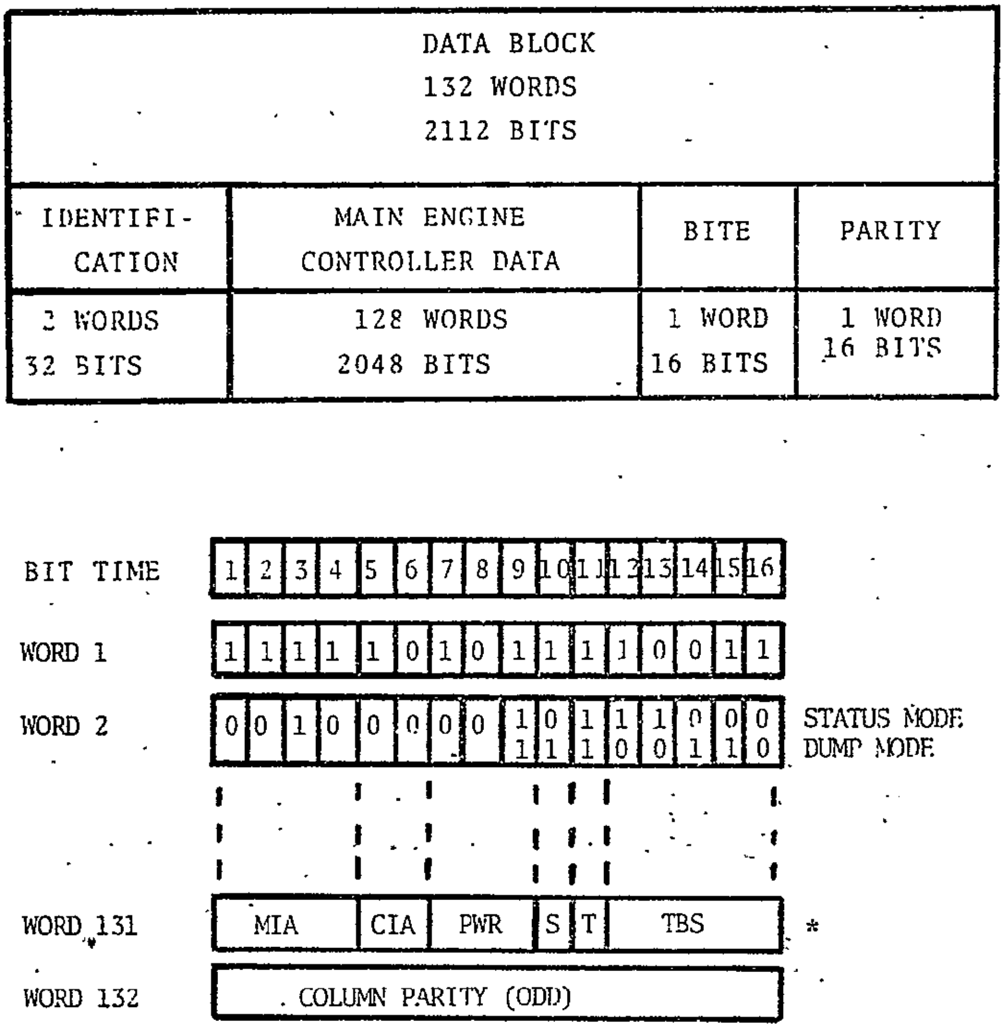
- Main Engine Data. Each of the three 60 kbps main engine (ME) data channels consists of successive Data Blocks separated by fill bits. A Data Block contains 132 16-bit words, the time between Data Blocks contains 288 "0" bits, and the data rate is 25 Data Blocks/second. Figure 2 indicates the frame structure of a main engine Data Block.

- Television. Figure 3 shows the television composite video waveform. The peak-to-peak composite video signal is the voltage difference between the synchronization pulse and the reference white levels as indicated by $(\alpha + \beta)$. Table 1 lists pertinent parameters. Color is provided by sequential fields of red, green, and blue picture video. The composite video signal is DC coupled to the FM transmitter modulator.
- Real-Time Attached Payload Data. Analog data up to 4 MHz or digital data up to 5 Mbps with formats are yet to be defined.
- Playback Data - OI. Playback main engine data, telemetry data, or TDM data will be structured the same as in real-time as shown by Figures 2, 4, and 5, respectively. Playback data rates are as described in Section 2.1.
- Playback Data - MSS. Any bit rate up to 1024 kbps. The frame structures are yet to be defined.

2.5 Orbiter Signal Design Parameters (Modulation Characteristics)

In FM, the instantaneous RF carrier frequency deviation from the nominal center frequency is proportional to the instantaneous modulating signal voltage. All FM (except TV) is symmetric about the nominal center frequency and is specified by the peak frequency deviation. At the G-STDN or SCF ground stations, a wideband FM demodulator will be used to recover the modulating signal.

- Main Engine Data. Each of the three main engine data subcarriers (576 kHz, 768 kHz, and 1024 kHz) frequency modulates the RF carrier at a peak frequency deviation of 635 ± 15 percent kHz.

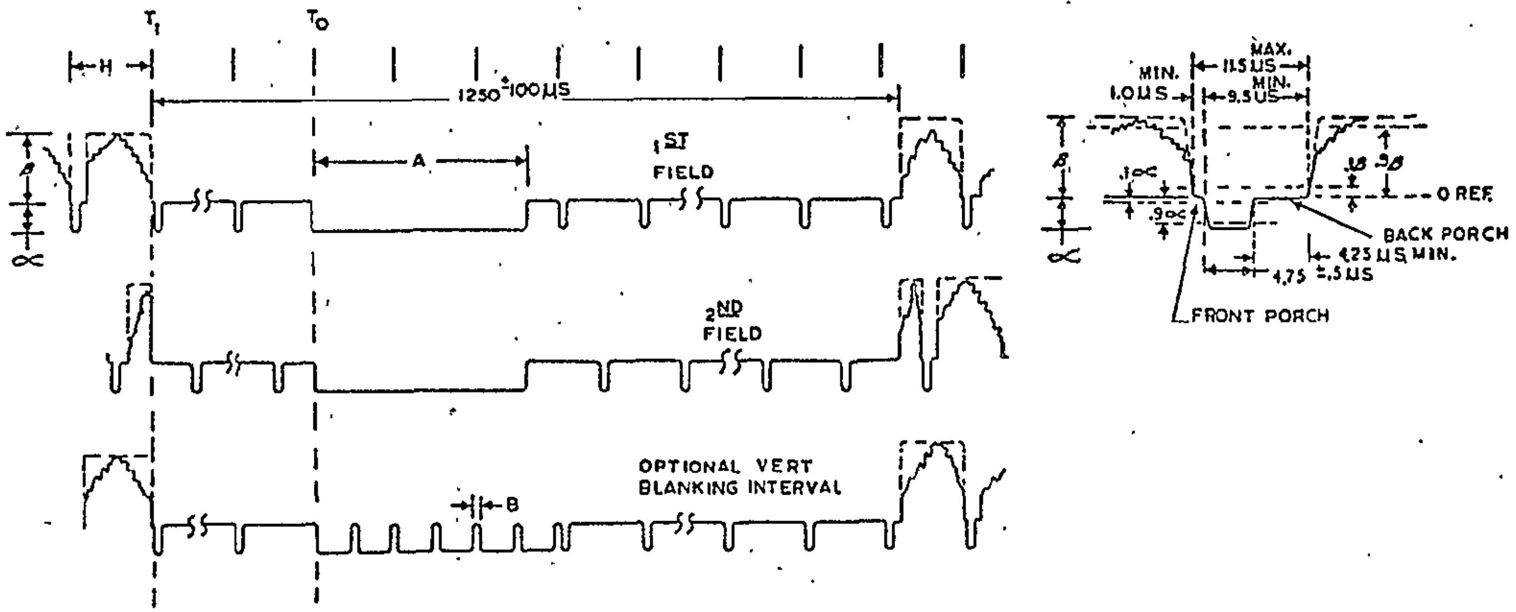


DATA BLOCK 132 WORDS 2112 BITS			
IDENTIFICATION	MAIN ENGINE CONTROLLER DATA	BITE	PARITY
2 WORDS 32 BITS	128 WORDS 2048 BITS	1 WORD 16 BITS	1 WORD 16 BITS

BIT TIME	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
WORD 1	1	1	1	1	1	0	1	0	1	1	1	1	0	0	1	1	
WORD 2	0	0	1	0	0	0	0	0	1	0	1	1	1	0	0	0	STATUS MODE
									1	1	1	0	0	1	1	0	DUMP MODE

*MIA - multiplex interface assembly flags
CIA - controller interface assembly flags
PWR - power flags
S - secondary flag
T - twice flag
TBS - spare bits

Figure 2. Main Engine Data Block Structure



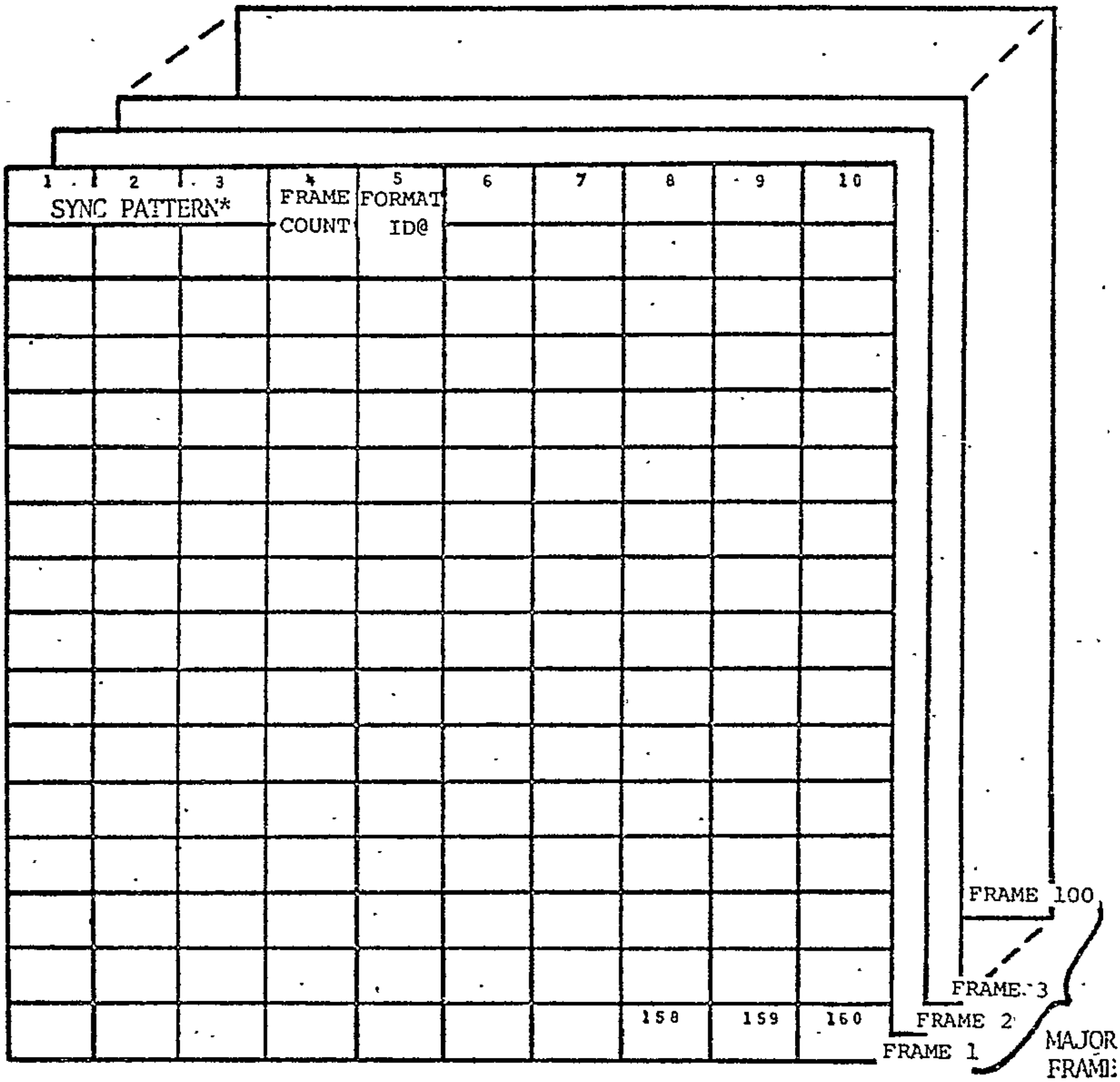
NOTES:

1. $\beta = 0.714 \pm 0.1$ volts (100 IRE Units).
2. $\alpha = 0.286$ (40 IRE Units) nominal.
3. Sync to total signal ratio $\left(\frac{\alpha}{\beta+\alpha}\right) = (28.6 \pm 5)\%$.
4. Blanking = 7.5 ±5 IRE Units (2.5% to 12.5% of β).
5. Horizontal Rise times measured from 10% to 90% amplitudes shall be less than 0.3 μsec.
6. Overshoot on horizontal blanking signal shall not exceed 0.02β at beginning of front porch and 0.05β at end of back porch.
7. Overshoot on sync signal shall not exceed 0.05β.
8. T_o = start of vertical sync pulse.
9. T_1 = start of vertical blanking.
10. $T_1 = T_o {}^{+0}_{-250}$ μsec
11. A – vertical sync pulse = 150 ±50 μsec measured between 90% amplitude points.
12. Rise and fall times of vertical blanking and vertical sync pulse, measured from 10% to 90% amplitudes, shall be less than 5 μsec.
13. Tilt on vertical sync pulse shall be less than 0.1α.
14. If horizontal information is provided during the vertical sync pulse it must be at 2H rate and as shown in the optional vertical blanking interval waveform.
15. B – vertical serration = 4.5 ±0.5 μsec measured between the 90% amplitude points. Rise times measured from 10% to 90% amplitudes shall be less than 0.3 μsec.
16. If equalizing pulses are used in the vertical blanking interval waveform they shall be 6 in number preceding the vertical sync pulse and be at 2H rate.

Figure 3. Television Composite Video Waveform

Table 1. Television Baseband Parameters

Frame Rate	Lines per Frame	Aspect Ratio	Color Field Sequence	Horizontal Scanning Frequency	Vertical Scanning Frequency	Video Bandwidth
29.97/sec	525 Interlaced	4/3	R-G-B	15,734.624 Hz	$\frac{\text{Horizontal Frequency}}{262.5}$	S-Band: 3.0 MHz Ku-Band: 4.5 MHz

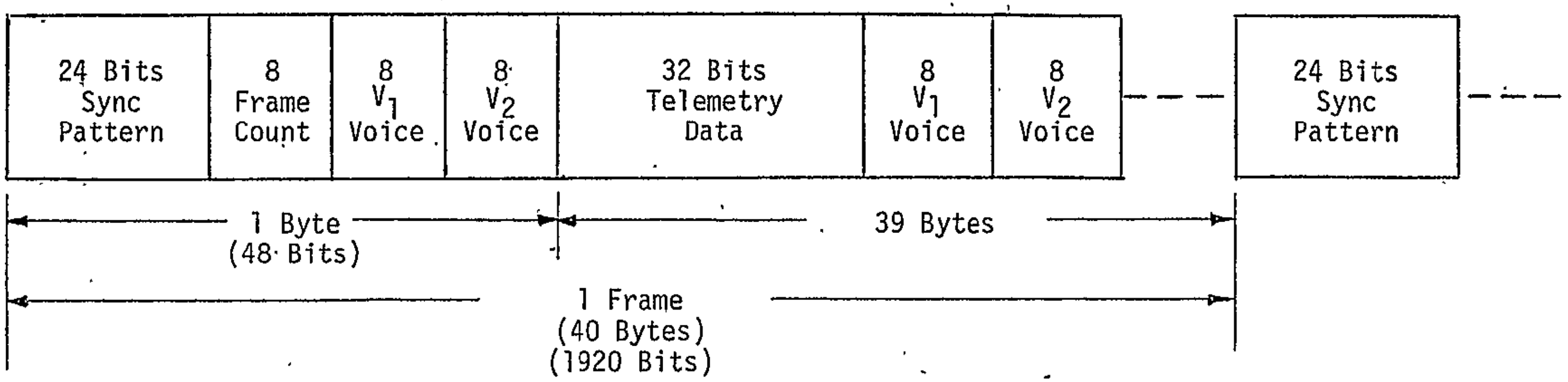


* SYNC PATTERN 76571440_8

@ FRAME 1 ONLY

128 KBPS
8 BITS/WORD
160 WORDS/MINOR FRAME
100 MINOR FRAMES/MAJOR FRAME
1 MAJOR FRAME/SECOND

Figure 4. Playback OI Telemetry Frame Format (High Data Rate Mode)



1920 Bits/Frame
100 Frames/Second
192 kbps

Sync Pattern: 76571440_8

Figure 5. Baseband TDM Frame Format for the Return and Direct Downlinks (High Data Rate Mode)

- Television. The TV composite video signal frequency modulates the RF carrier at a peak frequency deviation of 4.5 ± 15 percent MHz such that the instantaneous carrier frequency at each video synchronization pulse is 4.5 MHz less than the center frequency, regardless of the picture video between synchronization pulses, and is 4.5 MHz greater than the center frequency whenever the picture video reaches reference white.
- Real-Time Attached Payload Data. Real-time attached payload analog or digital data signals frequency modulate the RF carrier at a peak frequency deviation of 2 ± 15 percent MHz. For an analog modulating signal, the modulation sense is positive with respect to the payload source and the ground user sink, i.e., an increase in the payload output signal voltage causes an increase in the instantaneous RF carrier frequency and an increase in the receiver postdetection output signal voltage.
- Playback Data - OI or MSS. The playback digital data (main engine, attached payload, PCM telemetry, or TDM) at any playback data bit rate from 60 kbps to 1024 kbps frequency modulates the RF carrier at a peak frequency deviation of 635 ± 15 percent kHz.

2.6 Orbiter RF Parameters

The Orbiter FM transmitter power output is specified as 10 watts minimum at a carrier frequency of 2250.0 MHz ± 0.004%, but system losses are such that the power which is available at the antenna terminals is considerably less. Figure 6, which illustrates detailed cable runs and connectors, indicates a total transmit system loss of -10.6 dB for the OFT configuration (Flights 1-7, when the DFI multiplexer is used) and a total of -7.2 dB for the operational configuration (Flight 8 and all subsequent flights). The

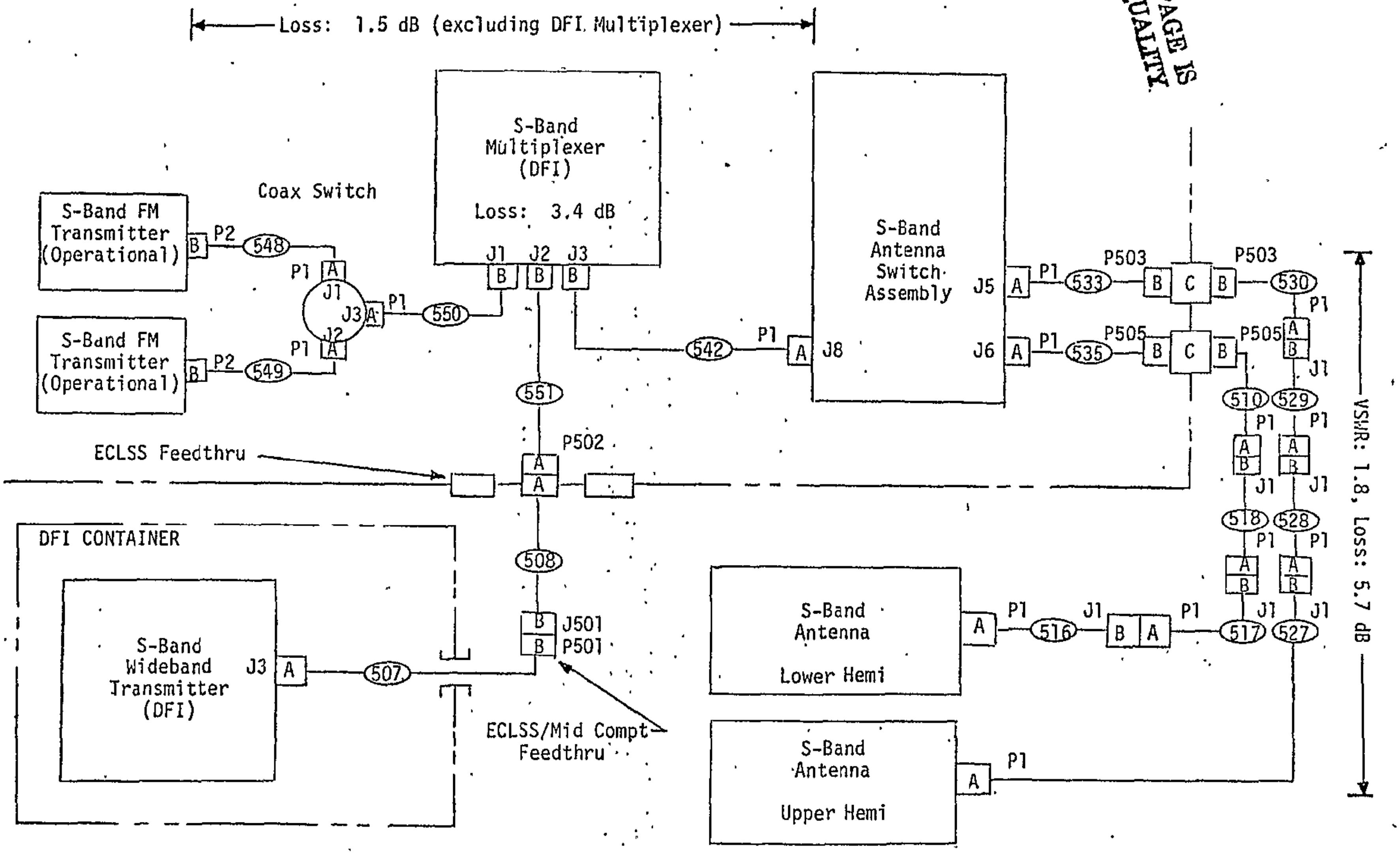


Figure 6. Interconnection Diagram - S-Band FM System Coaxial Cables and Antennas

OFT value is of primary significance, since the S-band FM link provides the only means of obtaining television for the early Shuttle flights (the Ku-band link is not scheduled to be available until Flight 4).

2.7 Orbiter Antenna Characteristics

Because the S-band FM direct link will be required during ascent and reentry (when it will not be possible to deploy steerable antennas) and because it will be desirable to achieve nearly spherical coverage about the Orbiter, a switched-element array of two right-circularly-polarized (RCP), flush-mounted, omnidirectional antenna elements (referred to as the hemi antennas) has been baselined for the Orbiter. Locations for these antennas are depicted in Figure 7. A set of desired gain contours for these elements is shown in Figure 8. It is desired that each hemi provide a gain of +1 dB over approximately a 145° cone, which would correspond to about 70% of total spherical coverage. Unfortunately, as the hemi antenna development progresses, it appears that the desired gain characteristics will not be provided, resulting in somewhat less coverage. Figure 8 also illustrates the expected gain contours for the hemi antennas. The upper hemi antenna provides a gain of 1.5 dB over an area 120° by 100°, while the lower hemi antenna provides a gain of 1 dB over a 140° cone. Thus, the hemi antennas provide a gain of at least 1 dB over approximately 54% of total spherical overage.

Additional considerations which limit available hemi antenna gain during ascent are the blockage and multipath effects due to the external tank and solid rocket boosters during the various phases of ascent. Figures 9 through 12 show the results of antenna pattern measurements made at the Lyndon B. Johnson Space Center using 1/10 scale models of the Orbiter, external tank, and solid rocket boosters, and using early models of the

