212
26-m Subnet Telemetry

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Note to Readers

There are two sets of document histories in the 810-005 document that are reflected in the header at the top of the page. First, the entire document is periodically released as a revision when major changes affect a majority of the modules. For example, this module is part of 810-005, Revision E. Second, the individual modules also change, starting as an initial issue that has no revision letter. When a module is changed, a change letter is appended to the module number on the second line of the header and a summary of the changes is entered in the module's change log.

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1 Introduction

1.1 Purpose

This module describes the telemetry capabilities of the Deep Space Network (DSN) 26-m subnet. It is intended to provide information to guide telecommunication engineers in selecting telemetry system designs that will be compatible with the 26-m subnet and in predicting or analyzing the performance of these designs.

The expected customer base for the 26-m subnet primarily is high Earth orbiters, including lunar missions, and secondarily, emergency low Earth orbiter (LEO) support, launch and early orbit phase (LEOP) support, and deep-space mission launch support. Earth orbiter missions that have used the 26-m subnet include GOES, NOAA, ProSEDs, TDRS, ACE, CHANDRA, INTEGRAL, WIND, POLAR, GEOTAIL, and SOHO.

1.2 Scope

This module provides a discussion of the type of telemetry modulation that can be received by the DSN 26-m stations and the characteristics of the equipment used for reception and processing. This module does not discuss additional capabilities of this equipment such as the command support provided by the Telemetry and Command Processor (TCP) that is described in module 213 of this document or the radiometric capabilities of the Multifunction Receiver (MFR) that are discussed in module 204. Telemetry capabilities of the 34-m and 70-m stations are discussed in modules 206, 207, and 208.

2 Telemetry Characteristics

The DSN 26-m stations are capable of receiving residual carrier phase-shift keyed (PSK) modulation. When this modulation is directly phase modulated onto the Radio Frequency (RF) carrier, it is referred to as PCM/PM modulation. When the information is first bi-phase modulated onto a subcarrier and then the modulated subcarrier is phase modulated onto the carrier, it is referred to as PCM/PSK/PM. PCM/PSK/PM modulation is normally used for low data rate transmission where a subcarrier is