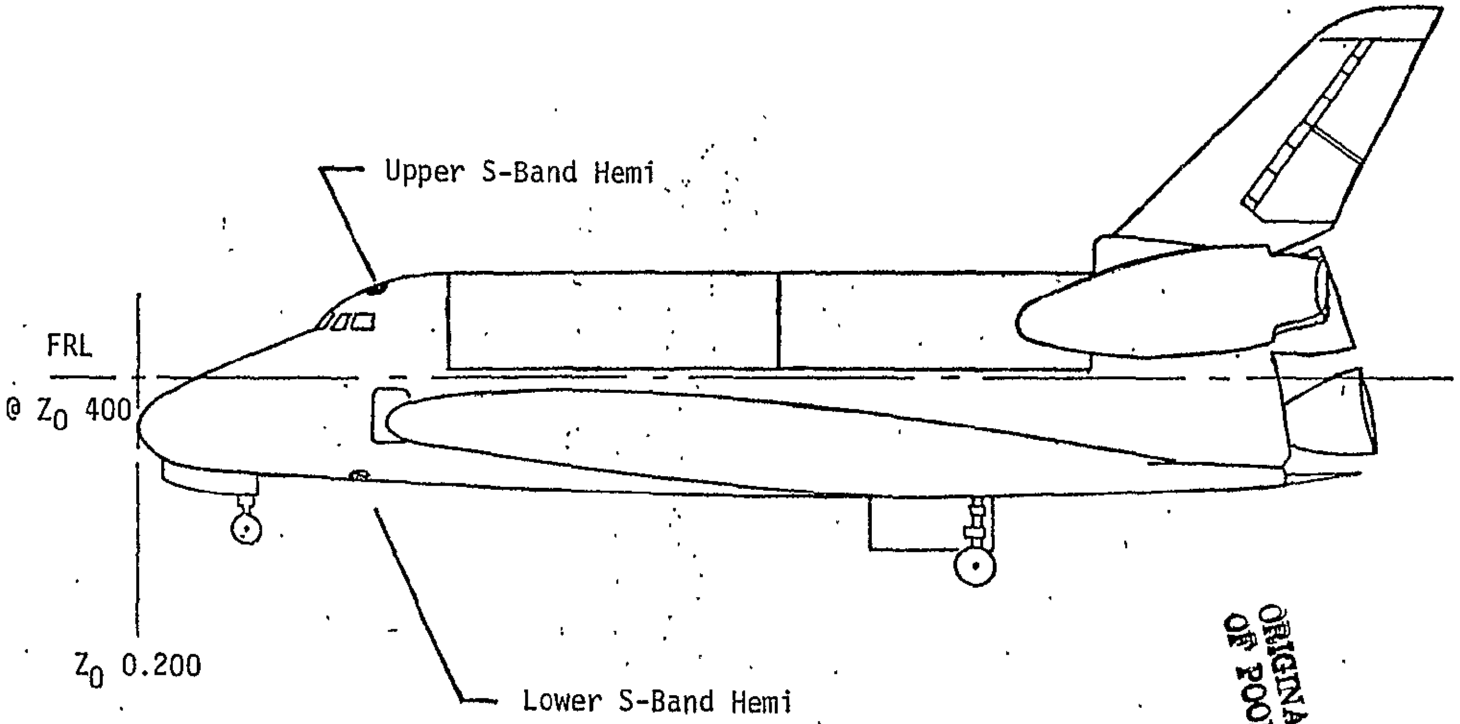


Figure 7. S-Band Flush-Mounted Antenna Locations

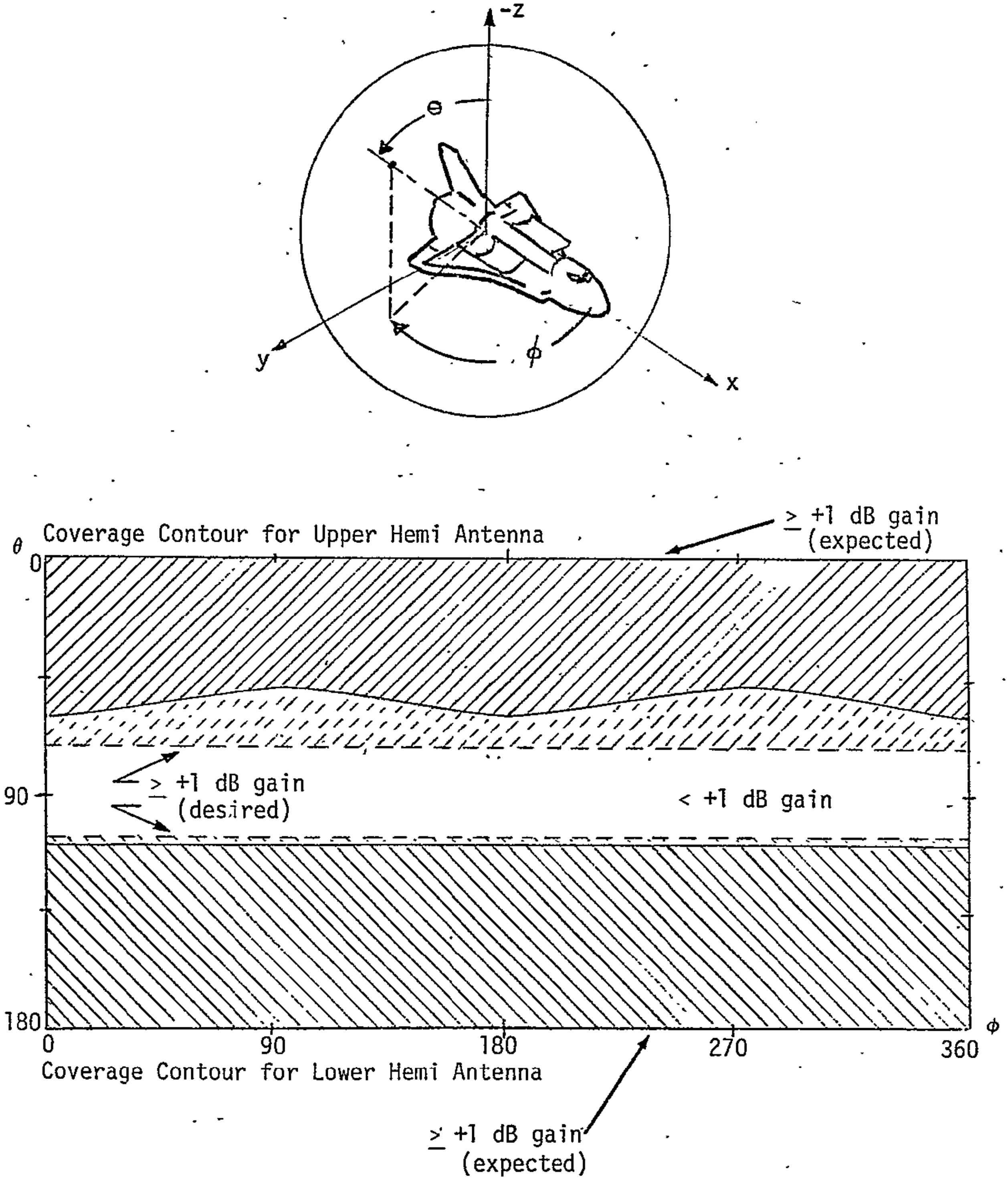
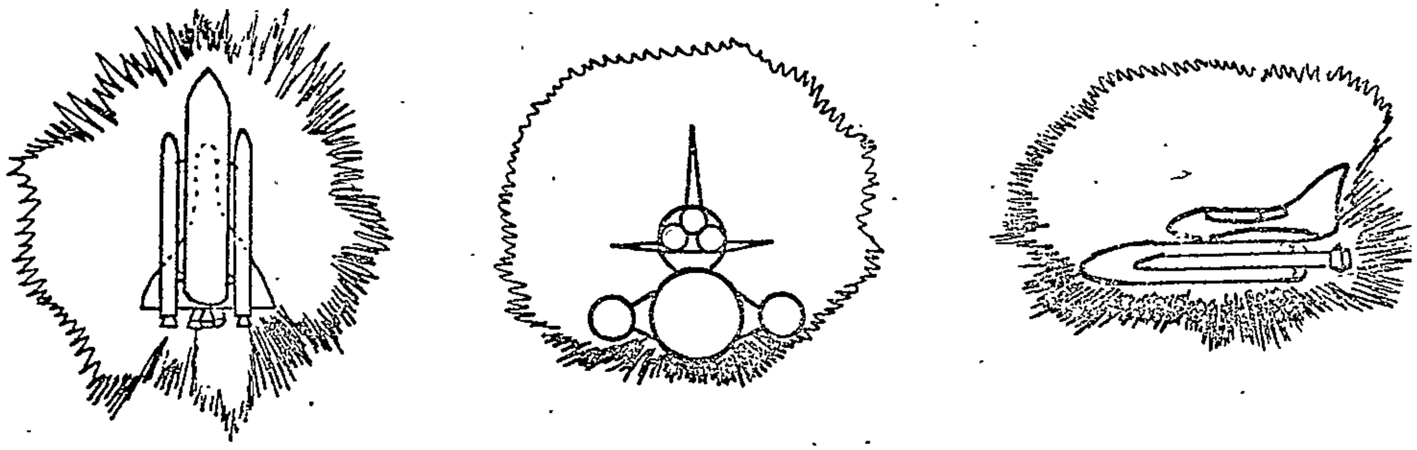
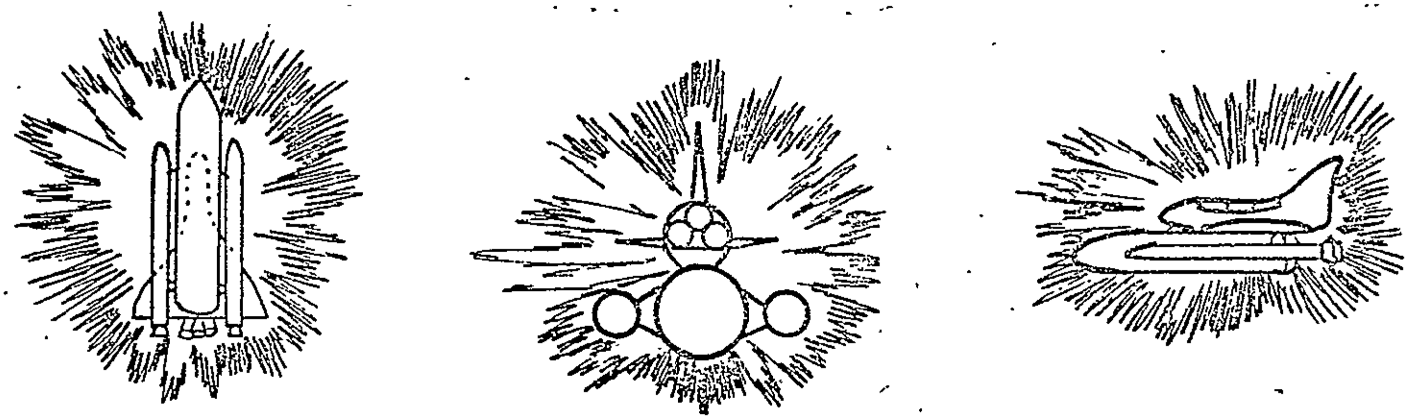


Figure 8. Expected and Desired Gain Contours for Hemi Antennas



X-Y Plane Cut Y-Z Plane Cut X-Z Plane Cut

(a) Upper Hemi Antenna



X-Y Plane Cut Y-Z Plane Cut X-Z Plane Cut

(b) Lower Hemi Antenna

Figure 9. Sketches Indicating General Nature of Pattern Measurements for Orbiter Hemi Antennas (Orbiter/ET/SRB Configuration)

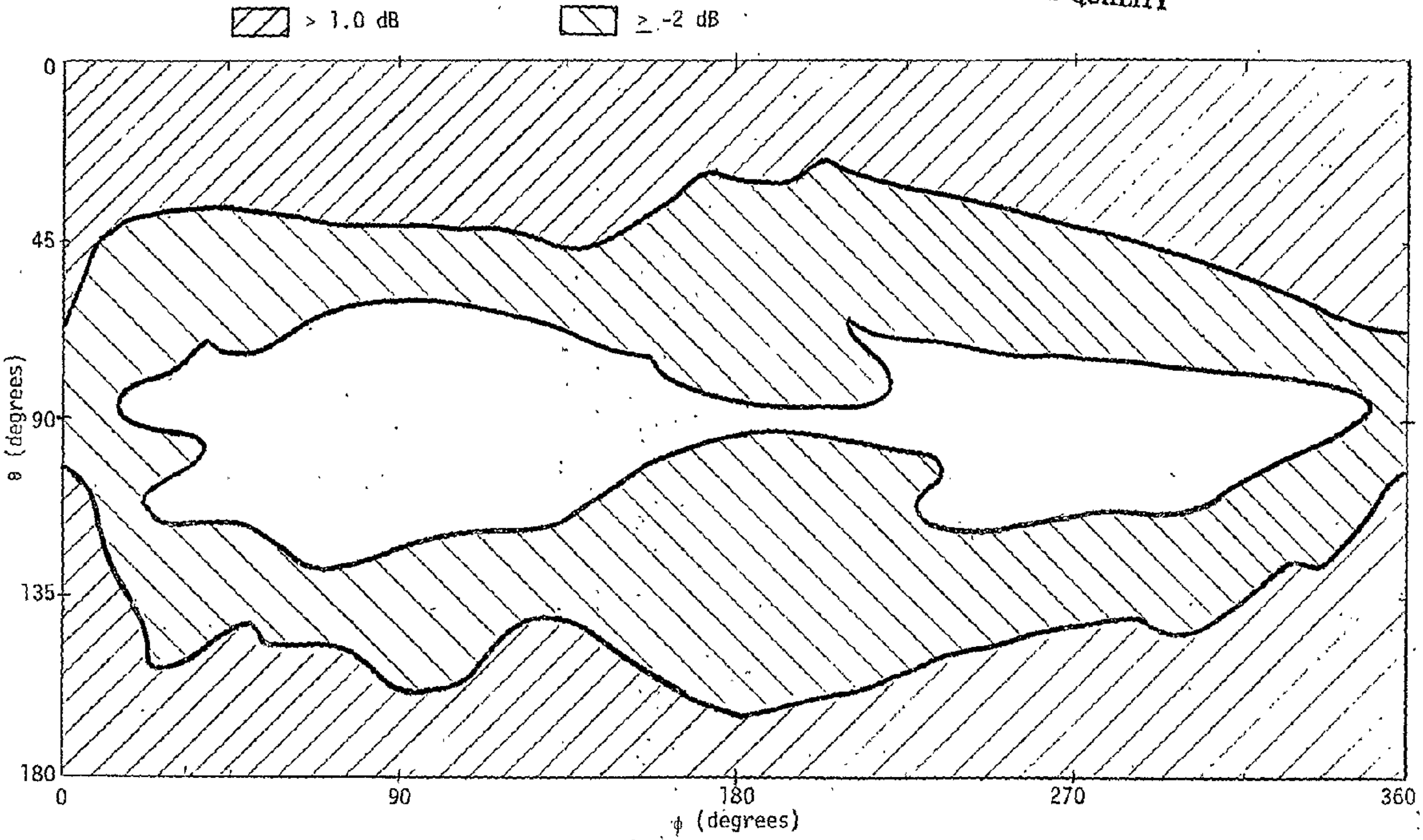


Figure 10. Composite Radiation Distribution Pattern for Shuttle S-Band Hemi Antennas (Orbiter Only)

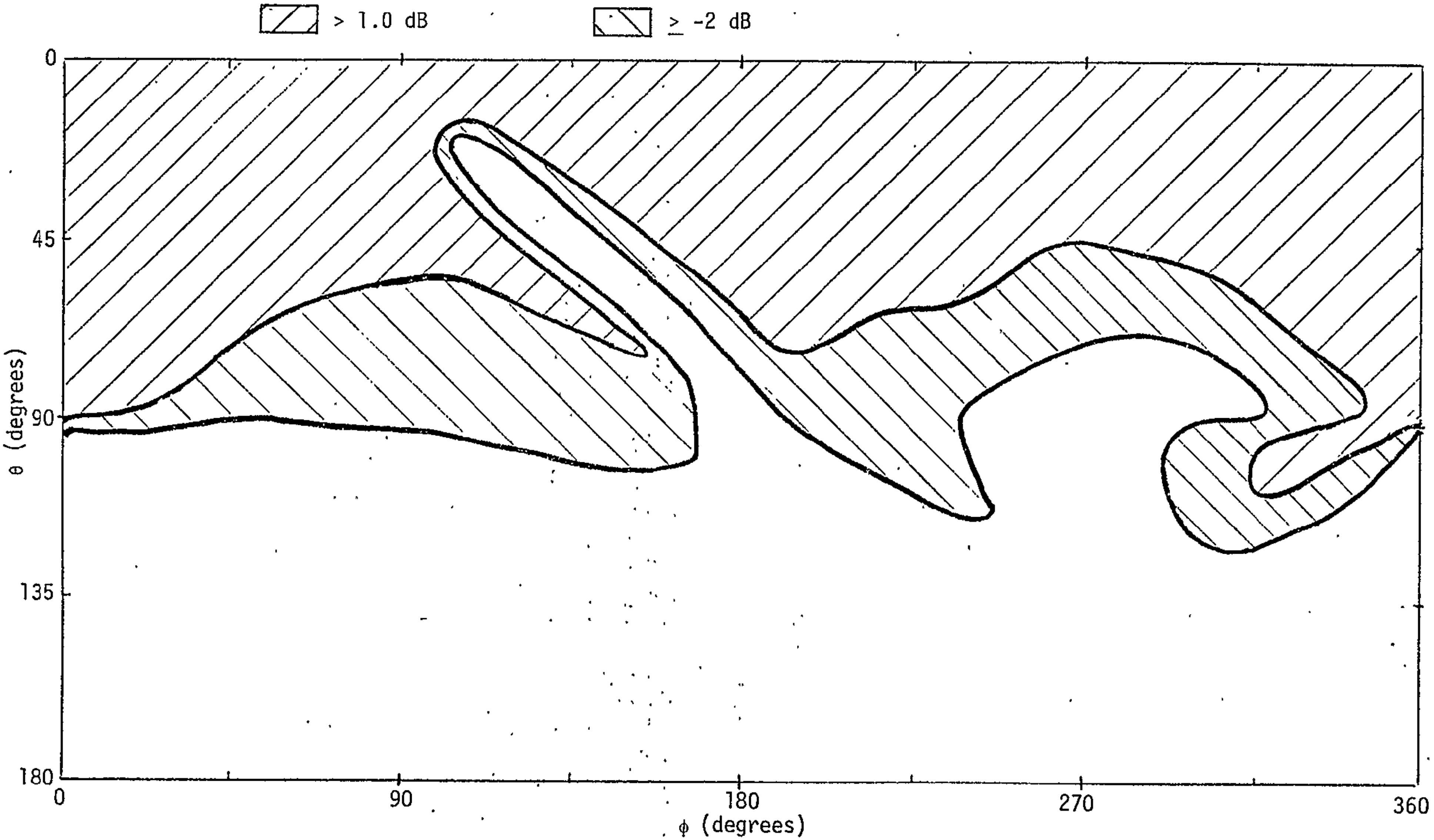


Figure 11. Composite Radiation Distribution Pattern for Shuttle S-Band Hemi Antennas (Orbiter/ET)

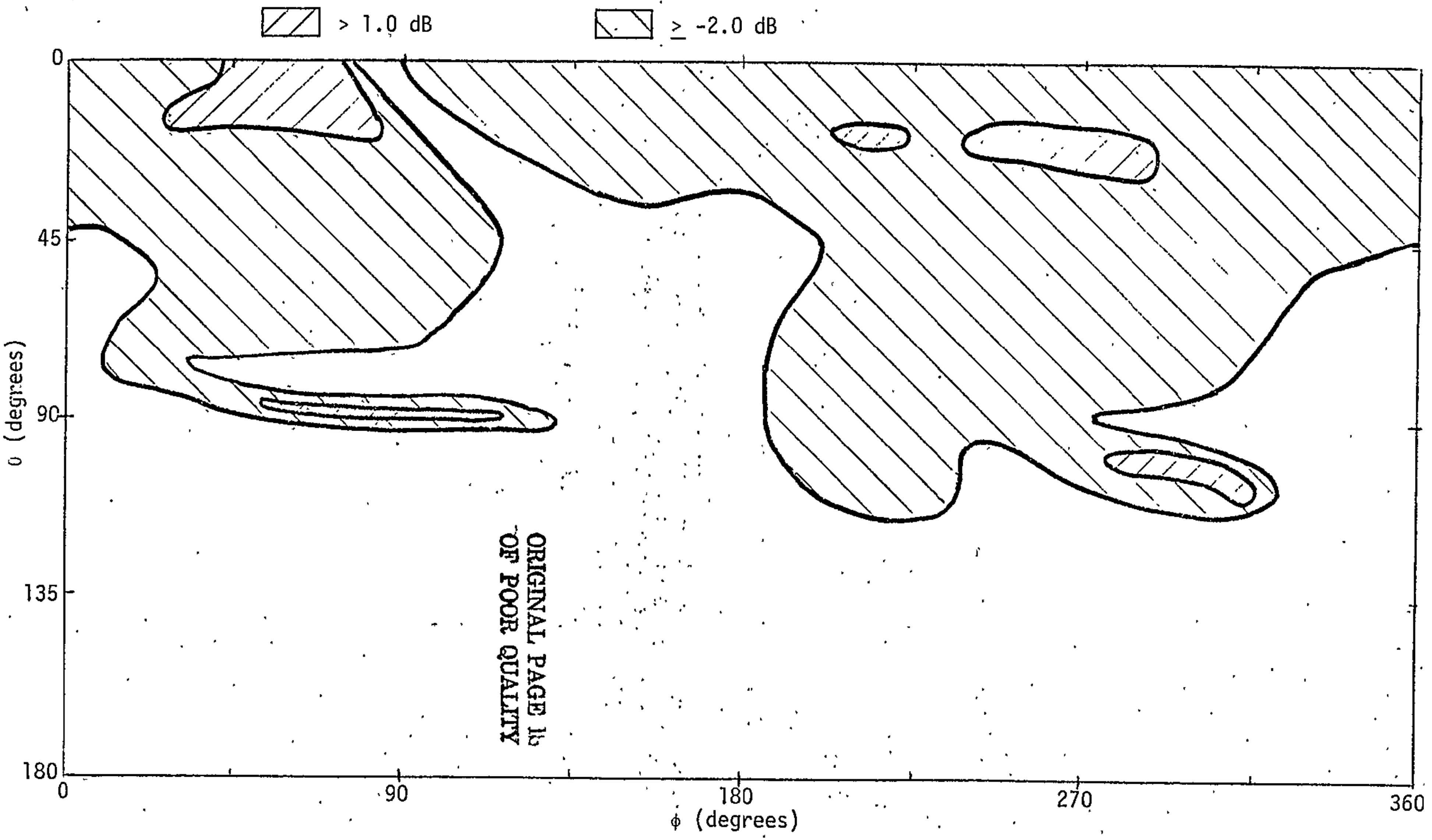


Figure 12. Composite Radiation Distribution Pattern for Shuttle S-Band Hemi Antennas (Orbiter/SRB/ET)

Orbiter hemi antennas. The results of these measurements indicate roughly that reflections and masking by the external tank and solid rocket boosters result in highly irregular patterns for the mated phases of ascent, even at aspect angles generally considered favorable. The patterns are particularly irregular along the tail of the Orbiter, with nulls as deep as about 30 dB. The absolute gain values along the Orbiter tail vary from about 0 dB to -30 dB. How severe these gain values and fluctuations are, of course, depends on the aspect angle to the ground station (and the corresponding antenna gain) versus the time from liftoff (and the corresponding slant range). If, at a particular time, the range is very short, then a very low antenna gain may be tolerable. The actual effects of the antenna patterns depicted in Figures 9 through 12, then, cannot be fully determined until signal strength calculations are performed versus time for various ascent trajectories. These calculations will be summarized in a subsequent section of this report.

2.8 Ground Station Characteristics

The NASA G-STDN presently consists of 12 stations, with antenna diameters of 30 feet (one is 85 feet). The number of G-STDN stations is planned to be reduced to 5 by OFT Flight 4 or 5, as the TDRSS becomes operational. Table 2 details the G-STDN S-band parameters which will be provided for the S-band FM downlink.

The USAF SCF consists of 9 stations at 6 different geographic locations, with antenna diameters of either 14 feet, 46 feet, or 60 feet. Table 3 details the applicable SCF S-band parameters.

Table 2. G-STDN S-Band Parameters

	30-Foot Antenna	85-Foot Antenna
Receive Frequency	2250 MHz	2250 MHz
Antenna Polarization	RCP	RCP
Receive Antenna Gain	43.5 dB	52.7 dB
Receive System Losses (Included in Antenna Gain)	---	---
System Noise Temperature	140°K	140°K
Predetection Bandwidth	3 MHz	3 MHz
FM Discriminator Degradation	-1.0 dB	-1.0 dB
FM Threshold	10 dB	10 dB
Bit Synchronization Degradation	-2.0 dB	-2.0 dB

Table 3. SCF S-Band Parameters

	14-Foot Antenna	46-Foot Antenna	60-Foot Antenna
Receive Frequency	2250 MHz	2250 MHz	2250 MHz
Antenna Polarization	RCP	RCP	RCP
Receive Antenna Gain	33.5 dB	47.5 dB	48.2 dB
Receive System Losses (Included in Antenna Gain)	---	---	---
System Noise Temperature	376°K	220°K	340°K
Predetection Bandwidth	5 MHz	5 MHz	5 MHz
FM Discriminator Degradation	-1.5 dB	-1.5 dB	-1.5 dB
FM Threshold	10 dB	10 dB	10 dB
Bit Synchronization Degradation	-2.0 dB	-2.0 dB	-2.0 dB

3.0 PERFORMANCE PREDICTIONS

3.1 Mathematical Models

The end-to-end performance for any communications link can be expressed in terms of a required SNR (signal-to-noise ratio in an appropriate bandwidth) at some point in the receiving system. For an analog channel, this may be the output SNR, or it may be the SNR at the demodulator input which is necessary to provide the required output SNR. For a digital channel, the SNR (in the bit rate bandwidth) at the bit detector input that is required for a given bit error probability at the detector output is frequently used. For either class of channel, a performance margin (or circuit margin) is the amount, in decibles (dB), by which the actual (or predicted) SNR exceeds the required SNR at whatever reference point is chosen. Thus,

$$\text{Circuit Margin} = \text{SNR}\Big|_{\substack{\text{actual (or}\\ \text{predicted)}}} - \text{SNR}\Big|_{\text{required}} \quad \text{(dB)} .$$

The required SNR can usually be referred to a predetection point in the receiving system where the noise has a constant power spectral density in a known bandwidth or where the noise is a known system constant. Thus, the performance margin may be expressed in terms of the received signal-to-noise spectral density ratio P_{rec}/N_0,

$$\text{Circuit Margin} = \frac{P_{rec}}{N_0}\Bigg|_{\substack{\text{actual (or}\\ \text{predicted)}}} - \frac{P_{rec}}{N_0}\Bigg|_{\text{required}} \quad \text{(dB)} ,$$

or simply in terms of the received signal power,

$$\text{Circuit Margin} = P_{rec}\Big|_{\substack{\text{actual (or}\\ \text{predicted)}}} - P_{rec}\Big|_{\text{required}} \quad \text{(dB)} .$$

Effective Isotropic Radiated Power

$$\mathrm{EIRP} = P_t + L_t + G_t \quad (\mathrm{dBW}) ,$$

where

EIRP = effective isotropic radiated power (dBW), a transmitting system parameter

P_t = transmitter power (dBW)

L_t = transmit circuit losses (dB)

G_t = transmit antenna gain (dB).

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Space Loss

$$L_s = -(20 \log f + 20 \log R + 37.8) \quad (\mathrm{dB}) ,$$

where

L_s = space loss (dB), range factor between transmitting and receiving antennas

f = frequency (MHz)

R = range between transmitting and receiving antennas (nmi).

Atmospheric Loss

L_a = atmospheric loss (dB), attenuation of the signal power due to the propagation absorption of atmosphere oxygen and water vapor (usually can be neglected for frequency less than 10 GHz).

Polarization Loss

$$L_p = 10 \log \left[\frac{1}{2} + \frac{2R_1R_2}{(1+R_1^2)(1+R_2^2)} + \frac{(1-R_1^2)(1-R_2^2)}{2(1+R_1^2)(1+R_2^2)} \cos 2\phi \right] \quad (\mathrm{dB})$$

where

L_p = polarization loss (dB), reduction of the signal power due to the mismatch of the received signal polarization (usually a design function of the transmitting antenna) with that of the receiving antenna

R_1 = axial ratio of elliptically polarized transmit antenna [ellipticity = $10 \log (1/R_1^2)$ dB]

R_2 = axial ratio of elliptically polarized receive antenna [ellipticity = $10 \log (1/R_2^2)$ dB]

ϕ = alignment angle between two polarization ellipses.

Antenna Pointing Loss

L_θ = antenna pointing loss (dB), reduction of the received signal power due to deviation of both transmitting and receiving antenna maximum gain directions from the line-of-sight.

Receiving Net Gain (or Loss) Ratio

$$\left(\frac{G}{L}\right) = G_r - 10 \log (L) \quad (\mathrm{dB}) ,$$

where

$\left(\frac{G}{L}\right)$ = receiving net gain (or loss) ratio (dB) measured from the antenna of the preamplifier input

G_r = receive antenna gain (dB)

L = receiving circuit loss ratio from antenna port to the preamplifier input (≥ 1).

Total Received Power

P_{rec} = total received power (dBW), which can be referred to the receive antenna input, the antenna output terminal, or the preamplifier input.

Referred to antenna input

$$P_{rec}\Big|_{in} = \mathrm{EIRP} + L_s + L_a + L_p + L_\theta \quad (\mathrm{dBW})$$

Referred to antenna terminal

$$P_{rec}\Big|_{ant} = EIRP + L_s + L_a + L_p + L_\theta + G_r \quad (dBW)$$

Referred to preamplifier input

$$P_{rec}\Big|_{pre} = EIRP + L_s + L_a + L_p + L_\theta + \left(\frac{G}{L}\right) \quad (dBW)$$

or

$$= P_{rec}\Big|_{ant} - 10 \log (L) \quad (dBW)$$

System Thermal Noise Temperature

T_s = system thermal noise temperature (K), a receiving system parameter which can be referred to the antenna terminal or the preamplifier input.

Referred to antenna terminal

$$T_s\Big|_{ant} = T_a + (L-1)(290) + L\,T_{pre} \quad (K)$$

where

T_a = antenna noise temperature (K)

T_{pre} = effective noise temperature of the terminated preamplifier (referred to the preamplifier input).

Referred to preamplifier input

$$T_s\Big|_{pre} = \frac{T_a}{L} + \left(1 - \frac{1}{L}\right)(290) + T_{pre} \quad (K)$$

Receiver Noise Spectral Density

N_0 = single-sided thermal noise spectral density (watts/Hz), which can be referred to the antenna terminal or the preamplifier input.

Referred to antenna terminal

$$N_0\Big|_{ant} = kT_s\Big|_{ant} \quad (watts/Hz)$$

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where

$$k = \text{Boltzmann's constant} = 1.38 \times 10^{-23} \quad \text{(watts/K/Hz)}$$

Referred to preamplifier input

$$N_0\Big|_{pre} = kT_s\Big|_{pre} \quad \text{(watts/Hz)}$$

Receiving Antenna Gain-to-System Thermal Noise Temperature Ratio

$$\left(\frac{G}{T}\right) = G_r - 10 \log \left(T_s\Big|_{ant}\right) \quad \text{(dB/K)}$$

or

$$= G_r - 10 \log (L) - 10 \log \left(\bar{T}_s\Big|_{pre}\right) \quad \text{(dB/K)}$$

where

$\left(\frac{G}{T}\right)$ = antenna gain-to-system thermal noise temperature ratio (dB/K), a receiving system parameter which is independent of reference point.

Total Received Power-to-Noise Spectral Density Ratio

$$\frac{P_{rec}}{N_0} = EIRP + L_s + L_a + L_p + L_\theta + \left(\frac{G}{T}\right) - 10 \log (k) \quad \text{(dB-Hz)}$$

or

$$= P_{rec}\Big|_{ant} - 10 \log \left(N_0\Big|_{ant}\right) \quad \text{(dB-Hz)}$$

or

$$= P_{rec}\Big|_{pre} - 10 \log \left(N_0\Big|_{pre}\right) \quad \text{(dB-Hz)}$$

where

$\frac{P_{rec}}{N_0}$ = total received power-to-noise spectral density ratio (dB-Hz), which is independent of reference point.

Signal-to-Noise Ratio at Demodulator Input

$$\left(\frac{S}{N}\right)_{in} = \frac{P_{rec}}{N_0} - 10 \log (B_{in}) \quad \text{(dB)}$$

where

$\left(\frac{S}{N}\right)_{in}$ = signal-to-noise ratio at demodulator input (dB), a quantity sometimes used in performance calculations

B_{in} = demodulator input bandwidth (Hz).

Bit Energy-to-Noise Spectral Density Ratio at Demodulator Input

$$\left(\frac{E_b}{N_0}\right)_{in} = \frac{P_{rec}}{N_0} - 10 \log (R) \quad (dB)$$

where

$\left(\frac{E_b}{N_0}\right)_{in}$ = bit energy-to-noise spectral density ratio at demodulator input (dB), a quantity sometimes used in performance calculations

R = information channel bit rate (bits/second)

Digital Data Bit Error Probability [For the S-band FM link, postdetection signals are obtained by noncoherent carrier frequency demodulation for both digital and analog modulating signals]

$$P_e = 0.5 \exp [-0.5\ \gamma_0\gamma_b\ (E_b/N_0)'_{in}]$$

where

P_e = bit error probability

γ_0 = degradation factor <1 for nonoptimum frequency shift and/or predetection bandwidth for the given bit rate

γ_b = bit syncronization degradation factor <1, estimated based on equipment specifications

$(E_b/N_0)'_{in}$ = ratio value of $(E_b/N_0)_{in}$.

Postdetection Subcarrier Signal-to-Narrowband Noise Ratio (RMS/RMS) [above FM threshold]

$$(S_s/N)_{out} = (S/N)_{in} + 10 \log [0.5(\Delta_p/f_s)^2(B_{in}/B_s)] \quad (dB)$$

where

$(S_s/N)_{out}$ = signal-to-noise ratio (RMS/RMS) at the output of the postdetection subcarrier bandpass filter (dB)

Δ_p = carrier peak frequency deviation by the subcarrier (Hz)

f_s = subcarrier frequency (Hz)

B_s = postdetection subcarrier filter noise bandwidth (Hz).

Conditions for the above:

$$\left.\begin{array}{l} (S/N)_{in} \geq 10 \text{ dB} \\ B_s << f_s \end{array}\right]$$

Postdetection Analog Baseband Signal-to-Noise Ratio (peak-to-peak/RMS) [above FM threshold]

$$(S_{pp}/N)_{out} = (S/N)_{in} + 10 \log [3(\Delta_{pp}/B_{out})^2 (B_{in}/B_{out})] \quad \text{(dB)}$$

where

$(S_{pp}/N)_{out}$ = signal-to-noise ratio (peak-to-peak/RMS) at the output of the postdetection analog signal baseband filter (dB)

Δ_{pp} = carrier peak-to-peak frequency deviation by the analog signal (Hz)

B_{out} = postdetection baseband filter (lowpass filter) noise bandwidth (Hz).

Condition for above:

$$(S/N)_{in} \geq 10 \text{ dB}$$

Postdetection Analog Baseband Signal-to-Noise Ratio (RMS/RMS) [above threshold]

$$(S_{rms}/N)_{out} = (S/N)_{in} + 10 \log \left[3 \left(\frac{\Delta_p/F}{B_{out}}\right)^2 (B_{in}/B_{out})\right] \quad \text{(dB)}$$

where

$(S_{rms}/N)_{out}$ = signal-to-noise ratio (RMS/RMS) at the output of the postdetection analog signal baseband filter (dB)

Δ_p = carrier peak frequency deviation by the analog signal (Hz)

F = analog signal peak-to-RMS voltage ratio.

Condition for the above:

$$(S/N)_{in} \geq 10 \text{ dB}$$

3.2 Circuit Margins Using Nominal (+1 dB) Antenna Gains and Orbital Slant Range

3.2.1 Link Geometry

As illustrated in Figure 13, it is assumed that the Orbiter is in a 270-nmi orbit with a maximum slant range of approximately 1122 nmi (5° elevation angle) to the ground station. This maximum slant range will be used in the subsequent performance margin calculations, along with a nominal (+1 dB) hemi antenna gain. It should be recognized that the nominal values thus obtained are valid only when the Orbiter attitudes are such that nominal (or better) antenna gains are available. As noted previously, for the on-orbit (unmated configuration), this condition is true for approximately 9% of all possible Orbiter attitudes for low altitude orbit of 100 nmi and approximately 25% for an orbit of 250 nmi with 12 G-STDN stations.

3.2.2 Television Circuit Margins

Using the mathematical models summarized in Section 3.1, and using the Orbiter and G-STDN parameters detailed in Sections 2.5, 2.6, and 2.8, it is a straightforward procedure to determine the performance margins for television transmission. Since television transmission to the SCF is not a requirement for DoD missions, then margin calculations are not performed for SCF stations. Table 4 presents the OFT (Flights 1-7 for OV-102) margin calculations for the case of a 30-foot G-STDN station. It can be seen that,

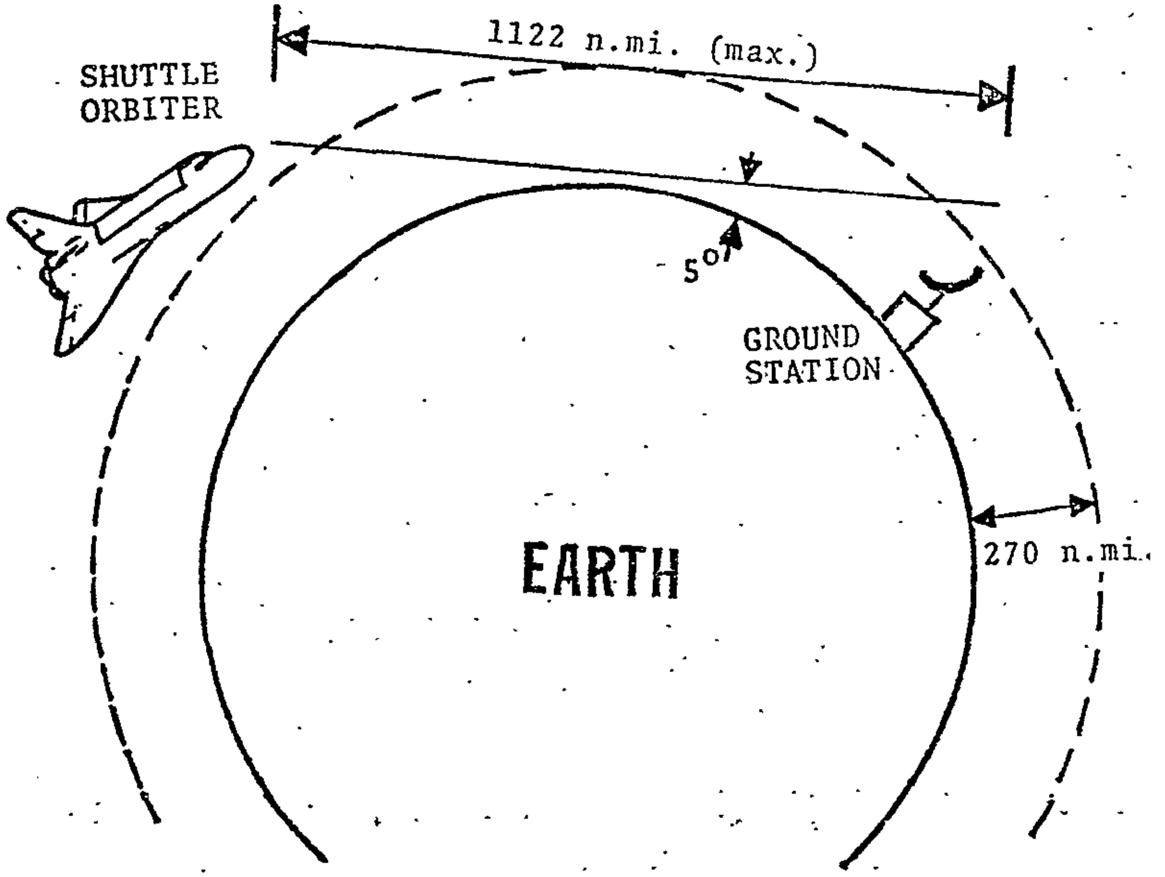

Figure 13. Link Geometry for S-Band FM Downlink

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Table 4. Circuit Margin Calculation Summary Sheet — Orbiter-to-G-STDN S-Band FM Downlink Television Channel (30-foot station, OFT Orbiter configuration)

Parameter	Value	Source
(1) SSO transmit power, dBW	10.0	10 W
(2) SSO transmit circuit loss, dB	-10.6	Rockwell estimate
(3) SSO transmit antenna gain, dB	1.0	Specified over 54% of coverage sphere
(4) SSO EIRP, dBW	0.4	Sum (1) through (3), ICD 2-0D004
(5) Space Loss, dB	-165.8	f = 2250 MHz, R = 1120 nmi (maximum slant range for 5° elevation and 270 nmi orbit)
(6) Pointing loss, dB	-0.5	Estimate
(7) Polarization loss, dB	-0.5	Estimate
(8) STDN receive antenna gain, dB	43.5	GSFC estimate (30-foot)
(9) STDN receive circuit loss, dB	---	Included in STDN antenna gain
(10) Total received power, dBW	-122.9	Sum (4) through (9)
(11) STDN system noise temperature, dBK	21.5	140 K (GSFC estimate)
(12) Boltzmann's constant, dB (W/K/Hz)	-228.6	1.38×10^{-23} W/K/Hz
(13) STDN noise spectral density, dB (W/Hz)	-207.1	Sum (11) and (12)
(14) STDN G/T, dB/K	22.0	(8) minus (11), ICD 2-0D004
(15) Total received power/noise spectral density (P_{rec}/N_0), dB-Hz	84.2	(10) minus (13) or sum (4) through (7) minus (12) plus (14)
(16) Predetection bandwidth (B_{in}), dB-Hz	71.2	13.2 MHz, ICD 2-0D004
(17) Signal-to-noise ratio $(S/N)_{in}$ at FM discriminator input, dB	13.0	(15) minus (16)
(18) FM threshold, dB	10.0	ICD 2-0D004
(19) FM threshold margin, dB	3.0	(17) minus (18)
(20) Signal-to-noise ratio $(S_{pp}/N)_{out}$ (peak-to-peak/RMS) at output of postdetection lowpass filter, dB	33.7	$\Delta_{pp} = 9.0$ MHz, $B_{out} = 3.0$ MHz, ICD 2-0D004
(21) Required output signal-to-noise ratio, dB	35.0	ICD 2-0D004
(22) Discriminator degradation, dB	-1.0	Estimate
(23) Required $(S_{pp}/N)_{out}$, dB	36.0	(21) minus (22)
(24) Required P_{rec}/N_0, dB-Hz	86.5	(23) plus (17) minus (20) plus (16), ICD 2-0D004
(25) TV margin (postdetection), dB	-2.3	(20) minus (23) or (15) minus (24)
(26) Circuit margin, dB	-2.3	(25) less than (19)

if a 13.2 MHz predetection bandwidth is used, along with a 3.0 MHz post-detection bandwidth, the margin above an assumed FM threshold of 10 dB is 3.0 dB, while the post-detection margin (above a 35 dB peak-to-peak/RMS SNR requirement) is -2.3 dB. Although the threshold margin could undoubtedly be improved by use of an extended threshold FM demodulator, the postdetection margin could not be improved. The postdetection margin can only be improved (assuming a constant ground station configuration) by increasing Orbiter antenna gain or transmitter power, by decreasing Orbiter transmit circuit loss, by reducing range, or by reducing the required output SNR. It should be noted that use of an 85-foot G-STDN station would provide an increase of 9.2 dB in antenna gain, thereby increasing the television post-detection margin to 6.9 dB. However, only one 85-foot G-STDN station will be available, while 10 locations will have 30-foot stations and one location will have a 40-foot station. Thus, the margin for 30-foot stations is of the utmost concern.

For the operational configuration (Flight 8 and subsequent flights), deletion of the DFI multiplexer reduces the Orbiter transmit circuit loss to -7.2 dB, thereby increasing the television threshold margin to 6.4 dB and the postdetection margin to 1.1 dB for the 30-foot G-STDN stations. Use of an 85-foot station would increase these margins to 15.6 and 10.3 dB, respectively.

The negative postdetection margin for the Orbiter OFT configuration is of real concern, since it is during early OFT that the S-band FM downlink will provide the only means of obtaining television. The marginal (+1.1 dB) performance for the Orbiter operational configuration is not nearly of as much concern. Section 5.0 of this report proposes a signal design change (increased Δf for television) that should alleviate the concern in this area.

3.2.3 Main Engine Data Circuit Margins

Using the appropriate mathematical models described in previous sections, together with the Orbiter and G-STDN parameters, the performance margins shown in Tables 5 through 7 were obtained for the worst case of interest (30-foot G-STDN station, Orbiter OFT configuration). As shown in the tables, the threshold margin is 9.4 dB, while the postdetection data margin (based on bit error rate of 10^{-4}) are 22.8 dB, 20.3 dB, and 17.8 dB, for the 576 kHz, 768 kHz, and 1024 kHz subcarrier channels, respectively. These margins all improve by 9.2 dB if transmission is to an 85-foot station.

It is doubtful that there will be a requirement for real-time transmission of main engine data to an SCF station, but should the need arise, the case of interest would be for the 14-foot station and the Orbiter OFT configuration. For these conditions, the ground station antenna gain is lower by 10.0 dB and the ground station receiver system temperature is higher by 3.9 dB, thereby resulting in a net reduction of 13.9 dB in all circuit margins for the main engine data channels. If a 46-foot or 60-foot SCF is utilized, the G-STDN margins would increase by 2.1 dB and 0.9 dB, respectively.

3.2.4 Real-Time Attached Payload Data Circuit Margins

3.2.4.1 Analog Data (Up to 4 MHz)

Table 8 summarizes the circuit margin calculations for the (worst) case of real-time transmission of 4 MHz of attached payload data to a 30-foot G-STDN site (Orbiter OFT configuration), with an output SNR requirement of SNR_{out} in a 4 MHz postdetection bandwidth. The IF bandwidth assumed is the Carson's rule bandwidth:

$$B_{IF} = 2(\Delta f + f_m) = 2(2\text{ MHz} + 4\text{ MHz}) = 12\text{ MHz} .$$

Table 5. Circuit Margin Calculation Summary Sheet - Orbiter-to-G-STDN S-Band FM Downlink Main Engine Data Channels, 576 kHz Subcarrier (30-foot station, OFT Orbiter Configuration)

Parameter	Value	Source
(1) SSO transmit power, dBW	10.0	10 W
(2) SSO transmit circuit loss, dB	-10.6	Rockwell estimate
(3) SSO transmit antenna gain, dB	1.0	Specified over 54% of coverage sphere
(4) SSO EIRP, dBW	0.4	Sum (1) through (3), ICD 2-00004
(5) Space loss, dB	-165.8	f = 2250 MHz, R = 1122 nmi (maximum slant range for 5° elevation and 270 nmi orbit)
(6) Pointing loss, dB	-0.5	Estimate
(7) Polarization loss, dB	-0.5	Estimate
(8) STDN receive antenna gain, dB	43.5	GSFC estimate (30-foot)
(9) STDN receive circuit loss, dB	---	Included in STDN antenna gain
(10) Total received power, dBW	-122.9	Sum (4) through (9)
(11) STDN system noise temperature, dBK	21.5	140 K (GSFC estimate)
(12) Boltzmann's constant, dB (W/K/Hz)	-228.6	1.38×10^{-23} W/K/Hz
(13) STDN noise spectral density, dB (W/Hz)	-207.1	Sum (11) and (12)
(14) STDN G/T, dB/K	22.0	(8) minus (11)
(15) Total received power/noise spectral density (P_{rec}/N_0), dB-Hz	84.2	(10) minus (13) or sum (4) through (7) minus (12) plus (14)
(16) Predetection bandwidth (B_{in}), dB-Hz	64.8	3 MHz, ICD 2-0D004
(17) Signal-to-noise ratio $(S/N)_{in}$ at FM discriminator input, dB	19.4	(15) minus (16)
(18) FM threshold, dB	10.0	ICD 2-0D004
(19) FM threshold margin, dB	9.4	(17) minus (18)
(20) Postdetection subcarrier power/noise spectral density (P_{sc}/N), dB	82.0	f_{sc} = 576 kHz, Δf = 635 kHz, ICD 2-0D004
(21) Bit rate bandwidth, dB-Hz	47.8	60 kbps
(22) SNR in bit rate bandwidth (E_b/nsd), dB	34.2	(20) minus (21)
(23) Theoretical required E_b/nsd, dB	8.4	For 10^{-4} BEP
(24) FM discriminator degradation, dB	-1.0	Estimate
(25) Bit synchronization degradation, dB	-2.0	Estimate (including bandlimiting effect)
(26) Required E_b/nsd (postdetection), dB	11.4	(23) minus (24) minus (25)
(27) Data margin, (postdetection), dB	22.8	(22) minus (26)
(28) Required P_{rec}/N, dB-Hz	74.8	(16) plus (18), ICD 2-00004
(29) CIRCUIT MARGIN, dB	9.4	(15) minus (28), constrained by FM threshold margin

Table 6. Circuit Margin Calculation Summary Sheet - Orbiter-to-G-STDN S-Band FM Downlink Main Engine Data Channels, 768 kHz Subcarrier (30-foot station, OFT Orbiter Configuration)

Parameter	Value	Source
(1) SSO transmit power, dBW	10.0	10 W
(2) SSO transmit circuit loss, dB	-10.6	Rockwell estimate
(3) SSO transmit antenna gain, dB	1.0	Specified over 54% of coverage sphere
(4) SSO EIRP, dBW	0.4	Sum (1) through (3), ICD 2-0D004
(5) Space loss, dB	-165.8	f = 2250 MHz, R = 1122 nmi (maximum slant range for 5° elevation and 270 nmi orbit)
(6) Pointing loss, dB	-0.5	Estimate
(7) Polarization loss, dB	-0.5	Estimate
(8) STDN receive antenna gain, dB	43.5	GSFC estimate (30-foot)
(9) STDN receive circuit loss, dB	---	Included in STDN antenna gain
(10) Total received power, dBW	-122.9	Sum (4) through (9)
(11) STDN system noise temperature, dBK	21.5	140 K (GSFC estimate)
(12) Boltzmann's constant, dB (W/K/Hz)	-228.6	1.38×10^{-23} W/K/Hz
(13) STDN noise spectral density, dBW/Hz	-207.1	Sum (11) and (12)
(14) STDN G/T, dB/K	22.0	(8) minus (11), ICD 2-0D004
(15) Total received power/noise spectral density (P_{rec}/N_0), dB-Hz	84.2	(10) minus (13) or sum (4) through (12) plus (14)
(16) Predetection bandwidth (B_{in}), dB-Hz	64.8	3 MHz, ICD 2-0D004
(17) Signal-to-noise ratio $(S/N)_{in}$ at FM	19.4	(15) minus (16)
(18) FM threshold, dB	10.0	ICD 2-0D004
(19) FM threshold margin, dB	9.4	(17) minus (18)
(20) Postdetection subcarrier power/noise spectral density (P_{sc}/N), dB	79.5	$f_{sc} = 768$ kHz, $\Delta f = 635$ kHz, ICD 2-0D004
(21) Bit rate bandwidth, dB-Hz	47.8	60 kbps
(22) SNR in bit rate bandwidth (E_b/nsd), dB	31.7	(20) minus (21)
(23) Theoretical required E_b/nsd, dB	8.4	For 10^{-4} BEP
(24) FM discriminator degradation, dB	-1.0	Estimate
(25) Bit synchronization degradation, dB	-2.0	Estimate (including bandlimiting effect)
(26) Required E_b/nsd (postdetection), dB	11.4	(23) minus (24) minus (25)
(27) Data margin (postdetection), dB	20.3	(22) minus (26)
(28) Required P_{rec}/N_0, dB-Hz	74.8	(16) plus (18), ICD 2-0D004
(29) CIRCUIT MARGIN, dB	9.4	(15) minus (28), constrained by FM threshold margin

Table 7. Circuit Margin Calculation Summary Sheet - Orbiter-to-G-STDN S-Band FM Downlink Main Engine Data Channels, 1024 kHz Subcarrier (30-foot station, OFT Orbiter Configuration)

Parameter	Value	Source
(1) SSO transmit power, dBW	10.0	10 W
(2) SSO transmit loss, dB	-10.6	Rockwell estimate
(3) SSO transmit antenna gain, dB	1.0	Specified over 54% of coverage sphere
(4) SSO EIRP, dBW	0.4	Sum (1) through (3), ICD 2-0D004
(5) Space loss, dB	-165.8	f = 2250 MHz, R = 1122 nmi (maximum slant range for 5° elevation and 270 nmi orbit)
(6) Pointing loss, dB	-0.5	Estimate
(7) Polarization loss, dB	-0.5	Estimate
(8) STDN receive antenna gain, dB	43.5	GSFC estimate (30-foot)
(9) STDN receive circuit loss, dB	---	Included in STDN antenna gain
(10) Total received power, dBW	-122.9	Sum (4) through (9)
(11) STDN system noise temperature, dBK	21.5	140 K (GSFC estimate)
(12) Boltzmann's constant, dB (W/K/Hz)	-228.6	1.38×10^{-23} W/K/Hz
(13) STDN noise spectral density, dB (W/Hz)	-207.1	Sum (11) and (12)
(14) STDN G/T, dB/K	22.0	(8) minus (11), ICD 2-0D004
(15) Total received power/noise spectral density (P_{rec}/N_0), dB-Hz	84.2	(10) minus (13) or sum (4) through (7) minus (12) plus (14)
(16) Predetection bandwidth (B_{in}), dB-Hz	64.8	3 MHz, ICD 2-0D004
(17) Signal-to-noise ratio $(S/N)_{in}$ at FM discriminator input, dB	19.4	(15) minus (16)
(18) FM threshold, dB	10.0	ICD 2-0D004
(19) FM threshold margin, dB	9.4	(17) minus (18)
(20) Postdetection subcarrier power/noise spectral density (P_{sc}/N), dB	77.0	$f_{sc} = 1024$ kHz, $\Delta f = 635$ kHz, ICD 2-0D004
(21) Bit rate bandwidth, dB-Hz	47.8	60 kbps
(22) SNR in bit rate bandwidth (E_b/nsd), dB	29.2	(20) minus (21)
(23) Theoretical required E_b/nsd, dB	8.4	For 10^{-4} BEP
(24) FM discriminator degradation, dB	-1.0	Estimate
(25) Bit synchronization degradation, dB	-2.0	Estimate (including bandlimiting effect)
(26) Required E_b/nsd (postdetection), dB	11.4	(23) minus (24) minus (25)
(27) Data margin (postdetection), dB	17.8	(22) minus (26)
(28) Required P_{rec}/N_0, dB-Hz	74.8	(16) plus (18), ICD 2-0D004
(29) CIRCUIT MARGIN, dB	9.4	(15) minus (28), constrained by FM threshold margin

Table 8. Circuit Margin Calculation Summary Sheet - Orbiter-to-G-STDN S-Band FM Downlink Real-Time Attached Payload Analog Data (4 MHz)

Parameter	Value	Source
(1) SSO transmit power, dBW	10.0	10 W
(2) SSO transmit circuit loss, dB	-10.6	Rockwell estimate
(3) SSO transmit antenna gain, dB	1.0	Specified over 54% of coverage sphere
(4) SSO EIRP, dBW	0.4	Sum (1) through (3), ICD 2-0D004
(5) Space loss, dB	-165.8	$f = 2250$ MHz, $R = 1122$ nmi (maximum slant range for 5° elevation and 270 nmi orbit)
(6) Pointing loss, dB	-0.5	Estimate
(7) Polarization loss, dB	-0.5	Estimate
(8) STDN receive antenna gain, dB	43.5	GSFC estimate (30-foot)
(9) STDN receive circuit loss, dB	---	Included in STDN antenna gain
(10) Total received power, dBW	-122.9	Sum (4) through (9)
(11) STDN system noise temperature, dBK	21.5	140 K (GSFC estimate)
(12) Boltzmann's constant, dB (W/K/Hz)	-228.6	1.38×10^{-23} W/K/Hz
(13) STDN noise spectral density, dB (W/Hz)	-207.1	Sum (11) and (12)
(14) STDN G/T, dB/K	22.0	(8) minus (11), ICD 2-0D004
(15) Total received power/noise spectral density (P_{rec}/N_0), dB-Hz	84.0	(10) minus (13) or sum (4) through (7) minus (12) plus (14)
(16) Predetection bandwidth (B_{in}), dB-Hz	70.8	12 MHz
(17) Signal-to-noise ratio $(S/N)_{in}$ at FM discriminator input, dB	13.4	(15) minus (16)
(18) FM threshold, dB	10.0	ICD 2-0D004
(19) Signal-to-noise ratio $(S_{rec}/N)_{out}$ (RMS/RMS) at output of postdetection lowpass filter	$10 \log \left[\frac{49.22}{F^2}\right]$	$\Delta_p = 2$ MHz, $B_{out} = 4$ MHz, ICD 2-0D004
(20) Required output signal-to-noise ratio, dB	$(S_{rms}/N)_{out,req}$	
(21) Discriminator degradation, dB	-1.0	Estimate
(22) Required $(S_{rms}/N)_{out}$, dB	$(S_{rms}/N)_{out,req} + 1$	(20) minus (21)
(23) FM threshold margin, dB	3.4	(17) minus (18)
(24) Postdetection margin, dB	$10 \log \left[\frac{49.22}{F^2}\right] - 1 - (S_{rms}/N)_{out,req}$	(19) minus (22)

As can be seen from Table 8, the threshold margin is 3.4 dB and postdetection margin is given by

$$10 \log \left[\frac{49.22}{F^2}\right] - 1 - \left(\frac{S_{rms}}{N}\right)_{out,req}$$

where F = analog signal peak-to-RMS voltage ratio

$(S_{rms}/N)_{out,req}$ = required signal-to-noise ratio (RMS/RMS) at the output of the postdetection lowpass filter.

3.2.4.2 Digital Data (Up to 5 Mbps)

Table 9 summarizes the circuit margin calculation for the (worst) case of transmission of 5 Mbps of real-time attached payload data to a 30-foot G-STDN site (Orbiter operational configuration). A bit error rate requirement of 10^{-4} is assumed. The signal parameters are optimized using the results from Appendixes A and B that present tests performed on the digital data on an FM link. For 5 Mbps NRZ data, the optimum IF bandwidth is 7.2 MHz with frequency deviation ratio of 0.36. With a frequency deviation Δf = 2 MHz as defined in ICD 2-0D004, the frequency deviation ratio is 0.4, which causes a 0.3 dB degradation from the optimum performance.

3.2.4.3 AFSCF Digital Data (256 kbps)

Table 10 summarizes the calculation for the case of 256 kbps transmission to an SCF station for either 14-foot or 46-foot with the Orbiter operational configuration. The circuit margin for a 60-foot antenna site is 1.2 dB less than the margin for the 46-foot antenna site. A bit error rate requirement of 10^{-5} is assumed.

3.2.5 Playback Data Circuit Margins

As discussed in Section 2.1, for playback of either main engine data, OI telemetry data, TDM data, or payload data, the maximum playback rate for NASA missions using the G-STDN is 1024 kbps, while that for DoD missions

Table 9. Circuit Margin Calculation Summary Sheet - Orbiter-to-G-STDN Operational S-Band FM Downlink Real-Time Attached Payload Digital Data (5 Mbps)

Parameter	Value	Source
(1) SSO transmit power, dBW	10.0	10 W
(2) SSO transmit circuit loss, dB	-7.2	Rockwell estimate
(3) SSO transmit antenna gain, dB	1.0	Specified over 54% of coverage sphere
(4) SSO EIRP, dBW	3.8	Sum (1) through (3), ICD 2-0D004
(5) Space loss, dB	-165.8	f = 2250 MHz, R = 1122 nmi (maximum slant range for 5°elevation and 270 nmi orbit)
(6) Pointing loss, dB	-0.5	Estimate
(7) Polarization loss, dB	-0.5	Estimate
(8) STDN receive antenna gain, dB	43.5	GSFC estimate (30-foot)
(9) STDN receive circuit loss, dB	---	Included in STDN antenna gain
(10) Total received power, dBW	-119.5	Sum (4) through (9)
(11) STDN system noise temperature, dBK	21.5	140 K (GSFC estimate)
(12) Boltzmann's constant, dB (W/K/Hz)	-228.6	1.38×10^{-23} W/K/Hz
(13) STDN noise spectral density, dB (W/Hz)	-207.1	Sum (11) and (12)
(14) STDN G/T, dB/K	22.0	(8) minus (11), ICD 2-0D004
(15) Total received power/noise spectral density (P_{rec}/N_0), dB-Hz	87.6	(10) minus (13) or sum (4) through (7) minus (12) plus (14)
(16) Predetection bandwidth (B_{in}), dB-Hz	68.6	7.2 MHz, Appendix B
(17) Signal-to-noise ratio $(S/N)_{in}$ at FM discriminator input, dB	19.0	(15) minus (16)
(18) Bit rate bandwidth, dB-Hz	67.0	5 Mbps
(19) SNR in bit rate bandwidth $(E_b/N_0)_{in}$, dB	20.6	(15) minus (18)
(20) Required $(E_b/N_0)_{in}$, dB	11.7	For 10^{-4} BEP, $\Delta f = 2$ MHz, ICD 2-0D004
(21) Discriminator degradation, dB	-1.0	Estimate
(22) Bit synchronization degradation, dB	-2.0	Estimate
(23) Required $(E_b/N_0)_{in}$ (postdetection), dB	14.7	(20) minus (21) minus (22)
(24) Required P_{rec}/N_0, dB-Hz	81.7	(23) plus (18), ICD 2-0D004
(25) CIRCUIT MARGIN, dB	5.9	(19) minus (23) or (15) minus (24)

Table 10. Circuit Margin Calculation Summary Sheet - Orbiter-to-SCF S-Band FM Downlink Payload Data Channel (256 kbps)

Parameter	Value	Source
(1) SSO transmit power, dBW	10.0	10 W
(2) SSO transmit circuit loss, dB	-7.2	Rockwell estimate
(3) SSO transmit antenna gain, dB	1.0	Specified over 54% of coverage sphere
(4) SSO EIRP, dBW	3.8	Sum (1) through (3), ICD 2-0D003
(5) Space loss, dB	-164.5	f = 2250 MHz, R = 966 nmi (maximum slant range for 5° elevation and 225 nmi orbit)
(6) Pointing loss, dB	---	Included in receive antenna gain
(7) Polarization loss, dB	---	Included in receive antenna gain
(8) AFSCF receive antenna gain, dB	47.5 33.5	AFSCF specification (46-foot) 14-foot site
(9) AFSCF receive circuit loss, dB	---	Included in AFSCF antenna gain
(10) Total received power, dBW	-113.2 *-127.2	Sum (4) through (9)
(11) AFSCF system noise temperature, dBK	23.4 *25.8	220 K for 46-foot site; 376 K for 14-foot site
(12) Boltzmann's constant, dB (W/K/Hz)	-228.6	1.38×10^{-23} W/K/Hz
(13) AFSCF noise spectral density, dB (W/Hz)	-205.2 *-202.5	Sum (11) and (12)
(14) AFSCF G/T, dB/K	24.1 * 7.7	(8) minus (11), ICD 2-0D003
(15) Total received power/noise spectral density (P_{rec}/N_0), dB-Hz	92.0 *75.7	(10) minus (13) or sum (4) through (7) minus (12) plus (14)
(16) Predetection bandwidth (B_{in}), dB-Hz	67.0	5.0 MHz, ICD 2-0D003
(17) Signal-to-noise ratio $(S/N)_{in}$ at FM discriminator input, dB	25.0 * 8.7	(15) minus (16)
(18) Bit rate bandwidth, dB-Hz	54.1	256 kbps
(19) SNR in bit rate bandwidth $(E_b/N_0)_{in}$, dB	37.9 *21.6	(15) minus (18)
(20) Required $(E_b/N_0)_{in}$, dB	17.3	For 10^{-5} BEP, $\Delta f = 635$ kHz, $B_{in} = 5$ MHz
(21) FM discriminator degradation, dB	-1.5	Estimate
(22) Bit sychronization degradation, dB	-2.0	AFSCF estimate
(23) Required $(E_b/N_0)_{in}$ (postdetection), dB	20.8	(20) minus (21) minus (22)
(24) Required P_{rec}/N_0, dB-Hz	74.9	(23) plus (18), ICD 2-0D003
(25) CIRCUIT MARGIN, dB	17.1 * 0.8	(19) minus (23) or (15) minus (24)

*For 14-foot site

using the SCF is 960 kbps; consequently, the performance margin calculations are summarized in Tables 11 and 12 for transmission to a 30-foot G-STDN station and to a 14-foot or 46-foot SCF station, respectively. Note that the circuit margin for the 60-foot SCF station is 1.2 dB less than for the 46-foot station.

3.3 Performance During Ascent

This section analyzes the performance of the FM downlink during ascent from Kennedy Space Center (KSC). Launches from Vandenberg Air Force Base (VAFB) are not considered here because of lack of trajectory data for these launches.

3.3.1 Ascent Geometry

For launches from KSC, Figure 14 indicates that the Shuttle, when on the launch pad, will be located 8.3 nautical miles to the northeast of the STDN station (MIL) at MILA. When on the pad, the Shuttle will be oriented such that the vertical stabilizer of the Orbiter is pointed south. Immediately after liftoff and tower clearance, the Shuttle goes through a roll maneuver which aligns the vertical stabilizer of the Orbiter with the launch azimuth plane, such that the Orbiter is in a heads-down orientation as it begins to pitch over in the ascent trajectory.

Figure 15 illustrates the Shuttle ascent trajectories for the two reference missions considered in this report. For reference mission 1, the launch azimuth is 90° (due east), and the orbital inclination is 28.5°. For reference mission 2, the launch azimuth is approximately 38°, with a resulting orbital inclination of 55°. For either of these reference missions, the solid rocket boosters (SRB) fire from liftoff until approximately 125 seconds (corresponding to an altitude of 23 nmi and a range of 24 nmi from MIL). After SRB separation, the Orbiter and external tank remain mated until approximately

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Table 11. Circuit Margin Calculation Summary Sheet - Orbiter-to-G-STDN S-Band FM Downlink Playback of Recorded OI or MSS Data (1024 kbps)

Parameter	Value	Source
(1) SSO transmit power, dBW	10.0	10 W
(2) SSO transmit circuit loss, dB	-7.2 *-10.6	Rockwell estimate
(3) SSO transmit antenna gain, dB	1.0	Specified over 54% of coverage sphere
(4) SSO EIRP, dBW	3.8 *0.4	Sum (1) through (3), ICD 2-0D004
(5) Space loss, dB	-165.8	f = 2250 MHz, R = 1122 nmi (maximum slant range for 5° elevation and 270 nmi orbit)
(6) Pointing loss, dB	-0.5	Estimate
(7) Polarization loss, dB	-0.5	Estimate
(8) STDN receive antenna gain, dB	43.5	GSFC estimate (30-foot)
(9) STDN receive circuit loss, dB	---	Included in STDN antenna gain
(10) Total received power, dBW	-119.5 *-122.9	Sum (4) through (9)
(11) STDN system noise temperature, dBK	21.5	140 K (GSFC estimate)
(12) Boltzmann's constant, dB (W/K/Hz)	-228.6	1.38×10^{-23} W/K/Hz
(13) STDN noise spectral density, dB (W/Hz)	-207.1	Sum (11) and (12)
(14) STDN G/T, dB/K	22.0	(8) minus (11), ICD 2-0D004
(15) Total received power/noise spectral density (P_{rec}/N_0), dB-Hz	87.6 *84.2	(10) minus (13) or sum (4) through (7) minus (12) plus (14)
(16) Predetection bandwidth (B_{in}), dB-Hz	64.8	3 MHz, ICD 2-0D004
(17) Signal-to-noise ratio $(S/N)_{in}$ at FM discriminator input, dB	22.8 *19.4	(15) minus (16)
(18) Bit rate bandwidth, dB-Hz	60.1	1024 kbps
(19) SNR in bit rate bandwidth $(E_b/N_0)_{in}$, dB	27.5 *24.1	(15) minus (18)
(20) Required $(E_b/N_0)_{in}$, dB	12.0	For 10^{-4} BEP, $\Delta f = 635$ kHz, $B_{in} = 3$ MHz
(21) Discriminator degradation, dB	-1.0	Estimate
(22) Bit synchronization degradation, dB	-2.0	Estimate
(23) Required $(E_b/N_0)_{in}$ (postdetection), dB	15.0	(20) minus (21) minus (22)
(24) Required P_{rec}/N_0, dB-Hz	75.1	(23) plus (18), ICD 2-0D004
(25) CIRCUIT MARGIN, dB	12.5 * 9.1	(19) minus (23) or (15) minus (24)

*OFT only

Table 12. Circuit Margin Calculation Summary Sheet - Orbiter-to-SCF S-Band FM Downlink Playback of OI or MSS Data (960 kbps)

Parameter	Value	Source
(1) SSO transmit power, dBW	10.0	10 W
(2) SSO transmit circuit loss, dB	-7.2	Rockwell estimate
(3) SSO transmit antenna gain, dB	1.0	Specified over 54% of coverage sphere
(4) SSO EIRP, dBW	3.8	Sum (1) through (3), ICD 2-0D003
(5) Space loss, dB	-164.5	f = 2250 MHz, R = 966 nmi (maximum slant range for 5° elevation and 225 nmi orbit)
(6) Pointing loss, dB	---	Included in receive antenna gain
(7) Polarization loss, dB	---	Included in receive antenna gain
(8) AFSCF receive antenna gain, dB	47.5 *33.5	AFSCF specification (46-foot)
(9) AFSCF receive circuit loss, dB	---	Included in AFSCF antenna gain
(10) Total received power, dBW	-113.2 *-127.2	Sum (4) through (9)
(11) AFSCF system noise temperature, dBK	23.4 *25.8	220 K for 46-foot site; 376 K for 14-foot site
(12) Boltzmann's constant, dB (W/K/Hz)	-228.6	1.38×10^{-23} W/K/Hz
(13) AFSCF noise spectral density, dB (W/Hz)	-205.2 -202.9	Sum (11) and (12)
(14) AFSCF G/T, dB/K	24.1 * 7.7	(8) minus (11), ICD 2-0D003
(15) Total received power/noise spectral density (P_{rec}/N_0), dB-Hz	92.0 *75.7	(10) minus (13) or sum (4) through (7) minus (12) plus (14)
(16) Predetection bandwidth (B_{in}), dB-Hz	67.0	5.0 MHz, ICD 2-0D003
(17) Signal-to-noise ratio $(S/N)_{in}$ at FM discriminator input, dB	25.0 * 8.7	(15) minus (16)
(18) Bit rate bandwidth, dB-Hz	59.8	960 kbps
(19) SNR in bit rate bandwidth $(E_b/N_0)_{in}$, dB	32.2 *15.9	(15) minus (18)
(20) Required $(E_b/N_0)_{in}$, dB	14.1	For 10^{-5} BEP, $\Delta f = 635$ kHz, $B_{in} = 5$ MHz
(21) FM discriminator degradation, dB	-1.5	Estimate
(22) Bit synchronization degradation, dB	-2.0	AFSCF estimate
(23) Required $(E_b/N_0)_{in}$ (postdetection), dB	17.6	(20) minus (21) minus (22)
(24) Required P_{rec}/N_0, dB-Hz	77.4	(23) plus (18), ICD 2-0D003
(25) CIRCUIT MARGIN, dB	14.6 *-1.7	(19) minus (23) or (15) minus (24)

*For 14-foot site

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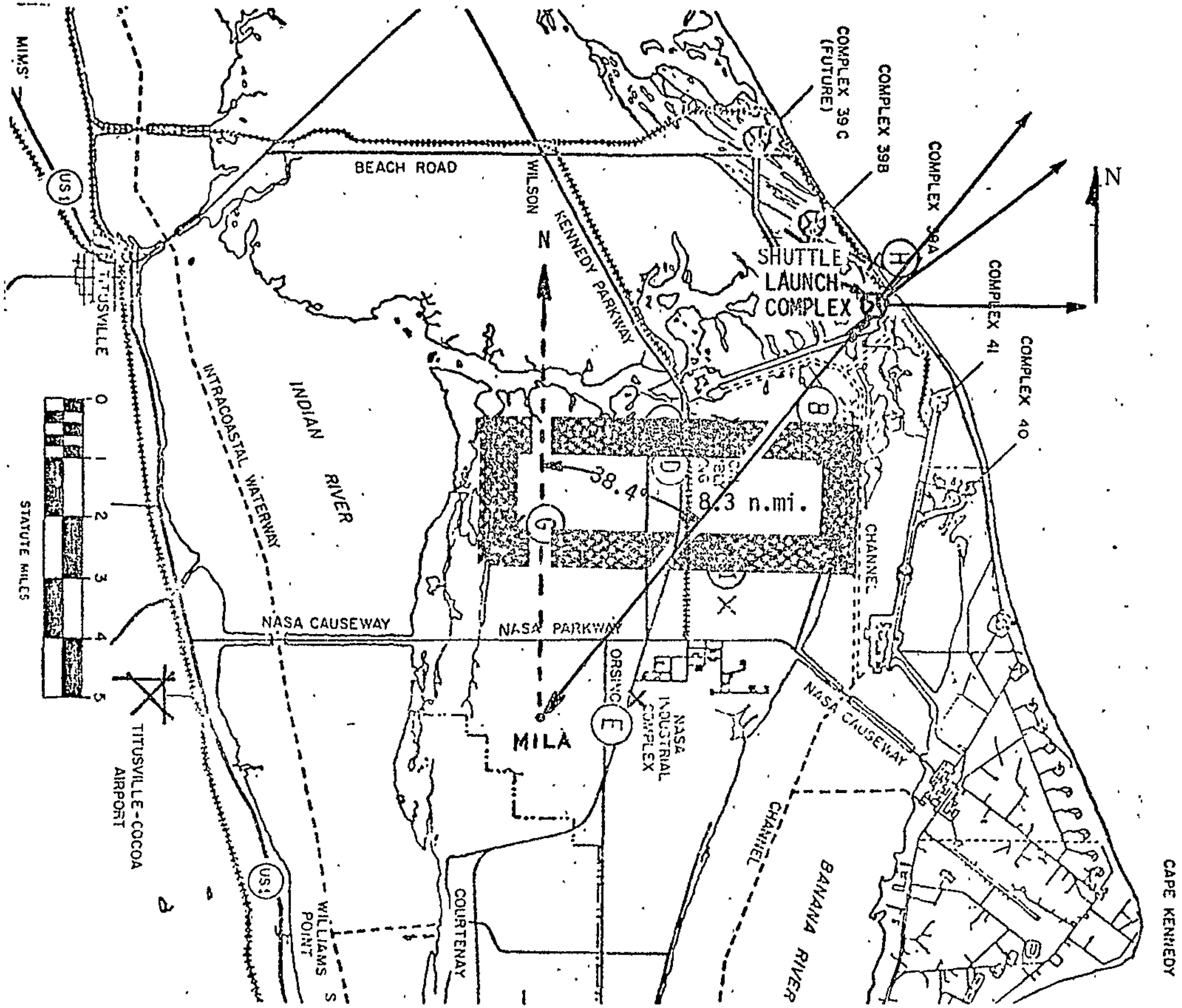

Figure 14. Shuttle Launch Pad/Ground Station Locations for KSC

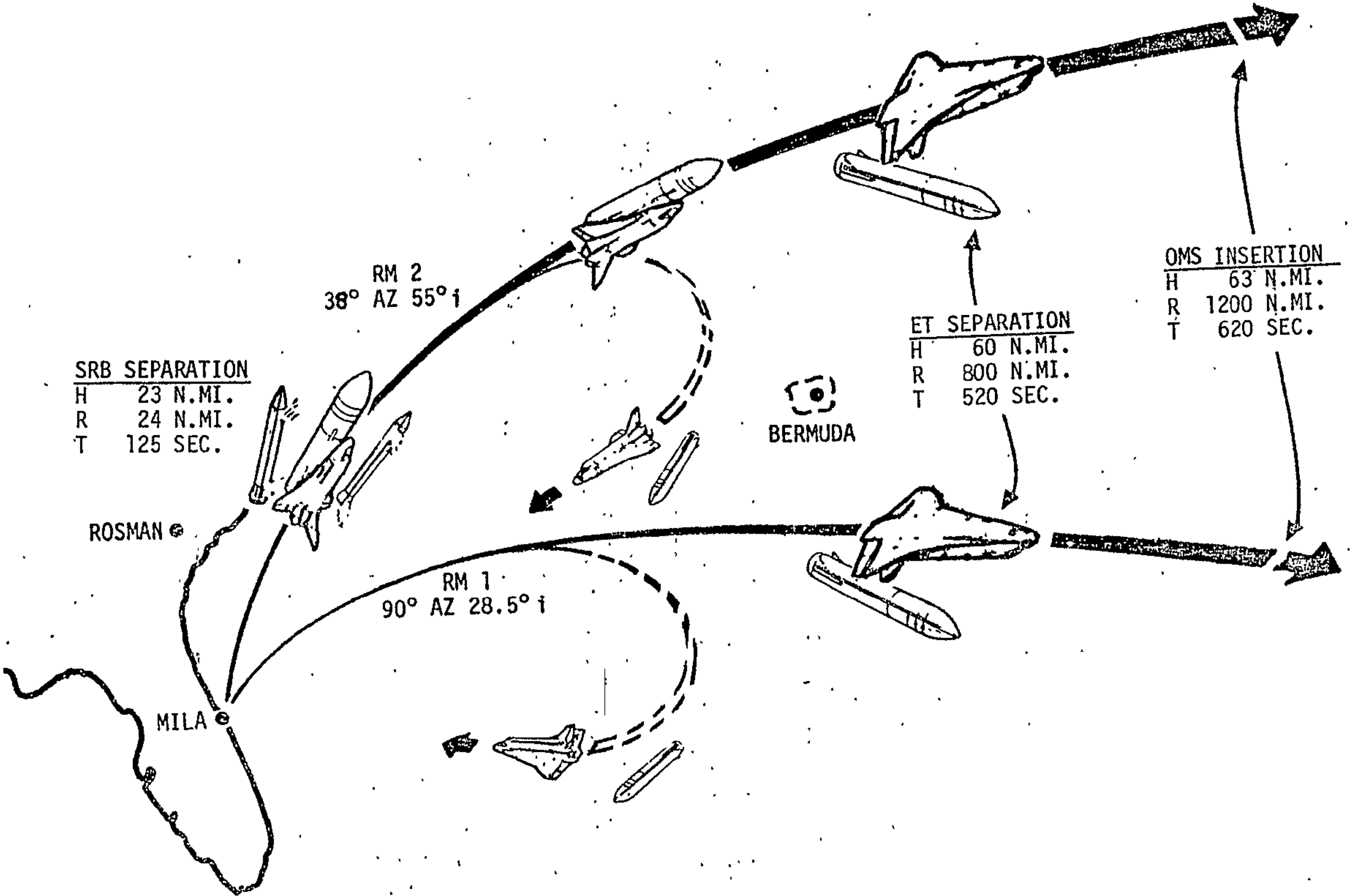

Figure 15. Shuttle Ascent Trajectories

520 seconds, which corresponds to an altitude of 60 nmi and a downrange distance of 800 nmi. Orbital insertion occurs at approximately 620 seconds, corresponding to an altitude of 63 nmi and a downrange distance of 1200 nmi.

3.3.2 Ground Station Availability

During early OFT (for an undetermined number of flights), the G-STDN stations at Mila (MIL) and Bermuda (BDA) will be available for communication support of the Shuttle during ascent. In addition, the Vanguard (VAN) tracking ship will be available. There is also a G-STDN station (ROS) at Rosman, North Carolina, which also could potentially provide some ascent coverage. The GBM station used for Apollo support has already been closed down and will not be available during the Shuttle time frame.

As illustrated in Figure 16, the Shuttle during ascent is within sight of MIL until approximately 450 seconds, corresponding to an altitude of 57 nmi and a downrange distance of 600 nmi. Also, Bermuda (BDA) could provide coverage from approximately 300 seconds through insertion for reference mission 1 and from about 426 seconds to 528 seconds for reference mission 2. ROS could provide about one minute of additional coverage over that using only MIL when the Shuttle launch azimuth is in a northerly direction, such as for reference mission 2. No additional coverage would be afforded for easterly launches. Present planning does not commit ROS for Shuttle support.

The Tracking and Data Relay Satellite System (TDRSS), according to current plans, will be an operational element of the STDN in time to support the fourth or fifth vertical flight of the Shuttle. The TDRSS will consist of two satellites (one over the Pacific Ocean at 171.37°W, the other over the Atlantic Ocean at 41.37°W) and one dedicated ground station at White Sands, New Mexico. Current planning is for the TDRSS to become fully operational by the fourth or fifth vertical flight of the Shuttle, and for most

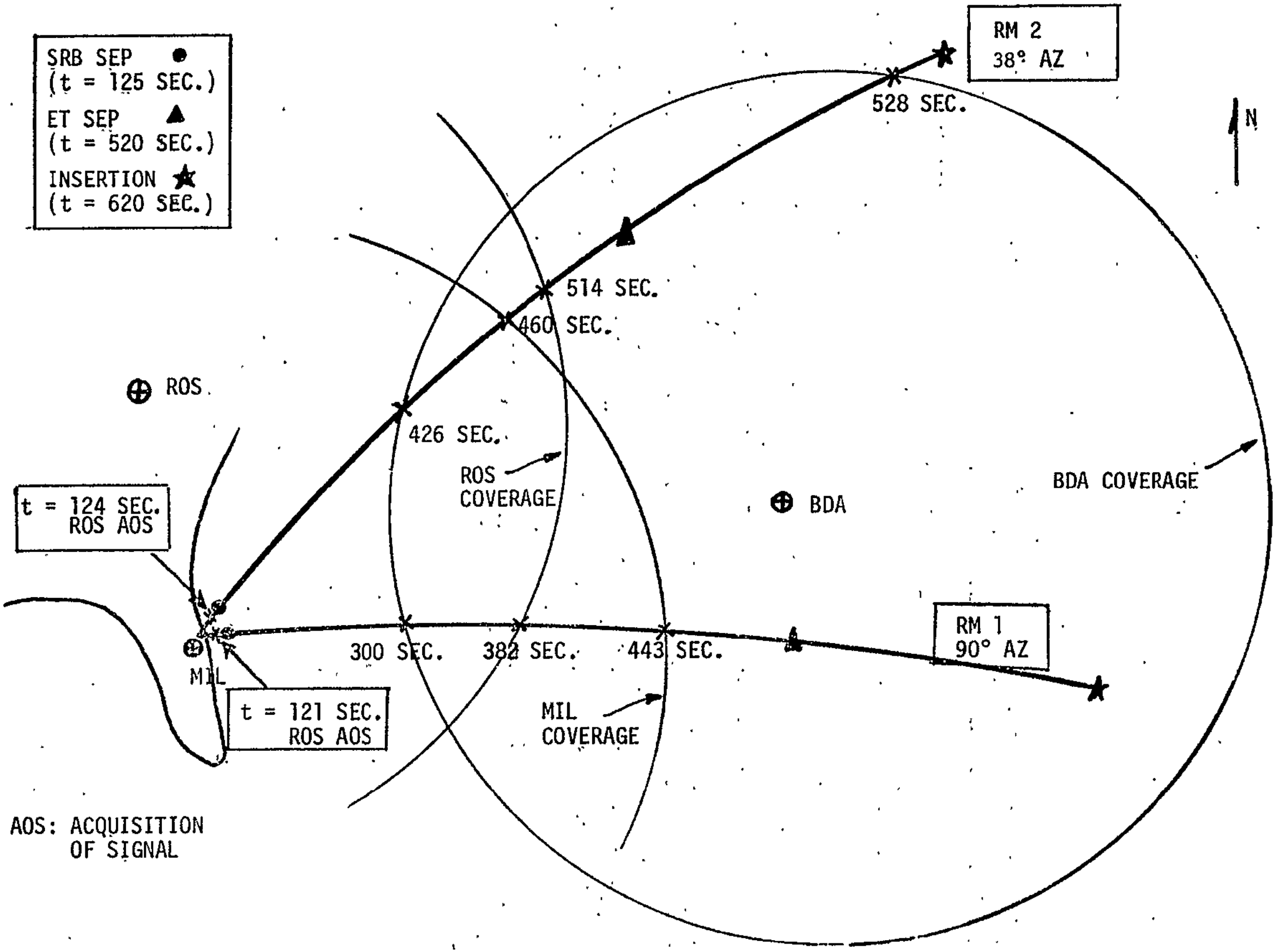

Figure 16. Potential Ground Station Coverage for Shuttle Ascent

of the G-STDN stations (including BDA and VAN) to be phased out of service. Thus, the S-band FM coverage available during ascent will be limited to that afforded by MIL since the TDRSS links are far too weak to support uncoded FM transmissions.

3.3.3 Ascent Signal Strength Calculations

Using the antenna pattern measurements described in Section 2.7, a set of signal strength calculations has been made for FM downlink communications. The results of the signal strength calculations are plotted versus time from liftoff in Figures 17 through 24, using MIL, VAN, BDA, and ROS as ground stations. VAN is assumed to be positioned at 28°N and 79°W to fill the period that the SRB plume blocks transmission to MIL, so Figures 17 through 24 do not consider the performance degradation due to the plume.

The main engine data circuit margins for MIL and BDA are shown in Figures 17 and 19 to vary from 57 dB to -3 dB for reference mission 1. The minimum margin is at 6 minutes from reference where BDA is not visible and MIL is at its minimum signal strength. For this case, there is a break in FM coverage for about 1 minute. The use of VAN at its present position does not help to improve this break in coverage. (If ROS should be configured for support of the FM link, however, then Figure 20 shows there is a minimum of 3 dB margin during the time MIL is approaching its minimum signal strength.)

For reference mission 2, the main engine data circuit margins for MIL and BDA are shown in Figures 21 and 23 to vary from 57 dB to 9 dB. The minimum margin is at 7 minutes from reference where BDA is not visible and MIL is at its minimum signal strength. Therefore, there is excellent coverage during ascent for this mission, except possibly during the plume period.

The problem of predicting the effects of rocket exhaust plumes on propagation of communications signals is a very difficult one. The problem

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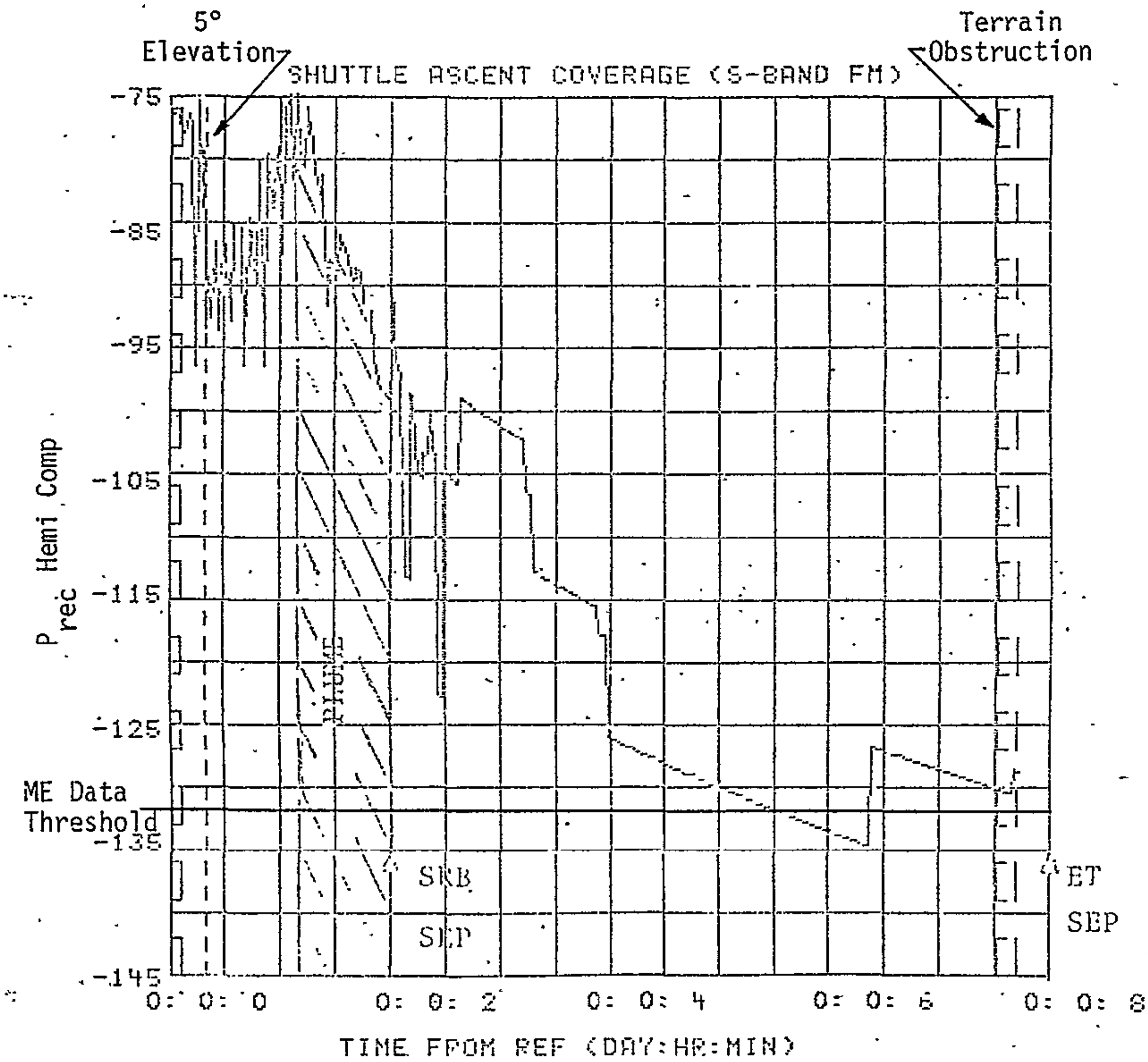

Figure 17. Signal Strength Measurements for Reference Mission 1 (Due East) at MIL

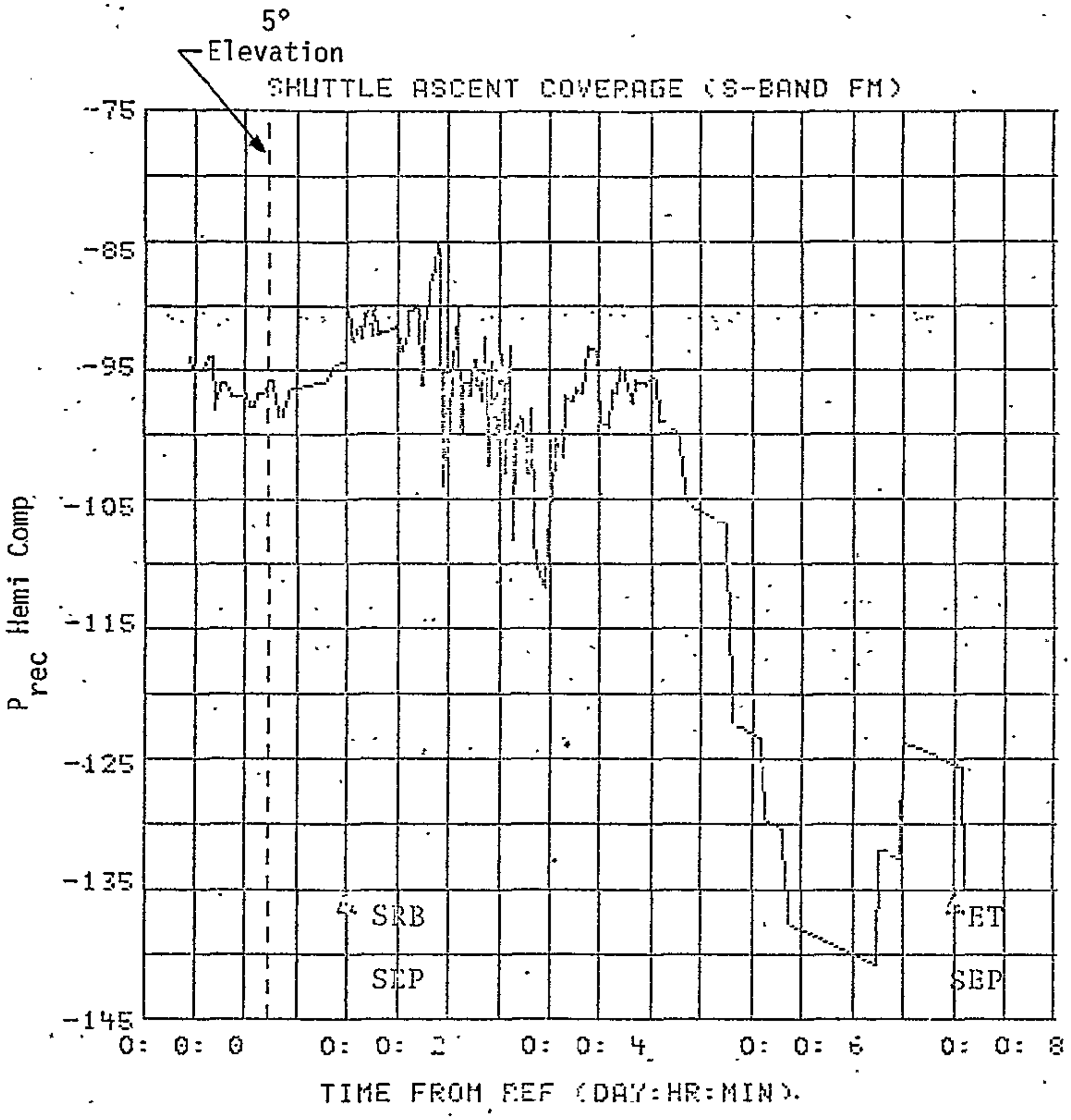

Figure 18. Signal Strength Measurements for Reference Mission 1 (Due East) at VAN

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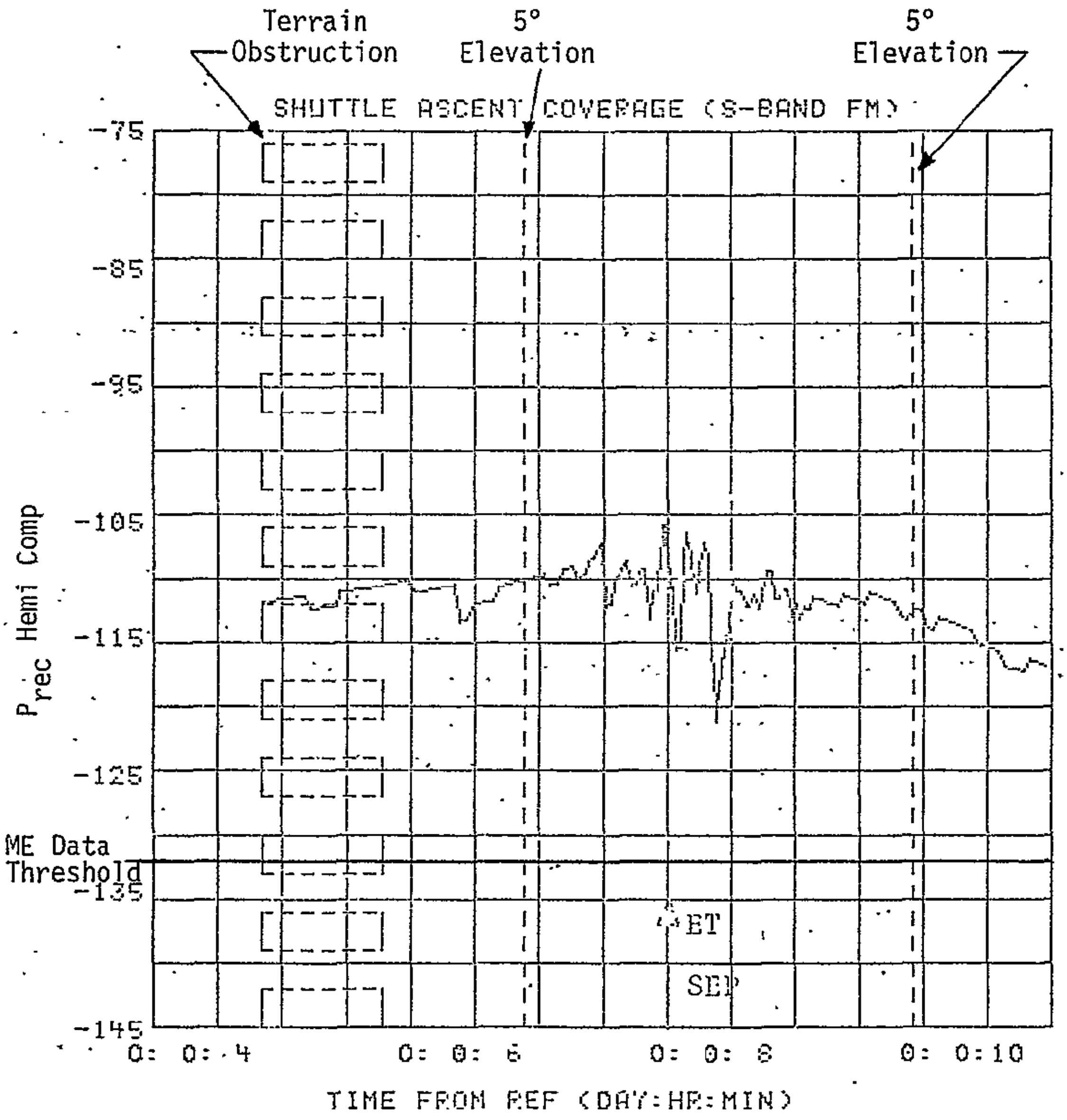

Figure 19. Signal Strength Measurements for Reference Mission 1 (Due East) at BDA

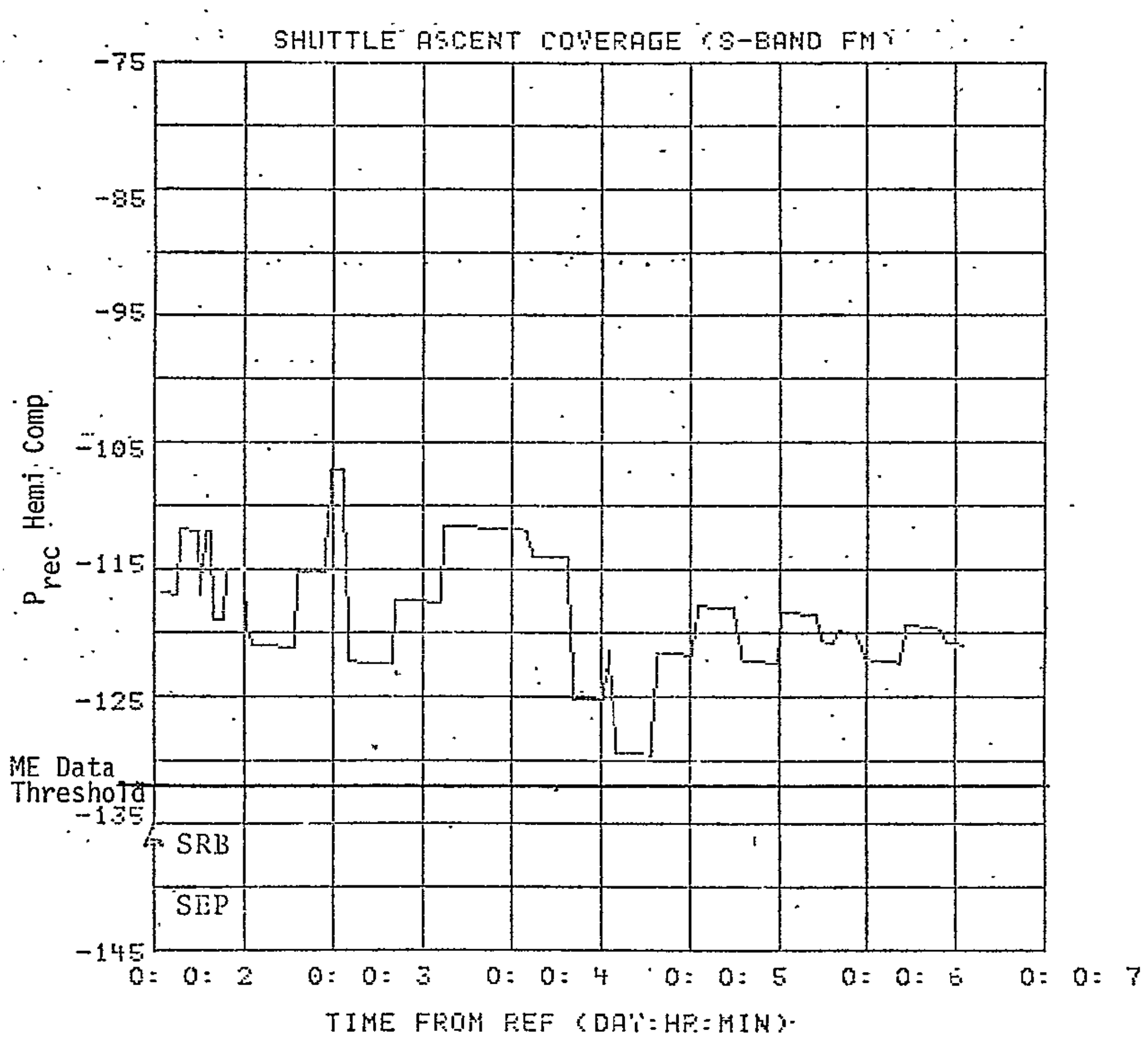

Figure 20. Signal Strength Measurements for Reference Mission 1 (Due East) at ROS

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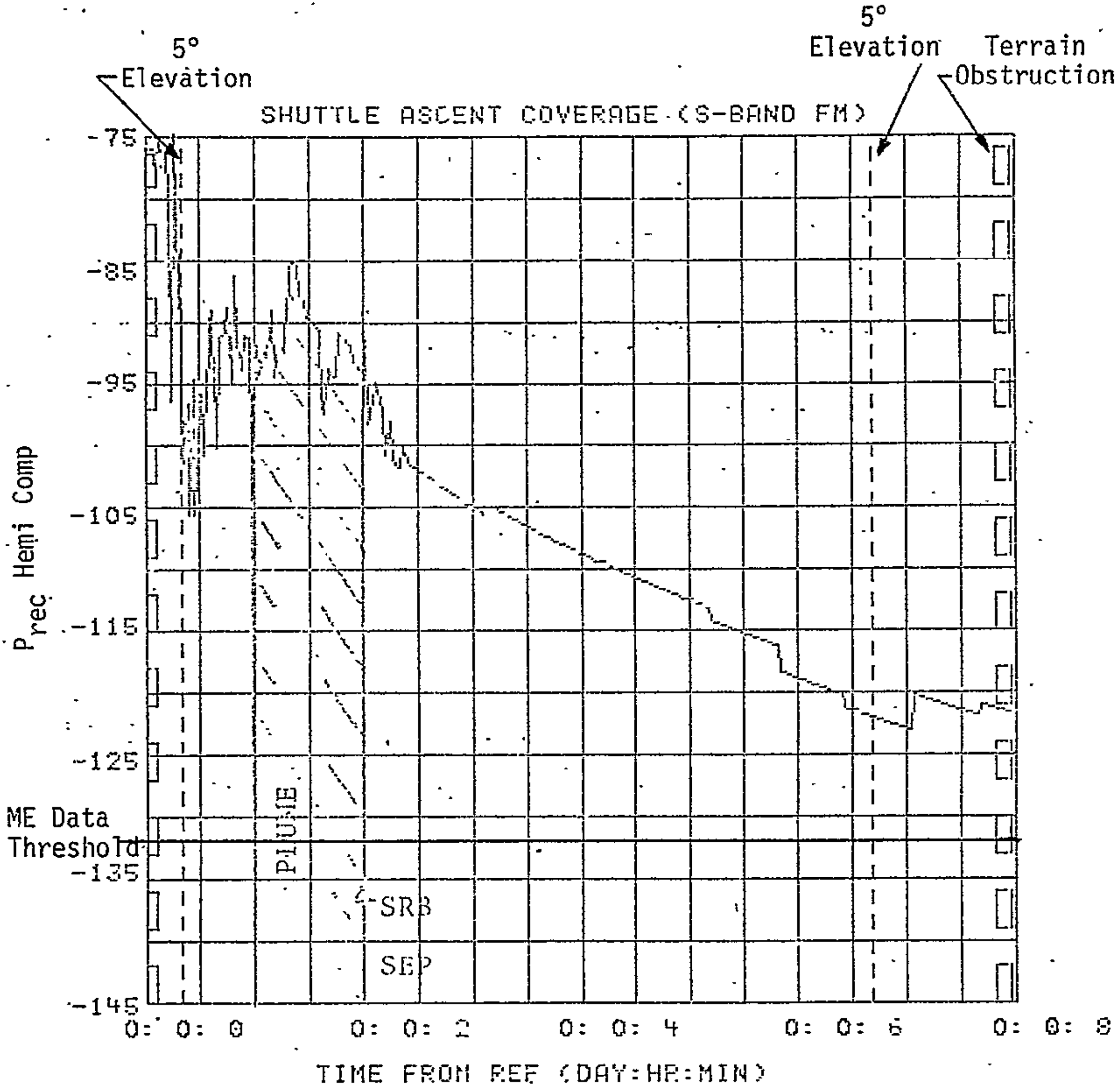

Figure 21. Signal Strength Measurements for Reference Mission 2 (37.88 Azimuth) at MIL

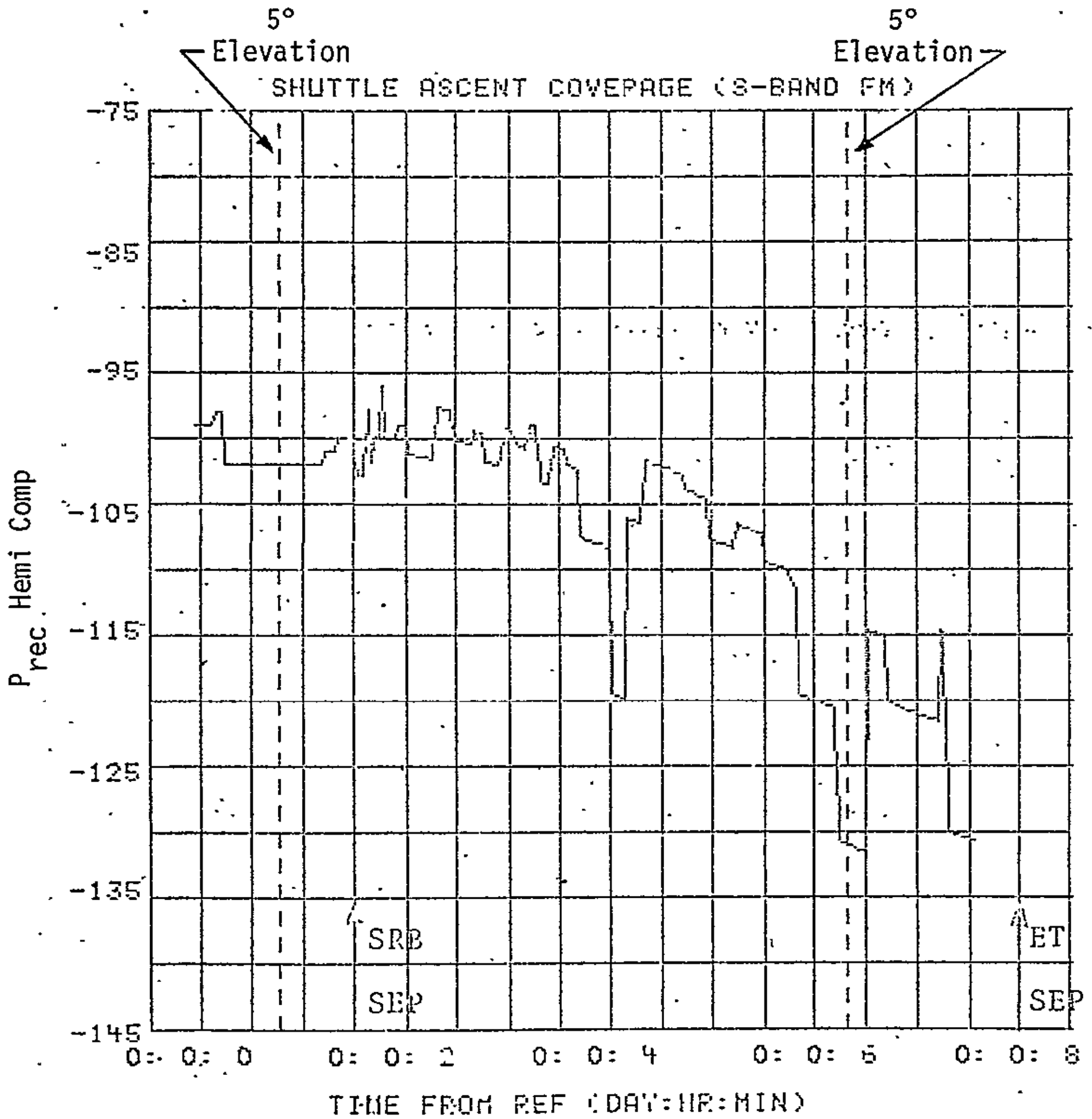

Figure 22. Signal Strength Measurements for Reference Mission 2 (37.88 Azimuth) at VAN

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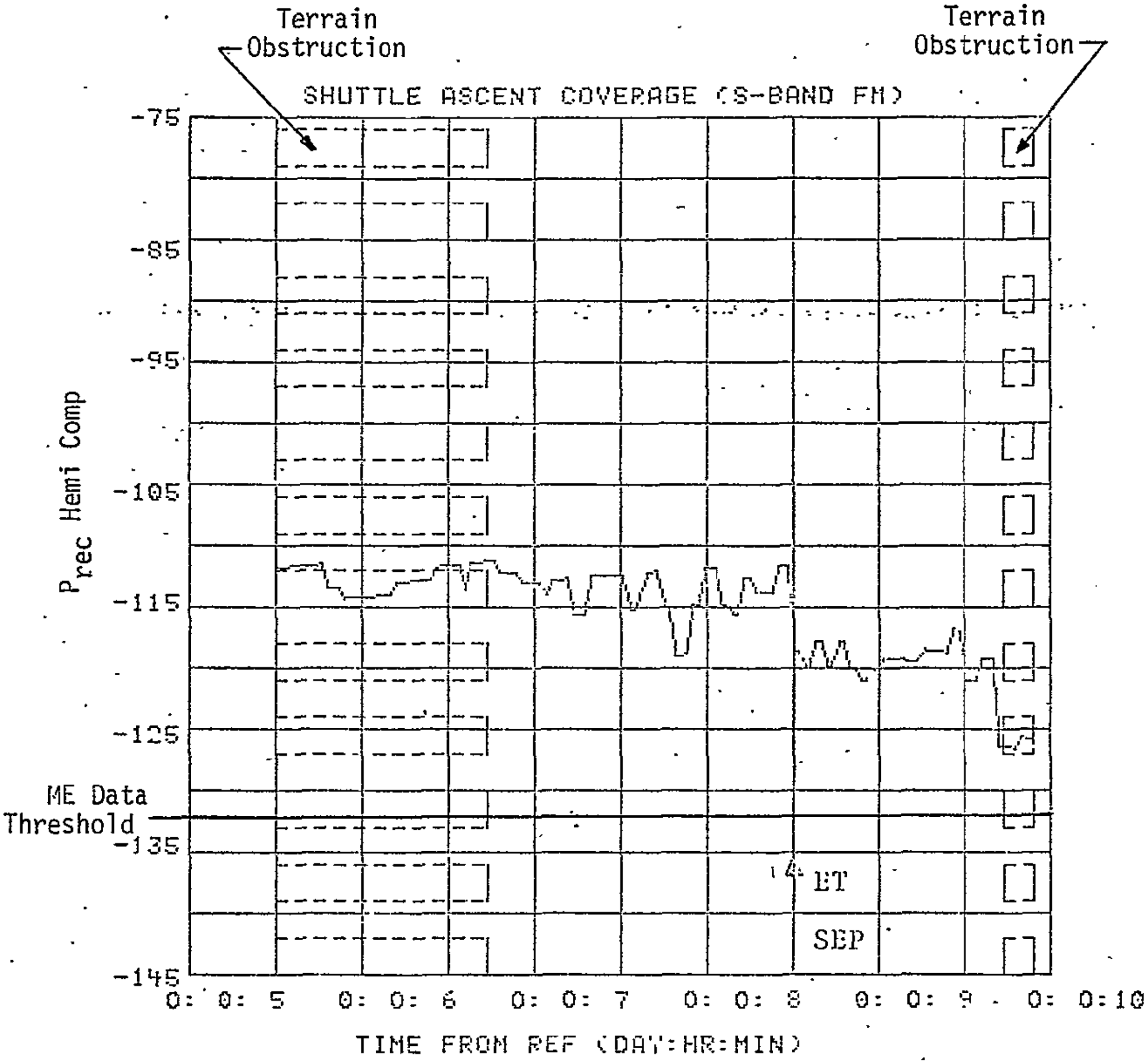

Figure 23. Signal Strength Measurements for Reference Mission 2 (37.88 Azimuth) at BDA

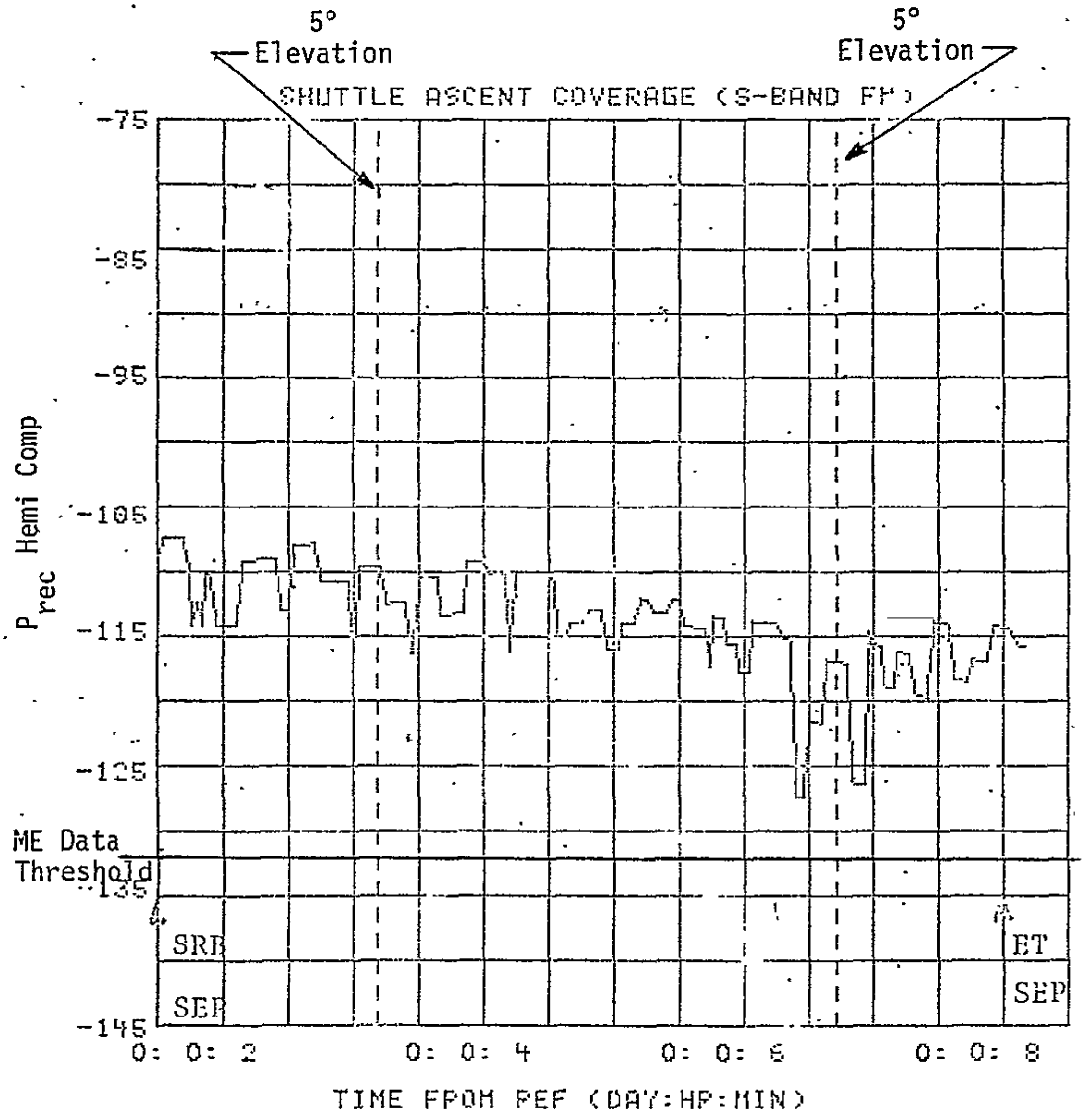

Figure 24. Signal Strength Measurements for Reference Mission 2 (37.88 Azimuth) at ROS

has a large number of variables; for example, signal attenuation turns out to be very sensitive to such things as minute variations of certain types of impurities in the propellant mixture. Many attempts at predicting plume attenuation effects by analysis for liquid-fuel rockets have been made—most have failed or have provided only crudely approximate results. The Shuttle case is much more difficult than the classical cases which have been studied, because:

1. There are two plumes to contend with (plus the main engine exhaust, which we are ignoring), rather than a single one.

2. The SRB engines use solid propellants and the resultant exhaust contains quantities of ionized metallic particles (sodium, potassium, and aluminum), which are byproducts of alkaline impurities inherent in the propellant mixture.

Even what should have been a relatively simple task, that of calculating the size of the SRB exhaust plume as a function of altitude, is extremely difficult due to the dependence on exact propellant composition. Therefore, some uncertainty exists as to when the line-of-sight from the various Orbiter antennas to MIL actually begin to pass through the SRB plumes.

From analysis of measured data for other programs utilizing solid rockets, signal attenuation of the order of 25 to 40 dB can be expected due to the plume. The main engine data circuit margin varies between 57 dB and 33 dB at MIL for reference mission 1 and between 47 dB and 35 dB for mission 2 during the period of estimated plume blockage. Therefore, there will likely be some FM communications for both missions 1 and 2 at MIL, even with the plume attenuation. While the main engine data threshold is not known exactly for VAN, because it has not yet been configured, it is clear that there will be a large margin. Thus, if VAN is used, the problem of plume blockage is completely eliminated.

4.0 ASSESSMENT OF ADEQUACY OF S-BAND FM LINK TO SAFETY REQUIREMENTS

The FM system design provides good margins in satisfying the link requirements presented in Section 2.0, except for three cases: (a) television, (b) the links to the SCF stations with 14-foot antenna diameters, and (c) G-STDN links during ascent.

The Orbiter-to-G-STDN S-band FM downlink television channel has a -2.3 dB margin. Changes in the system design will be required to improve this margin. Section 5.0 recommends a relatively simple change that provides a +0.2 dB margin. While this margin is not large, it is felt that the cable losses are very conservative and will be significantly reduced. Also, the required output signal-to-noise ratio of 35 dB is conservative. Therefore, it is recommended that a system design change be made to insure a positive margin but a large positive margin is probably not needed.

The high-rate payload data and the playback of OI and MSS data to SCF stations with 14-foot antenna diameters have very small positive or negative margins. It has been found, however, that there is only one remaining SCF 14-foot antenna and that is at the Greenland station. Note that the recommended change to the system design to improve the television channel will also adversely affect the margins for these data channels by about 0.8 dB. The circuit margins at the Greenland site can be made positive if the IF bandwidth is optimized as described in Appendixes A and B.

S-band FM communications during ascent is predicted to be generally good during early OFT for the cases examined (KSC launches with coverage afforded by MIL, VAN, and BDA), with the exception of one short period (~1 minute) during reference mission 1, which could possibly be covered by repositioning VAN, if desired. For those later missions in which the number of G-STDN stations is reduced due to the phasing in of TDRSS, FM coverage will be limited to that afforded by MIL. Performance using only MIL will be affected by the SRB plume, but the plume effect may turn out to be tolerable. In any event, the importance of FM communications during ascent is felt to be greatly reduced for later KSC launches. For DoD missions launched from Vandenberg AFB, the FM link may be required during ascent for relay of payload data, and hence its importance may be somewhat greater. Although no trajectory data was available to perform coverage analyses for Vandenberg launches, it is clear that some downrange station (or stations) will be required if the link is required throughout the ascent phase.

5.0 RECOMMENDATIONS

As described in Section 4.0, only one potentially real problem associated with the S-band FM link design is judged to warrant a system design change. It is recommended that the FM transmitter sensitivity (MHz/v) be increased such that the peak frequency deviation for television is changed from 4.5 MHz to 6.0 MHz. This recommended change will provide an increase of 2.5 dB in output signal-to-noise ratio and will thus increase the circuit margin from -2.3 dB to +0.2 dB. There will be a slight reduction (on the order of 1.0 dB) in threshold margin for the TV channel, due to a resulting increase in required predetection bandwidth, but this is considered acceptable because of the relatively high (3.0 dB) threshold margin. There will also be an effect for each of the other S-band FM services, due to the fact that the proposed increase in transmitter sensitivity will increase each of the other peak frequency deviations by the same ratio ($6/4.5 = 4/3$). This effect will be adverse for those channels which now have optimum Δf's, but will not drastically affect performance (the margins for these channels are relatively high, and the adverse effect should only be on the order of 1.0 dB).

Although only the single system design change noted above is proposed, the need for various activities has become apparent as a result of this study effort. It is suggested that the following actions be taken by NASA:

(a) Additional RF coverage analyses need to be made for Vandenberg AFB launches.

(b) If S-band FM coverage should potentially be required for the reentry/landing phase, then RF coverage analyses need to be made for landings at each of the various landing sites.

(c) If a more accurate assessment of SRB plume effects is desired (perhaps to facilitate preflight planning, to firm up requirements for VAN support, etc.), then plume loss measurements taken during one or more regularly scheduled SRB static firings would be highly desirable. These measurements could be used to provide a <u>bound</u> on the effects of the plume.

APPENDIX A

LOW DATA RATE FM LINK TEST REPORT

APPENDIX A

LOW DATA RATE FM LINK TEST REPORT*

1.0 INTRODUCTION

The Air Force has been assigned a data channel of the Shuttle FM Wideband Signal Processor which will operate in the 250 bps to 256 kbps range, with a split-phase data format and a frequency deviation of ± 635 kHz. The channel designated for NASA use will accommodate a range from 200 bps to 5 Mbps, with split-phase data and a ± 2.0 MHz frequency deviation. This appendix provides results of laboratory tests conducted with various data rates and frequency deviations using split-phase, to aid in establishing the ICD modulation specification.

Additional testing was performed for 1 Mbps NRZ data, in order to determine the performance of an FM link at a frequency deviation of ± 2.36 MHz.

2.0 TEST PROCEDURES

The test configuration shown in Figure 1 was used to determine system performance for the 200 bps split-phase FM link. The specified frequency deviations of ± 2.0 MHz and ± 635 kHz were achieved by varying the modulation voltage at the input to the FM transmitter. Predetection filtering was provided by either a 2.7 MHz or a 6.25 MHz IF filter. For the first test of the 200 bps link, a frequency deviation of ± 635 kHz and a 2.7 MHz IF filter were employed. During the second test, the IF filter was held at 2.7 MHz and the frequency deviation was increased to ± 2.0 MHz. Test 3 employed the 6.25 MHz IF filter and a frequency deviation of ± 2.0 MHz. System performance was measured with the aid of the bit error detector and was recorded as a function of total received power.

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*This appendix is extracted from Report EE7-75-209, Lockheed Electronics Company, Inc., October 1975.

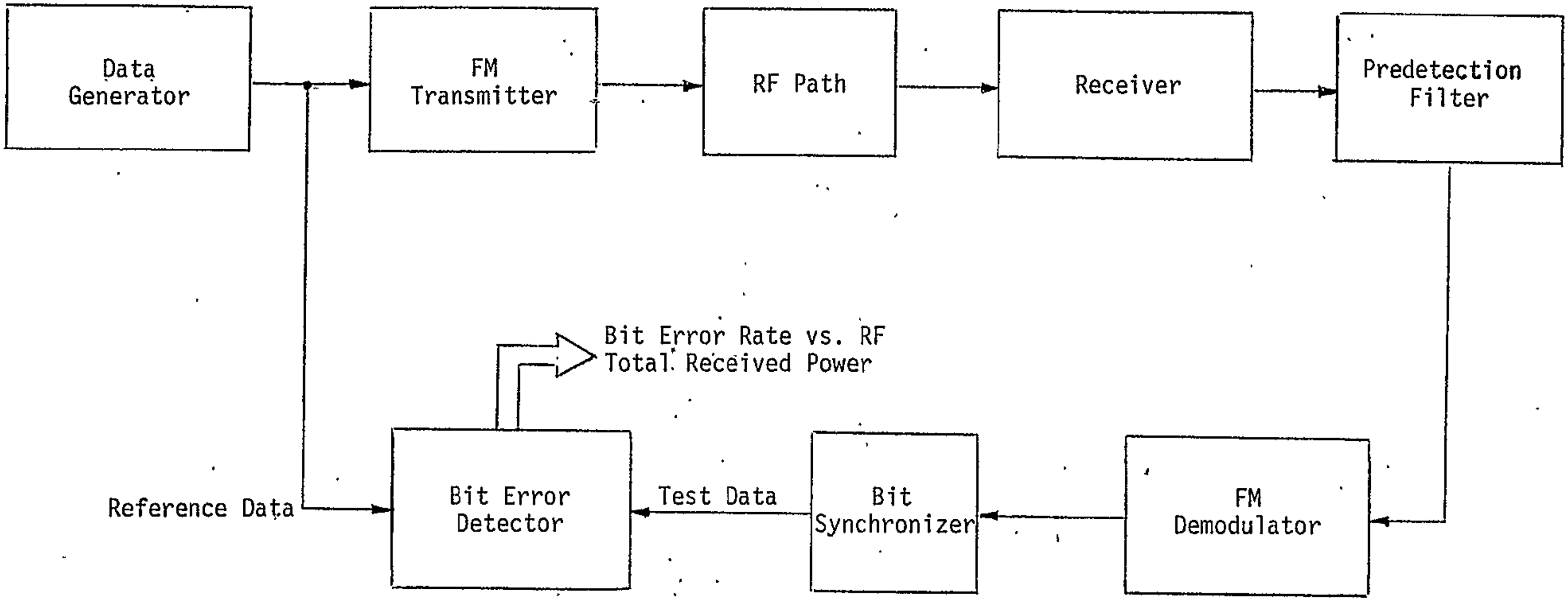

Figure 1. Bit Error Rate Test Configuration

An investigation was also conducted with NRZ data on the FM link at a data rate of 1 Mbps. These tests employed the specified frequency deviations of ± 2.36 MHz and ± 360 kHz, with various combinations of predetection filters. The frequency deviation of ± 360 kHz was first evaluated with 1.439 MHz and 6.25 MHz IF filters and the results were verified with the results from optimization tests previously performed. The frequency deviation was then changed to ± 2.36 MHz and the tests repeated.

3.0 TEST RESULTS

The test results obtained on the 200 bps FM link are shown in Figure 2. Test 1, which employed the 2.7 MHz IF filter, split-phase data, and frequency deviation of ± 2.0 MHz, required a total received power of -86.4 dBm to achieve a bit error rate of 1×10^{-4}. By increasing the IF bandwidth to 6.25 MHz, a 4 dB improvement in system performance was noted. Test 3 used the 2.7 MHz IF filter with a frequency deviation of ± 635 kHz and required a total received power of -93.4 dBm for a bit error rate of 1×10^{-4}.

Figure 3 shows an improvement of approximately 23 dB for the 200 bps data rate compared to a system operating at a rate of 1 Mbps with the same bandwidth and nearly identical deviations. Since the ratio of data rates is 5000 (37 dB), a much greater improvement might be expected. However, the bandwidth and deviation which were selected for the 1 Mbps data rate are not optimum for the lower rate. Additional improvement is likely to be obtained if these parameters are optimized.

The results obtained from the test conducted with ± 360 kHz frequency deviation and 1.439 MHz IF filter using NRZ data were compared with previously performed optimization tests, as seen in Figure 4. Performance proved to be within 0.2 dB of the earlier tests. The frequency deviation was then increased to the specified value of ± 2.36 MHz and, using the

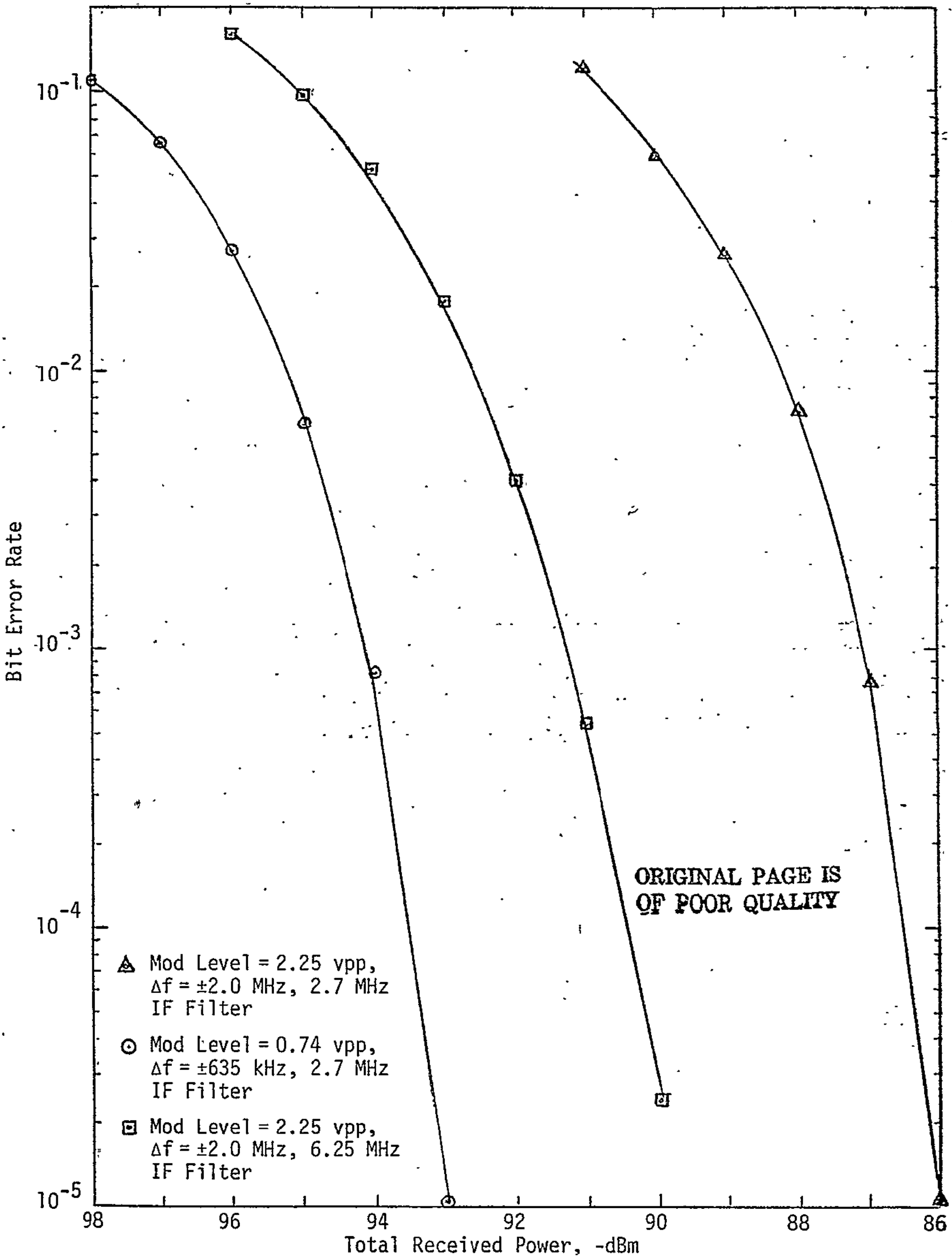

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Figure 2. Bit Error Rate vs. Total Received Power Using 200 bps, Split-Phase Data

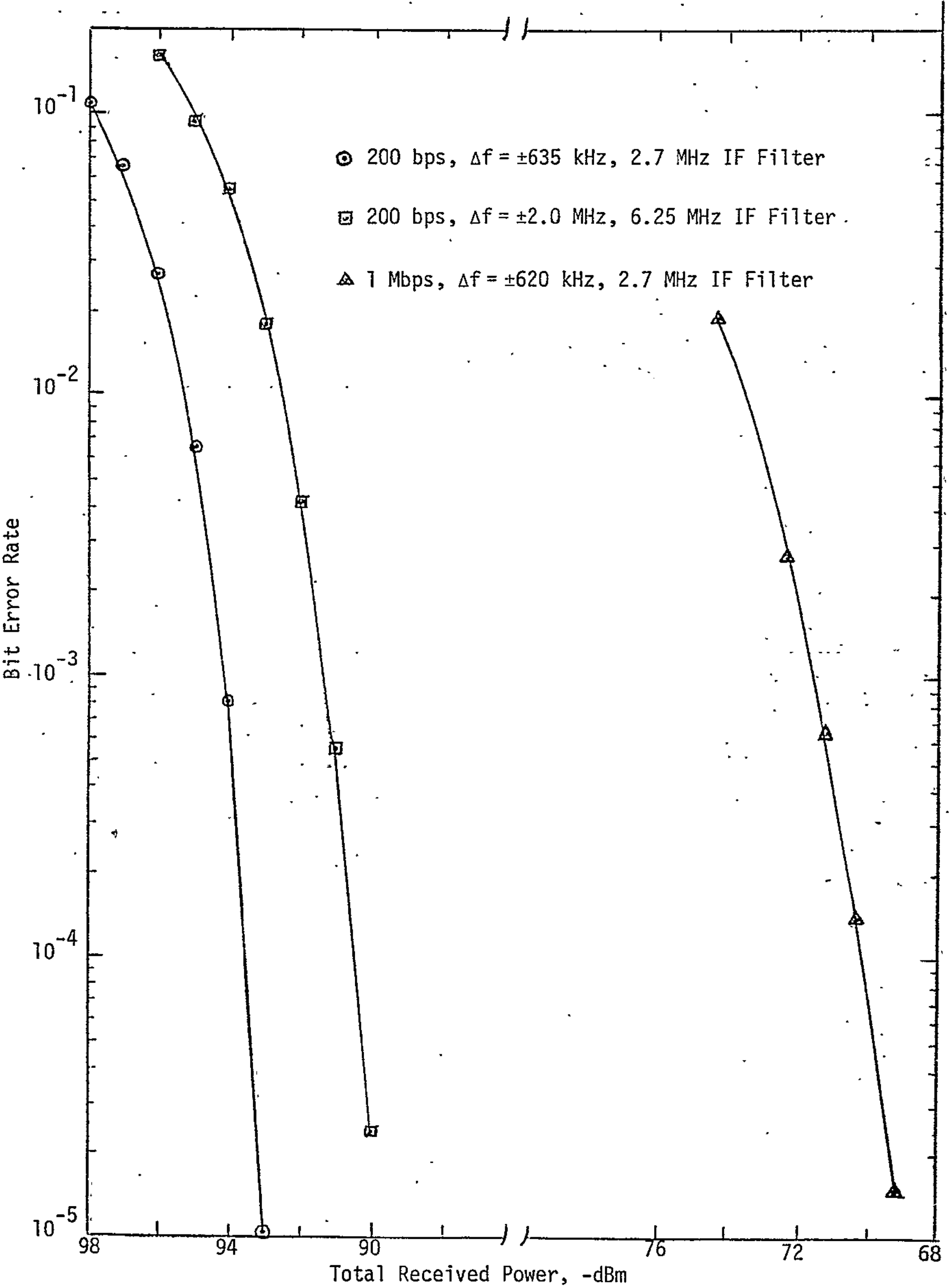

Figure 3. Bit Error Rate vs. Total Received Power Using 1 Mbps and 200 bps Split-Phase Data

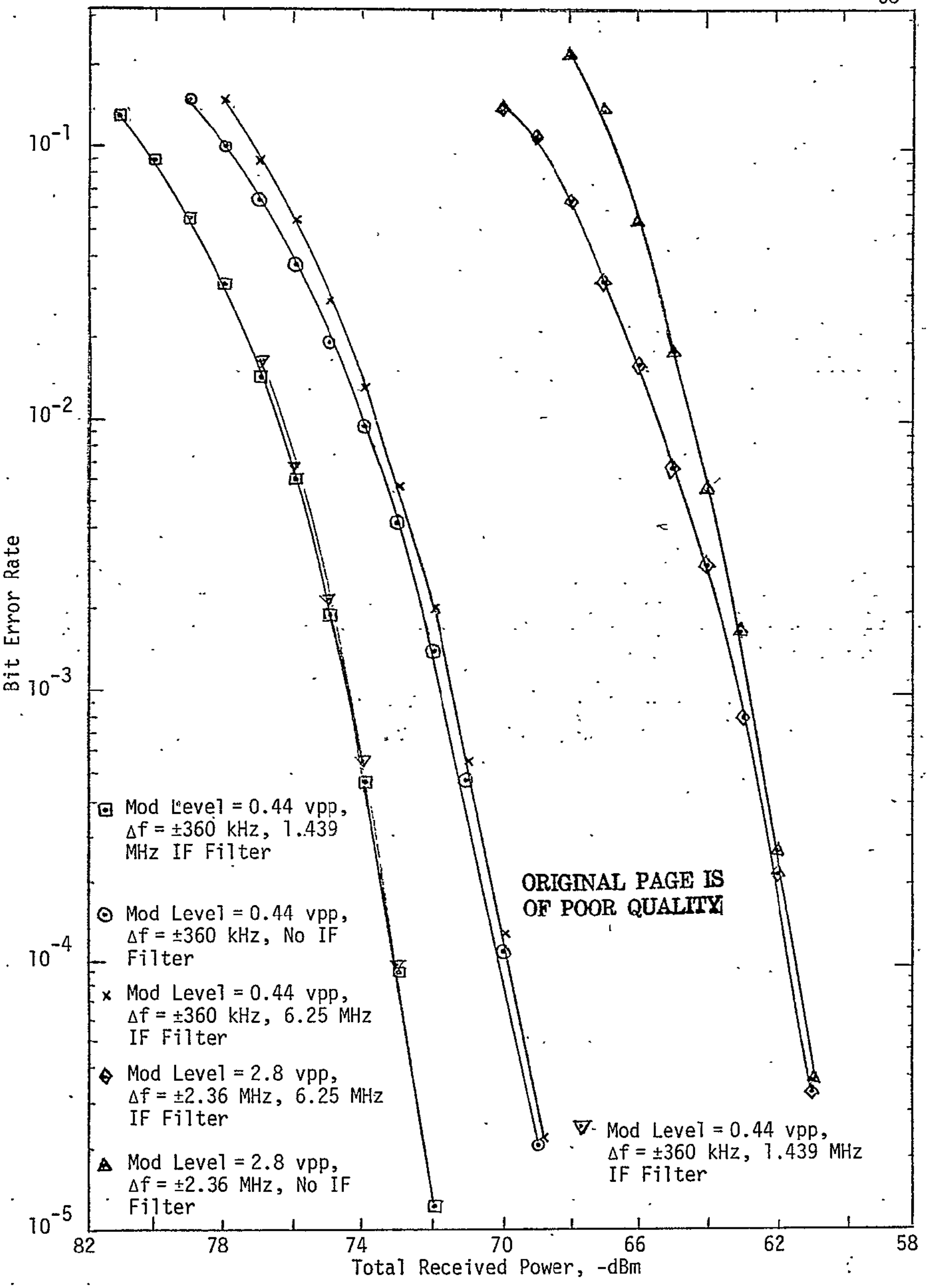

Figure 4. Bit Error Rate vs. Total Received Power Using 1 Mbps NRZ Data

6.25 MHz IF filter, a system performance degradation of 11.5 dB was observed. To determine whether the system was bandwidth limited, the 6.25 MHz filter was removed and the test was repeated with no IF filter. At a bit error rate of 10^{-4}, no significant difference was noted. A modulation level investigation using no IF filter was conducted to support this conclusion. Starting at a modulation voltage of 2.8 vpp, which produced a frequency deviation of ± 2.36 MHz, the modulation voltage was attenuated by various amounts up to 10 dB and then increased by 0.3 dB. The bit error rate was recorded as a function of modulation level, as shown in Table 1. The results show that the specified value of ± 2.36 MHz is, in fact, not the optimum frequency deviation.

4.0 SUMMARY AND CONCLUSIONS

Three primary tests were performed on the Low Data Rate FM Link. The first test, which employed a 2.7 MHz bandwidth IF filter and a frequency deviation of ± 635 kHz, resulted in a bit error rate of 1×10^{-4} for a total received power of -93.5 dBm (referenced to 1 milliwatt in 50 ohms). The frequency deviation was then increased to ± 2.0 MHz, while retaining the 2.7 MHz filter. This increase in frequency deviation caused a 7.0 dB degradation in system performance. Finally, while retaining the frequency deviation of ± 2.0 MHz, a 6.25 MHz IF filter was inserted, resulting in a bit error rate of 7.0×10^{-4} at a total received power of -90.4 dBm, still 3.1 dB worse than the lower deviation test.

An additional investigation was conducted with the FM link operating at a data rate of 1 Mbps, with a NRZ data format, at a frequency deviation of ± 2.36 MHz and using a 6.25 MHz IF filter. Test results revealed an 11.5 dB degradation in system performance, compared to the optimum conditions, which employ a 1.439 MHz IF filter and a frequency deviation of

Table 1. Modulation Level Investigation Summary

Modulation Input Voltage	Frequency Deviation	TRP-dBm	BER
*2.8 volts, peak-to-peak	±2.36 MHz	65.9	5.8×10^{-2}
Voltage Attenuated 0.3 dB	±2.28 MHz	65.9	2.8×10^{-2}
Voltage Attenuated 0.6 dB	±2.20 MHz	65.9	1.4×10^{-2}
Voltage Attenuated 1.0 dB	±2.10 MHz	65.9	5.1×10^{-3}
Voltage Attenuated 1.5 dB	±1.99 MHz	65.9	1.1×10^{-3}
Voltage Attenuated 2.0 dB	±1.87 MHz	65.9	2.7×10^{-4}
Voltage Attenuated 2.5 dB	±1.77 MHz	65.9	5.1×10^{-5}
Voltage Attenuated 3.0 dB	±1.67 MHz	65.9	2.0×10^{-5}
Voltage Attenuated 4.0 dB	±1.49 MHz	65.9	1.5×10^{-5}
Voltage Attenuated 5.0 dB	±1.33 MHz	65.9	1.2×10^{-5}
Voltage Attenuated 6.0 dB	±1.18 MHz	65.9	2.0×10^{-6}
Voltage Attenuated 10.0 dB	±746 kHz	65.9	1.0×10^{-7}
Voltage Increased 0.3 dB	±2.44	65.9	1.4×10^{-1}

*Deviated f_c ±2.36 MHz

± 360 kHz. Therefore, the ± 2.36 MHz frequency deviation is not an optimum condition for this data rate.

APPENDIX B

SHUTTLE FSK DATA LINK OPTIMIZATION TEST REPORT

APPENDIX B

SHUTTLE FSK DATA LINK OPTIMIZATION TEST REPORT*

1.0 INTRODUCTION

The proposed use of a wideband FM digital data link for Shuttle communications has prompted efforts directed at optimizing the performance of such a link. The peak frequency deviation (Δf) of the transmitted signal and the intermediate frequency filter bandwidth (B_{IF}) of the receiver are the parameters usually varied.

In particular, two reports dealing with the question of optimizing FM system performance suggest that a definite relationship exists between the bit rate and the optimum values of Δf and B_{IF} for a given system. Batson [1] concludes that, for an NRZ data format and matched-filter (coherent) detection of binary FSK data, a frequency deviation ratio (β) of 0.358 and a B_{IF} equal to or slightly greater than the bit rate will result in optimum performance. The basis for this selection of β is that the optimum system performance occurs when the correlation coefficient between the two FSK tones is at its most negative value. For β equal to 0.358, the value of the correlation coefficient is -0.22. Trumpis [2] presents a compilation of several studies that conclude, for a limiter-discriminator detection technique and NRZ-L data format, optimum FSK performance occurs with β equal to 0.35 and B_{IF} approximately equal to the bit rate. These reports conclude that, while the coherent detection scheme represents the optimum for FSK, the performance of the limiter-discriminator detection scheme is only about 0.2 to 0.4 dB worse than the theoretical optimum FSK performance.

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*This appendix is abstracted from NASA-JSC Internal Note JSC-09113, prepared by Lockheed Electronics Company, Inc., under Contract NAS9-12200, December 1974.

An earlier effort was made to obtain experimental results under laboratory conditions that would substantiate these proposed system parameters. The tests were performed using a split-phase data format and a threshold extension FM demodulator having a modulation tracking loop. The test report [3] concluded that additional testing was required to experimentally establish optimum parameters for the wideband digital FM channel. However, the data from these earlier tests tended to indicate that a β equal to approximately 0.75 provided the best performance and that a B_{IF} equal to the bit rate was inadequate for split-phase FM data reception.

Presented in this appendix are the results of the tests conducted to determine β and B_{IF} that result in optimum performance of a binary FSK data transmission system. Emphasis was placed on the use of split-phase data at 1.0 Mbps. However, split-phase data at 128 kbps and 256 kbps and NRZ-L data at 1.0 Mbps were also used. In all tests, the parameter used for the basis of data comparison is the bit error rate as a function of the total received power at the receiver input. A Microdyne Corporation Model 7100-SS(3) FM transmitter and a breadboard wideband FM receiver were used at an S-band frequency of 2272.5 MHz. The threshold extension FM demodulator (Motorola 50 MHz Demodulator) and Monitor Model 335 bit synchronizer were used throughout the test series. S-band spectrum photographs and calibration test data were obtained in addition to the bit error rate test data. All test data have been compiled in a data package [4].

2.0 DISCUSSION OF TEST RESULTS

Test results presented include equipment calibration data, equipment performance verification data, and bit error rate test data required for evaluation of the binary FSK data transmission system.

2.1 System Description

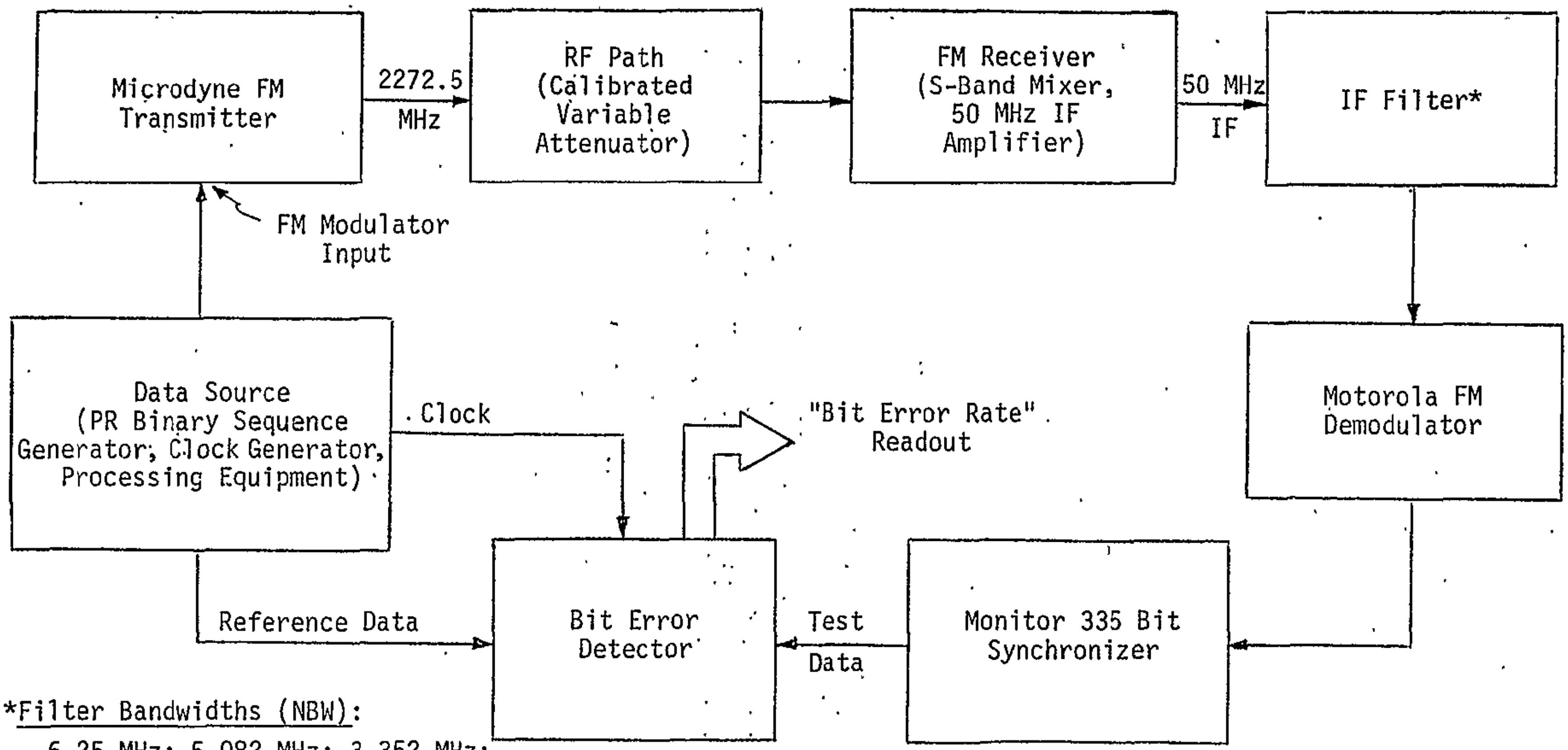
The binary FSK data transmission system was comprised of a data source, a FM transmitter, a calibrated radio frequency (rf) path, a wideband FM receiver, and data detection equipment. A block diagram of the system is shown in Figure 1.

2.1.1 Equipment Calibration

Equipment calibration data includes all test data recorded for the purpose of determining the transmitter modulator sensitivity, the rf path calibration, the receiver sensitivity, and IF filter bandwidth measurements. The transmitter modulator sensitivity, expressed as MHz per volts peak-to-peak, ranged from 0.787 at a sinewave frequency of 125 kHz to 0.998 at a sinewave frequency of 3.0 MHz. This information was used when adjusting the peak-to-peak voltage of the data signal into the modulator to provide a particular β. The seven-bit pseudorandom sequence, 1100101, was selected for the data signal.

A major objective of this program was to determine the effects of changes in system bandwidth on the bit error rate performance for various frequency deviations and bit rates. Therefore, a system frequency response was performed for the FM receiver with each IF filter installed. The filter characteristics are given in Table 1.

The unfiltered FM receiver noise bandwidth is 13.8 MHz centered at 48.90 MHz. The response peaks from 50.89 MHz to 51.89 MHz and is attenuated 0.2 dB at a frequency of 50.0 MHz. The measured carrier-to-noise ratio values were within measurement accuracy of the calculated values for the 6.25 MHz IF filter configuration. The 0 dB carrier-to-noise ratio values for each IF filter were as calculated.



*Filter Bandwidths (NBW):
6.25 MHz; 5.082 MHz; 3.352 MHz;
2.7 MHz; 1.439 MHz; 0.982 MHz;
0.447 MHz

Figure 1. Binary FSK Data Transmission System

Table 1. Intermediate Frequency Bandpass Filter Characteristics

Filter	Response at 50.00 MHz, dB	Peak. Response, MHz	3dB System Bandwidth, MHz	Equivalent Noise Bandwidth (System) MHz
6MHz MU-DEL	0	49.25 to 50.50	6.0	6.25
5MHz I-TEL	0	49.5 to 50.25	5.45	5.082
3MHz TEXSCAN	0	49.5 to 50.25	3.2	3.352
2.5MHz TRW	-0.1	50.2 to 50.4	2.7	2.7
1MHz TEXSCAN	0	49.8 to 50.0	1.37	1.439
1MHz TRW	-0.1	49.95	0.90	0.982
256kHz TEXSCAN	-0.5	49.82 to 49.88	0.420	0.447

2.1.2 Data Processing Equipment Performance

Data processing equipment, as referred to in this discussion, includes a Motorola 50 MHz FM demodulator and a Monitor Model 335 bit synchronizer. Tests to verify proper operation of this equipment were conducted under laboratory conditions. The performance of both pieces of equipment was well within previous performance levels and was concluded to be adequate for the FSK tests.

2.2 Bandwidth Requirements for 1.0 Mbps Data

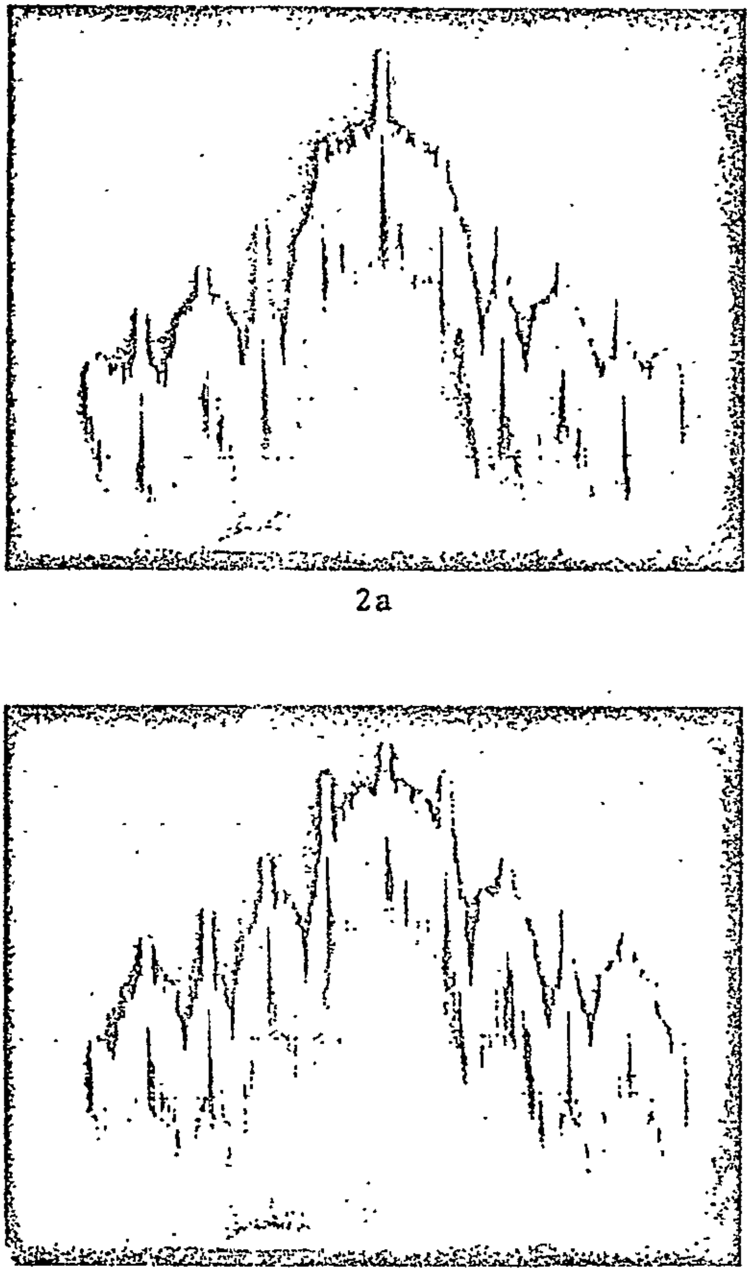
S-band spectrum photographs were taken at the output of the Microdyne FM transmitter for both split-phase and NRZ-L formats. Examples of these photographs are shown in Figures 2 and 3, respectively. A complete set of photographs are included in the Shuttle PCM/FM Test Data Package [4]. The bit rate was maintained at 1.0 Mbps and β was varied between 0.25 and 1.0 for both data formats. The following criteria were used in determining approximate bandwidth requirements from the spectrum photographs:

- Split-phase. Include first sideband clock components and all spectral components within 10 dB of the peak response of these sideband components.
- NRZ-L. Include all spectral components within 10 dB of the peak response.

These criteria were selected for ease of implementation and because of the need to allow adequate power for sufficient recovery of data.

2.2.1 Split-Phase Data Format

When applying the aforementioned criteria to the spectrum photographs, it was possible to determine a minimum bandwidth for which adequate clock component power would be recovered. For β of 0.5 through 1.0, the



2a

β = 0.36
Vertical: 10 dB/div
Horizontal: 1 MHz/div

2b

β = 0.62
Vertical: 10 dB/div
Horizontal: 1 MHz/div

Figure 2. FM Spectrum Photographs of 1.0 Mbps Split-Phase Data Format

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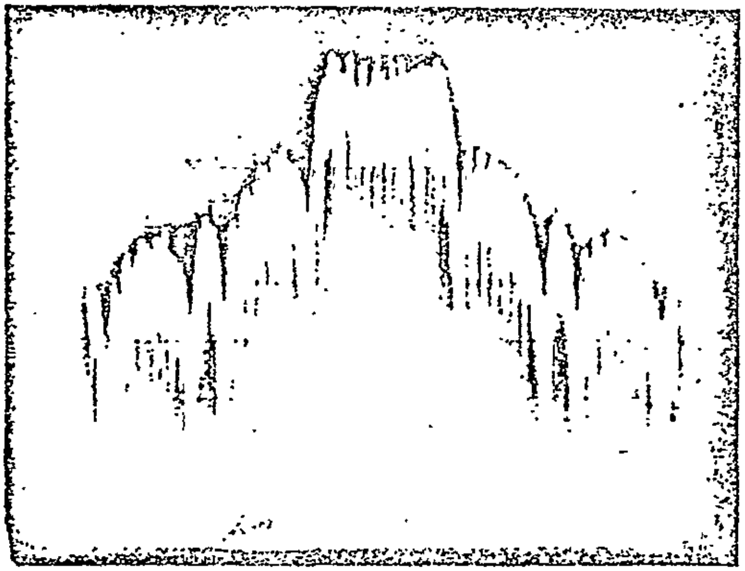
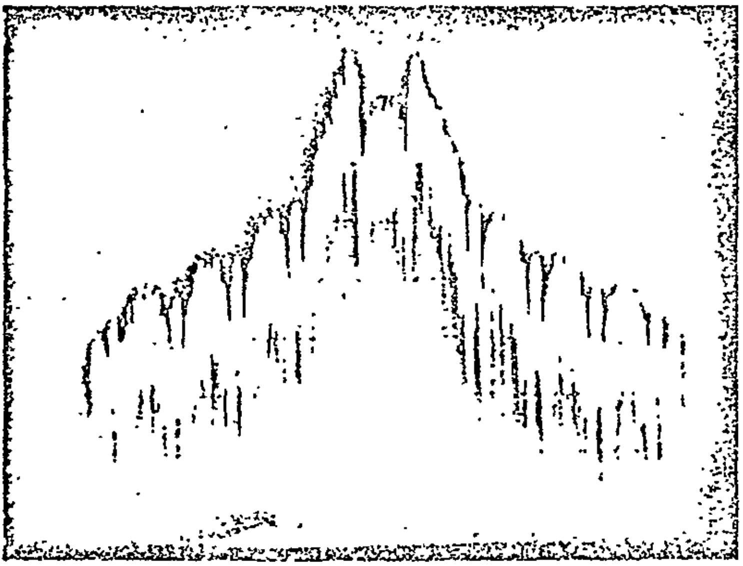


3a

β = 0.36
Vertical: 10 dB/div
Horizontal: 500 kHz/div



3b

β = 0.62
Vertical: 10 dB/div
Horizontal: 1 MHz/div

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Figure 3. FM Spectrum Photographs of 1.0 Mbps NRZ-L Data Format

minimum required bandwidth was determined to be approximately 2.3 MHz. For β of 0.25 and 0.36, additional bandwidth was required to include those components within 10 dB of the first sideband clock components. These approximate bandwidths are 2.7 MHz and 2.5 MHz, respectively. These results are presented in Table 2.

2.2.2 NRZ-L Data Format

The same technique in evaluating the photographs for split-phase data format was used for the NRZ-L data format case. The evaluation revealed that the approximate bandwidth requirement was slightly less than $(\beta + R)$ for β of 0.5 and less, and was slightly more than $(\beta + R)$ for β of 0.62 and higher. The results of this evaluation are also presented in Table 2.

2.3 FM Bit Error Rate Tests

Bit error rate tests were performed for the FSK data transmission system using split-phase data format at 1.0 Mbps, 128 kbps and 256 kbps, and NRZ-L data format at 1.0 Mbps. The values of β and B_{IF} that provided the best overall performance were determined for each set of conditions. An overall summary of the test results for split-phase data is presented in Figure 4.

2.3.1 1.0 Mbps Split-Phase Data

Using the criteria for bandwidth requirements discussed in Section 2.2 as an aid, bit error rate testing was performed whereby β was varied from 0.25 to 1.5 for each of several IF bandwidth conditions. Table 3 and Figure 5 show the total received power in dBm that resulted in a bit error rate of 1×10^{-4} for various values of β and B_{IF}.

It is evident that a β of 0.62 provides the best bit error rate performance of any β tested, regardless of IF filter used. As indicated by

Table 2. Approximate Two-Sided Bandwidth Required for 1.0 Mbps Binary FSK

β	Two Sided Bandwidth, MHz	
	Split-Phase	NRZ-L
0.25	2.7	1.1
0.36	2.5 (Fig. 2a)	1.3 (Fig. 3a)
0.5	2.3	1.4
0.62	2.3 (Fig. 2b)	2.0 (Fig. 3b)
0.75	2.3	2.4
0.865	2.3	2.4
1.0	2.3	2.6

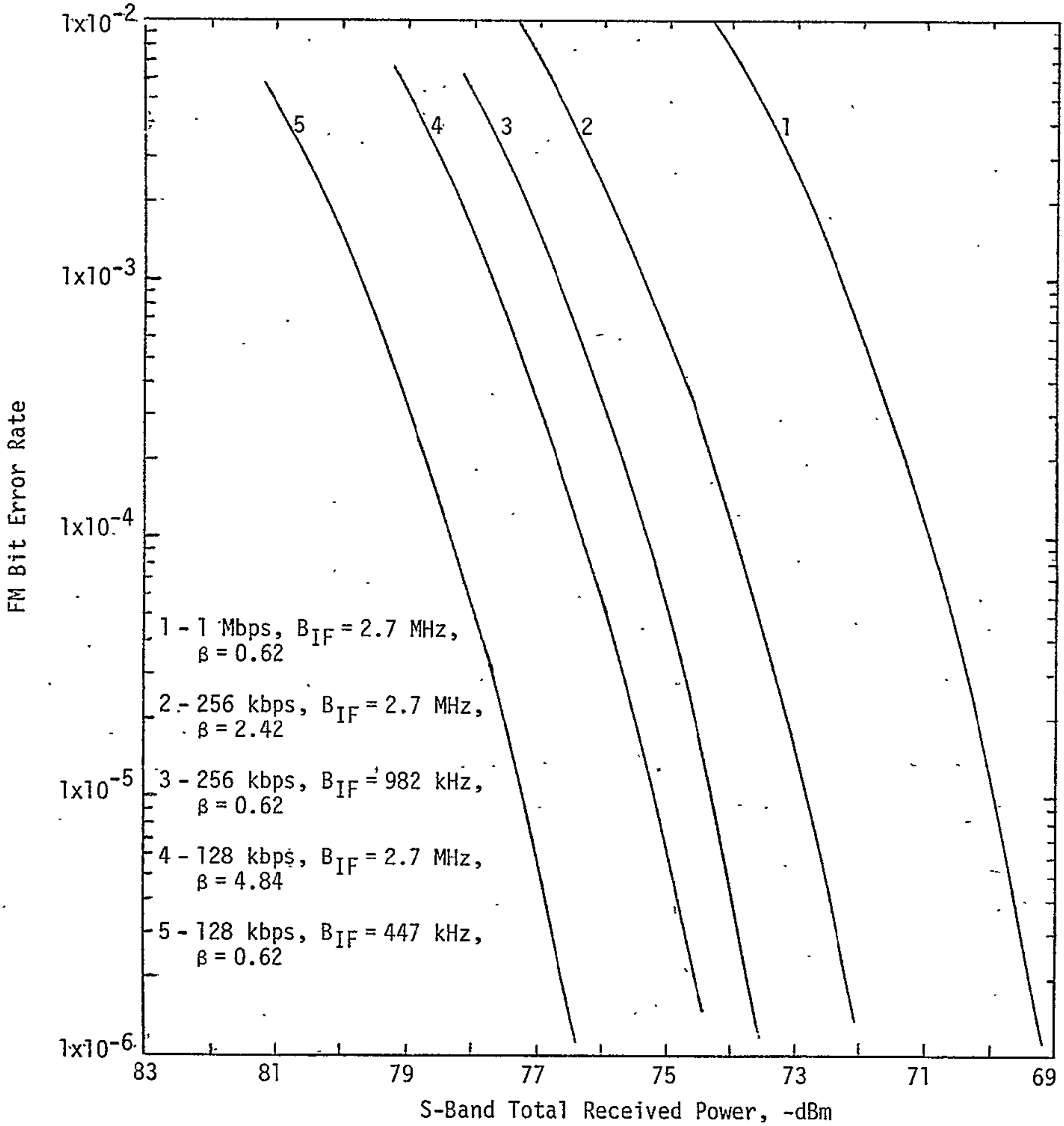

Figure 4. FM Bit Error Rate for Split-Phase Data as a Function of S-Band Total Received Power

Table 3. Binary FSK System Performance for 1.0 Mbps Split-Phase Data Format

β	Total received Power for 1×10^{-4} Bit Error Rate					
	IF Filter Equivalent Noise Bandwidth					
	Unfiltered 13.8 MHz	6.25 MHz	5.082 MHz	3.352 MHz	2.7 MHz	1.439 MHz
1.5	-68.1	-68.6	-67.9	-67.0	-67.2	-
1.0	-68.3	-68.3	-68.0	-68.7	-69.3	-59.8
0.865	-68.7	-68.7	-68.5	-69.2	-69.9	-63.9
0.75	-69.1	-69.1	-69.0	-69.7	-70.5	-67.6
0.62	-69.4	-69.4	-69.5	-70.2	-70.9	-69.4
0.5	-69.0	-69.1	-69.2	-69.9	-70.3	-68.0
0.36	-66.8	-67.0	-67.2	-67.7	-68.0	-65.5
0.25	-63.5	-63.7	-64.0	-64.4	-64.7	-62.2

⬚ Designates best performance in each row as a function of B_{IF} and in each column as a function of β.

▨ Designates best combined performance (β, B_{IF}).

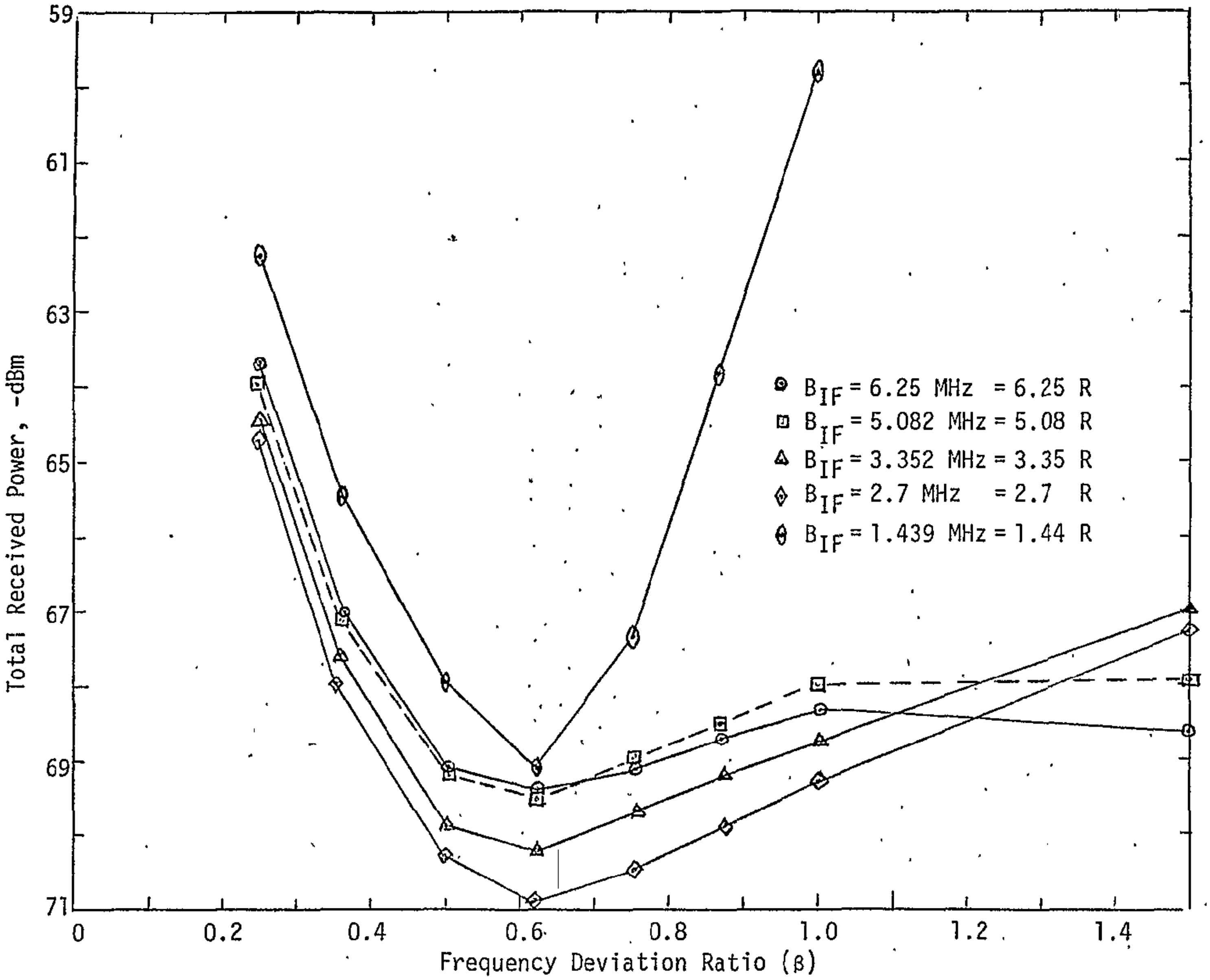

Figure 5. Total Received Power Required to Provide 1×10^{-4} Bit Error Rate for 1.0 Mbps Split-Phase Data as a Function of Peak Frequency Deviation

the symmetry of the curves in Figure 5, a β equal to 0.62 appears to be a near-optimum value.

The best combined performance for the 1.0 Mbps split-phase data, that is, β of 0.62 and B_{IF} of 2.7 MHz, is shown as Curve 1 of Figure 4. This same information is shown on Figure 6 (Curve 1) as a function of signal-to-noise ratio in the bit rate bandwidth (E_b/N_0) assuming an ideal bit synchonizer, that is, adjusting E_b/N_0 by the measured bit synchronizer degradation. At a bit error rate of 1×10^{-4}, the required E_b/N_0 for split-phase FSK was approximately 3.3 dB worse than theoretical optimum coherent PSK (11.7 dB versus 8.4 dB).

As expected, bandwidth limitation was most apparent with the 1.439 MHz B_{IF}. These results confirm the criteria of Section 2.2, and the data tend to indicate that a B_{IF} slightly less than 2.7 times the bit rate at a β of 0.62 will provide optimum bit error rate performance for split-phase data.

2.3.2 128 kbps Split-Phase Data

Bit error rate test results for a bit rate of 128 kbps and using a B_{IF} approximately equal to 3.5 times the bit rate indicate that the best performance occurred for the cases of β = 0.5 and β = 0.62. The total received power required for a bit error rate of 1×10^{-4} is shown in Table 4 as a function of β for B_{IF} of 447 kHz (≈3.5 R) and for B_{IF} equal to 2.7 MHz (optimum B_{IF} for 1.0 Mbps data rate). Curve 3 of Figure 6 shows the bit error rate as a function of E_b/N_0 for the best case test results (B_{IF} = 447 kHz, β = 0.62) and for an ideal bit synchronizer. At a bit error rate of 1×10^{-4}, the required E_b/N_0 was 5.5 dB worse than theoretical optimum coherent PSK (13.9 dB versus 8.4 dB). Somewhat better bit error rate performance would be expected if a narrower bandwidth (B_{IF} ≈ 2.5 R) had been

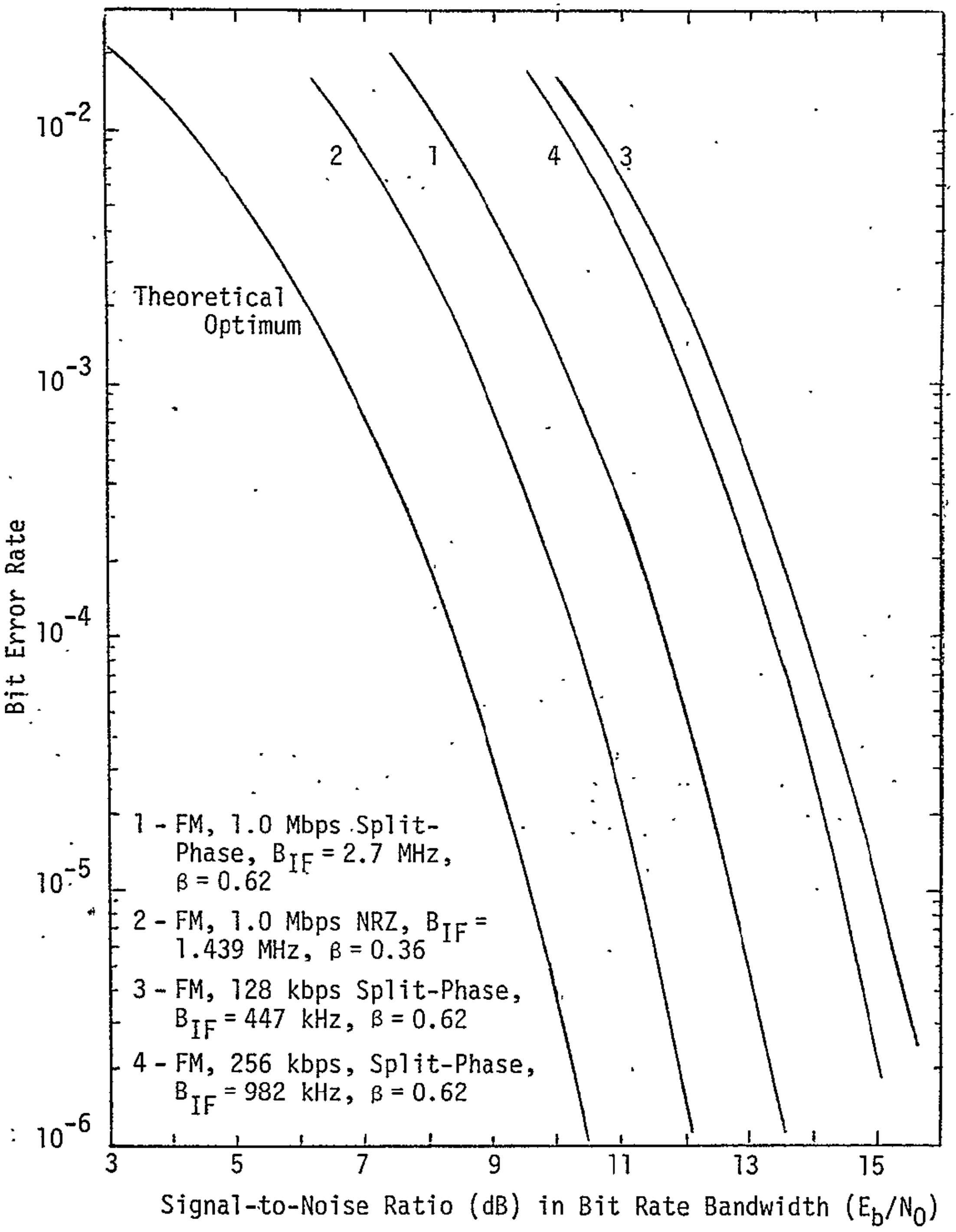

Figure 6. Bit Error Rate as a Function of Signal-to-Noise Ratio in Bit Rate Bandwidth (E_b/N_0)

Table 4. Binary FSK System Performance for 128 kbps Split-Phase Data Format

β	Total Received Power for 1×10^{-4} Bit Error Rate	
	IF Filter Equivalent Noise Bandwidth	
	447 kHz	2.7 MHz
1.5	-75.6	-74.4
1.0	-77.0	-72.8
0.865	-77.4	-72.8
0.75	-77.8	-72.8
0.62	⬚ -78.3	-72.8
0.5	▨ -78.5	-72.7
0.36	—	-70.9
3.9	—	-76.1
4.84	—	▨ -76.4
7.81	—	-76.0
9.69	—	-74.6

⬚ Designates best performance in each column as a function of β.

▨ Designates best combined performance (β, B_{IF}).

used. Based on the 1.0 Mbps results, this potential improvement should be about 1 dB.

As shown in Figure 4, the 128 kbps performance using the optimized 1.0 Mbps parameters (B_{IF} = 2.7 MHz, Δf = 620 kHz, β = 4.84 at 128 kbps) was only 2.0 dB worse than the best performance obtained at this lower rate. This is also over 5 dB better than the 1.0 Mbps performance. Thus, a single B_{IF} and Δf might be used for both high and low bit rate data in order to simplify the system design.

2.3.3 256 kbps Split-Phase Data

Bit error rate tests using a 256 kbps bit rate with a B_{IF} of 982 kHz yielded best performance for the cases of β = 0.5 and β = 0.62. These results are tabulated in Table 5, along with results obtained for a B_{IF} of 2.7 MHz. The best case results for both bandwidths are plotted in Figure 4, Curves 2 and 3. Curve 4 of Figure 6 shows the bit error rate as a function of E_b/N_0 for the best case test results (B_{IF} = 982 kHz and β = 0.62) and for an ideal bit synchronizer. At a bit error rate of 1×10^{-4}, the required E_b/N_0 was 5.0 dB worse than the theoretical optimum coherent PSK (13.4 dB versus 8.4 dB).

Results for the 1.0 Mbps bit rate discussed in Section 2.3.1 indicate that the 982 kHz B_{IF}, or 3.8 R, was wider than optimum. An improvement of about 1 dB could be expected if a B_{IF} of approximately 2.5 R, or 640 kHz, had been available for the 256 kbps data.

As shown in Figure 4, the 256 kbps performance obtained using the optimized 1.0 Mbps parameters (B_{IF} = 2.7 MHz, Δf = 620 kHz, β = 2.42 at 256 kbps) was only 1.4 dB worse than the best performance obtained at this lower rate. This is also 3 dB better than the 1.0 Mbps performance. Thus, we conclude

Table 5. Binary FSK System Performance for 256 kbps Split-Phase Data Format

β	Total Received Power for 1×10^{-4} Bit Error Rate	
	IF Filter Equivalent Noise Bandwidths	
	982 kHz	2.7 MHz
0.36	-72.8	-71.8
0.5	▨ -75.3	-73.0
0.62	▨ -75.3	-73.1
0.72	⬚ -75.1	-72.8
0.75	-74.9	-72.8
0.865	-74.6	-72.6
1.0	-74.1	-72.5
1.5	-74.5	-73.5
1.95	—	▨ -74.1
2.42	—	⬚ -73.9

⬚ Designates best performance in each column as a function of β.

▨ Designates best combined performance (β, B_{IF}).

that the system might be optimized for the 1.0 Mbps rate and still perform well at the lower rates.

2.3.4 1.0 Mbps NRZ Data

Bit error rate tests were performed with β varied from 0.25 to 1.0 for each of several IF bandwidth conditions. Table 6 and Figure 7 show the total received power that results in a 1×10^{-4} bit error rate for various β and B_{IF} values.

It is apparent that a β of 0.36 provides the best bit error rate performance of any β tested, regardless of IF filter used. The best overall performance was the result of using the 1.439 MHz B_{IF} along with a β of 0.36. Curve 2 of Figure 6 depicts these results in terms of bit error rate versus E_b/N_0, assuming an ideal bit synchronizer. At a bit error rate of 1×10^{-4}, the required E_b/N_0 for NRZ FSK is approximately 1.9 dB worse than theoretical optimum coherent PSK (10.3 dB versus 8.4 dB). The best performance as a function of B_{IF} and β shown in Table 6 and Figure 7 confirms the bandwidth criteria of Section 2.2. These results generally agree with the analysis of Batson [1] and Trumpis [2] for optimum β when NRZ-L data is transmitted, but tend to indicate somewhat greater bandwidths are required for optimum performance. In particular, the abovementioned references indicate that an IF bandwidth of 1.0 R (or slightly greater) should minimize error probability for binary FSK systems employing discriminator detection. The nearest filter bandwidths available for testing were 0.98 R and 1.44 R. Results with the 1.44 R filter were 2.2 dB better than for the 0.98 R filter. A comparison of results for all filters tested, shown in Figure 7, indicates that 1.44 R (or slightly greater) values of B_{IF} should yield the best performance.

As shown in Figure 6, Curve 2, an optimized NRZ FM PCM channel performs about 1.5 dB better than an optimized split-phase FM PCM channel.

Table 6. Binary FSK System Performance for 1.0 Mbps NRZ-L Data Format

β	Total Received Power for 1×10^{-4} Bit Error Rate IF Filter Equivalent Noise Bandwidth					
	6.25 MHz	5.082 MHz	3.352 MHz	2.7 MHz	1.439 MHz	.982 MHz
0.25	-67.1	-68.4	-69.6	-69.8	-71.4	-69.3
0.31	—	-69.7	—	—	—	—
0.36	-70.3	-70.3	-71.5	-71.7	-73.1	-70.9
0.5	-70.2	-70.1	-71.1	-71.3	-72.0	-69.7
0.62	-69.7	-69.7	-70.6	-70.7	-70.2	-65.7
0.75	-69.0	-69.1	-69.8	-69.9	-67.5	—
0.865	-68.4	-68.5	-69.1	-69.1	-65.1	—
1.0	-67.8	-67.7	-68.2	-68.2	-56.7	—

⬚ Designates best performance in each row as a function of B_{IF} and in each column as a function of β.

▨ Designates best combined performance (β, B_{IF}).

C-2

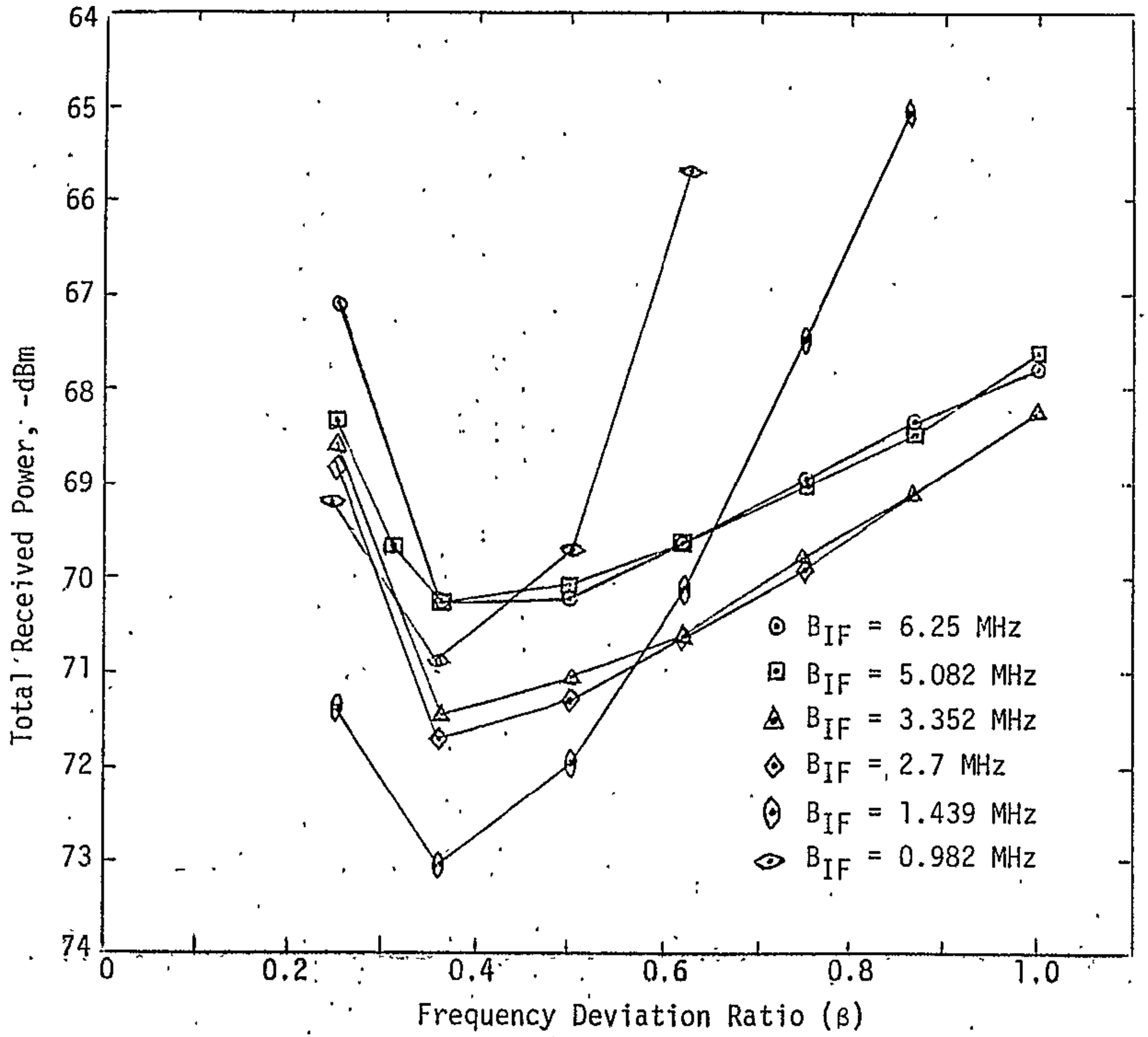

Figure 7. Total Received Power Required to Provide 1×10^{-4} Bit Error Rate for 1.0 Mbps NRZ-L Data as a Function of Frequency Deviation Ratio

3.0 CONCLUSIONS

Extensive testing of a binary FSK system using 1.0 Mbps split-phase data indicates that the best overall performance can be obtained with a modulation index of 0.62 and IF bandwidth of 2.7 MHz. Additional tests at 128 kbps and 256 kbps indicate a similar conclusion, that is, best performance should occur with modulation index of 0.62 and IF bandwidth about 2.5 times the bit rate. Measured results for the optimized 1.0 Mbps bit rate were within 3.6 dB of an ideal PSK system at a bit error rate of 1×10^{-4}.

The best case modulation index of 0.62 corresponds to a peak frequency deviation of 620 kHz at a 1.0 Mbps split-phase bit rate. When the lower bit rates were run with this same 620 kHz peak frequency deviation and using the 2.7 MHz IF bandwidth (optimum for 1.0 Mbps), the bit error rate performance degraded from the optimized conditions by 1.0 to 2 dB, but still remained superior to 1.0 Mbps performance by 3 to 5 dB at the 1×10^{-4} bit error rate. Consequently, a system optimized for the higher bit rate, and providing adequate performance at that rate, could be expected to perform satisfactorily at the lower rates while still using the same peak frequency deviation and receiver bandwidth.

Tests of the FSK system using 1.0 Mbps NRZ-L data indicated that the best overall performance occurred with the use of a β of 0.36 and B_{IF} of 1.439 MHz. For these parameters, the FSK system performance was 1.9 dB worse than an ideal PSK system when operating at a bit error rate of 1×10^{-4}. These results confirm the optimum modulation index of 0.36 predicted by Batson [1] and Trumpis [2] but tend to indicate a somewhat greater optimum bandwidth than the predicted value of 1.0 to 1.2 times the bit rate.

4.0 REFERENCES

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APPENDIX C

DEVELOPMENT FLIGHT INSTRUMENTATION (DFI) LINK

APPENDIX C

DEVELOPMENT FLIGHT INSTRUMENTATION (DFI) LINK

In addition to the operational C&T interface links, an SSO-to-STDN S-band DFI link is provided to transmit telemetry consisting of one PCM channel and 15 FM subcarrier channels during Orbital Flight Tests (OFT).

1.0 FUNCTIONAL DESIGN

Figure 1 shows a functional interface configuration for this link. The 128 kbps DFI PCM data in a bi-phase-L (Manchester II) format phase-shift-keys (PSK) the 1.024 MHz subcarrier prior to frequency-division multiplexing with the 15 FM subcarrier channels. The multiplexed composite signal is then used to frequency modulate the 2205.0 MHz carrier before being power amplified and radiated from the antenna. At the ground station, an FM carrier demodulator in series with a 1.024 MHz subcarrier demodulator is used to convert the DFI RF signal to the 128 kbps baseband signal, which is then detected by the bit synchronizer. For the 15 FM subcarrier channels, the baseband signals are restored after the output of the FM carrier demodulator is processed through 15 subcarrier FM demodulators.

2.0 DATA CHARACTERISTICS

2.1 PCM Channel

The data content of the 128 kbps DFI PCM channel includes SSO status, housekeeping information, and instrumentation-related data. The frame structure is the same as the PCM frame format shown in Figure 4, page 10.

2.2 FM Subcarrier Channels

For the 15 FM subcarrier channels, there are 7 channels with 500 Hz frequency response, 7 analog channels with 2000 Hz response, and 1 digital bi-phase-L channel with 12 kbps external tank PCM data.

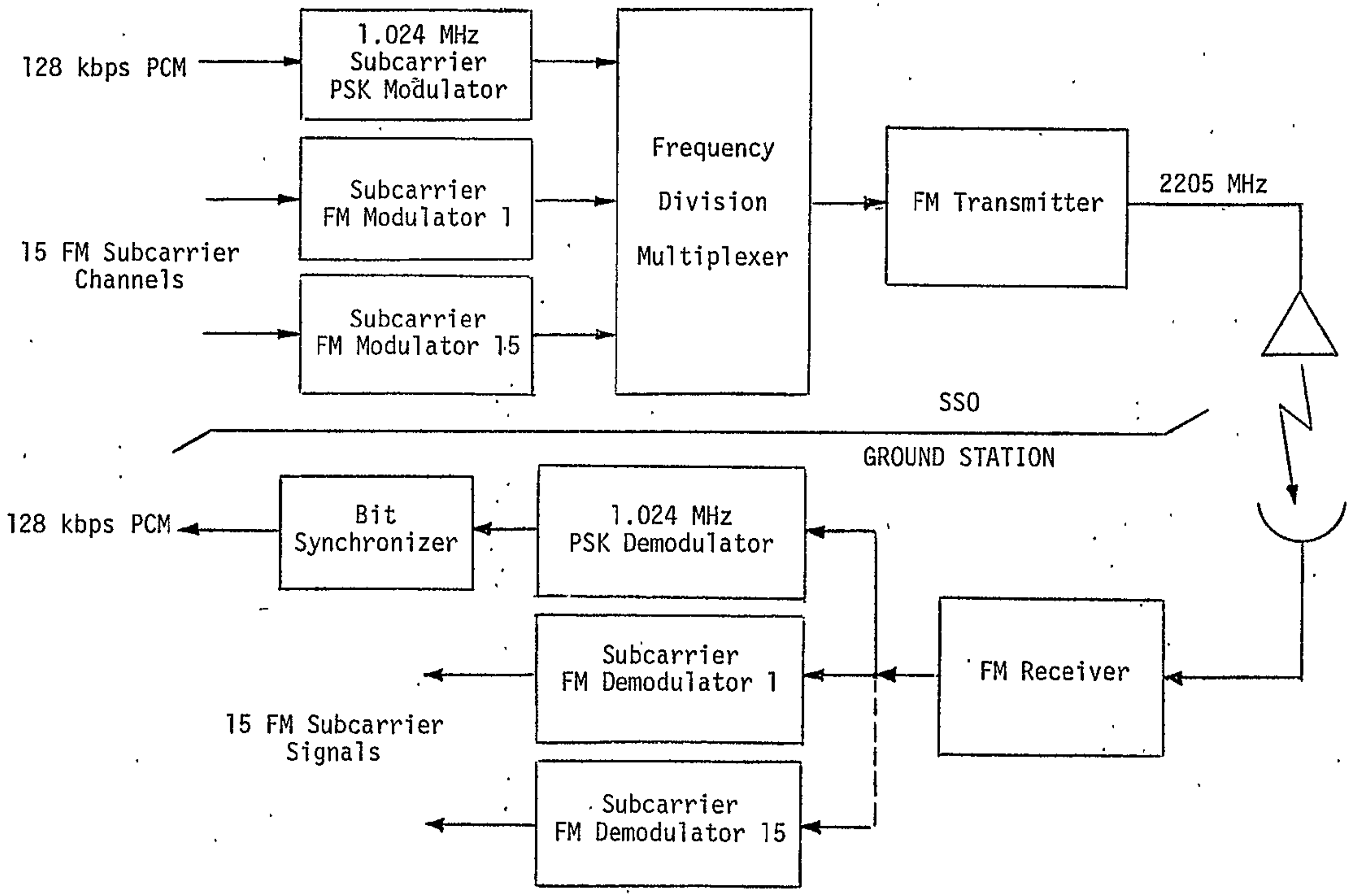

Figure 1. SSO-to-STDN S-Band DFI Link Functional Configuration

3.0 RF CHARACTERISTICS

3.1 Modulation/Demodulation

The 128 kbps DFI PCM data in a bi-phase-L format phase-shift-keys the 1.024 MHz subcarrier and each of the 15 FM subcarrier signals frequency modulates its respective subcarrier. The FM subcarrier frequencies and peak-to-peak frequency deviations are listed in Table 1. The frequency-division multiplexed subcarriers frequency modulate the link RF carrier. The carrier peak-to-peak frequency deviation by each subcarrier is listed in Table 1.

At the ground station, the 1.024 MHz subcarrier PSK demodulator coherently demodulates the suppressed subcarrier to obtain the 128 kbps DFI baseband signal. Standard subcarrier FM demodulators are used to reconstruct the FM subcarrier data signals prior to being processed by the ground signal processor.

3.2 Effective Isotropic Radiated Power (EIRP)

The minimum EIRP from the SSO, which includes the SSO transmit power, circuit loss, and antenna gain, is 0.4 dBW.

Table 1. SSO-to-STDN DFI Link Interface Characteristics

Carrier Frequency	SSO Minimum EIRP	STDN Minimum G/T		Antenna Polarization	STDN Requirement (P_{rec}/N_0)
		Feet	dB/K		
2205.0 MHz	0.4 dBW*	12	7.6	RCP	76.0 dB-Hz**
TBD		30	22.0		
		40	21.2		
		85	31.2		

Information Channels			Subcarriers			Carrier Peak Deviation††
No.	Signal Format	Bandwidth or Bit Rate	Frequency†	Modulation	Peak Deviation††	
1	Analog	500 Hz	12 kHz	FM	1 kHz	20 kHz
2	Analog	500 Hz	16 kHz	FM	1 kHz	20 kHz
3	Analog	500 Hz	20 kHz	FM	1 kHz	20 kHz
4	Analog	500 Hz	24 kHz	FM	1 kHz	20 kHz
5	Analog	500 Hz	28 kHz	FM	1 kHz	20 kHz
6	Analog	500 Hz	32 kHz	FM	1 kHz	20 kHz
7	Analog	500 Hz	36 kHz	FM	1 kHz	20 kHz
8	Analog	2 kHz	48 kHz	FM	4 kHz	33.6 kHz
9	Analog	2 kHz	64 kHz	FM	4 kHz	44.8 kHz
10	Analog	2 kHz	80 kHz	FM	4 kHz	56.0 kHz
11	Analog	2 kHz	96 kHz	FM	4 kHz	67.2 kHz
12	Analog	2 kHz	112 kHz	FM	4 kHz	78.4 kHz
13	Analog	2 kHz	128 kHz	FM	4 kHz	89.6 kHz
14	Analog	2 kHz	144 kHz	FM	4 kHz	100.0 kHz
15$^{\Delta}$	Bi-ϕ-L	12 kbps	184 kHz	FM	-TBD-	---TBD---
PCM	Bi-ϕ-L	128 kbps	1.024 MHz	PSK	-N/A-	700.0 kHz

*Based on SSO antenna gain of 1 dB with about 54% coverage

**Based on 10 dB minimum SNR in 4 MHz predetection bandwidth

†±TBD%

††±10%

ΔExternal tank PCM

APPENDIX D

APPROACH AND LANDING TEST (AL-T) TELEMETRY LINK

APPENDIX D.

APPROACH AND LANDING TEST (ALT) TELEMETRY LINK

During the Approach and Landing Test (ALT), the operational C&T links and the DFI link are not implemented. The SSO ALT telemetry data are transmitted to the STDN ground station via an SSO-to-STDN S-band ALT telemetry link. This link function continuously during both the mated and released phases when line-of-sight exists. The SSO ALT telemetry data transmitted consists of one 128-kbps pulse code modulated (PCM) digital data channel and, simultaneously, 15 analog data channels. Figure 4, page 10, shows the PCM frame format.

Figure D-1 shows the functional interface configuration for this link. In the SSO, the 128-kbps PCM data in a bi-phase-L (Manchester II) signal format phase-shift-keys (PSK) a 1.024 MHz subcarrier, and each analog data signal frequency modulates (FM) a corresponding subcarrier. The 16 modulated subcarriers are frequency division multiplexed (FDM), and the FDM composite signal frequency modulates (FM) the 2205.0 MHz RF carrier, which is then power amplified and radiated from the antenna. At the ground station, an FM receiver, a PSK demodulator, and 15 FM subcarrier demodulators are used to convert the RF signal to the baseband. Bit detection of the 128-kbps PCM data is performed in a bit synchronizer.

The carrier aircraft receives the modulated 2205.0 MHz RF carrier from the SSO, translates the RF frequency to 2250.0 MHz, and retransmits the modulated 2250.0 MHz RF carrier to the STDN station. This relay functions continuously during both the mated and released phases.

The pertinent signal characteristics and interface parameters for the SSO-to-carrier aircraft S-band link are summarized in Table D-1. Table D-2 summarizes the signal characteristics and interface parameters for the SSO-to-STDN S-band ALT telemetry link.

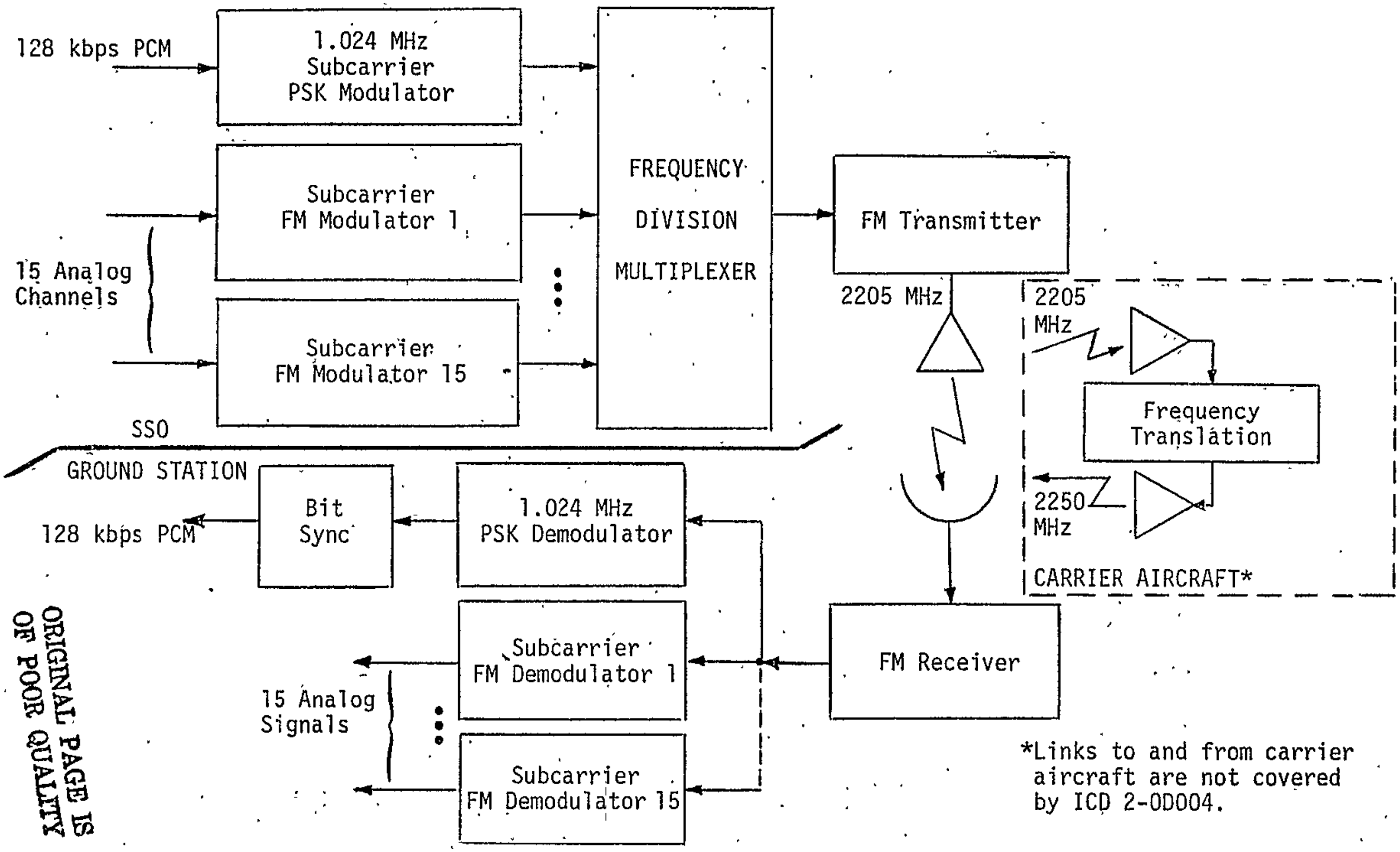

Figure D-1. SSO-to-STDN S-Band ALT Telemetry Link Functional Configuration

Table D-1. SSO-to-Carrier Aircraft S-Band Link Characteristics

SSO			Carrier Aircraft				
Frequency	EIRP*	Antenna Polarization	Frequency	Antenna Polarization	G/T**	S/N Degradation†	EIRP
2205.0 MHz ± TBD MHz	7.0 dBW$^{\Delta}$	RCP	2205.0 MHz ± TBD MHz (Received) 2250.0 MHz ± TBD MHz (Transmitted)	RCP	TBD	Total 1 dB	TBD

Δ Based on nominal +3.0 dB SSO antenna gain.

* Effective isotropic radiated power.

** Receive antenna gain/system temperature, where system temperature is referred to the antenna terminal.

† Signal-to-noise ratio degradation in the process of receiving, translation, and retransmitting.

Table D-2. SSO-to-STDN S-Band ALT Telemetry Link Interface Characteristics

Carrier Frequency	SSO Minimum EIRP	STDN Minimum G/T	Antenna Polarization	STDN Requirement (P_{rec}/N_0)
2205.0 MHz ± TBD	0.0 dBW*	7.6 dB/K**	RCP	76.0 dB-Hz$^{\Delta}$

Information Channels			Subcarriers			Carrier Peak Deviation (kHz)††
No.	Signal Format	Bandwidth or Bit Rate	Frequency (kHz)†	Modulation	Peak Deviation (kHz)††	
1	Analog	500 Hz	12	FM	1	20
2	Analog	500 Hz	16	FM	1	20
3	Analog	500 Hz	20	FM	1	20
4	Analog	500 Hz	24	FM	1	20
5	Analog	500 Hz	28	FM	1	20
6	Analog	500 Hz	32	FM	1	20
7	Analog	500 Hz	36	FM	1	20
8	Analog	2 kHz	48	FM	4	33.6
9	Analog	2 kHz	64	FM	4	44.8
10	Analog	2 kHz	80	FM	4	56.0
11	Analog	2 kHz	96	FM	4	67.2
12	Analog	2 kHz	112	FM	4	78.4
13	Analog	2 kHz	128	FM	4	89.6
14	Analog	2 kHz	144	FM	4	100.0
15	Analog	8 kHz	184	FM	16	257.0
PCM	Bi-ϕ-L	128 kbps	1.024 MHz	PSK	NA	700.0

* Based on SSO antenna gain of -4 dB with about 36% coverage.

** STDN 12-foot antenna.

Δ Based on 10 dB minimum SNR in 4 MHz predetection bandwidth.

† ± TBD%

†† ± 10%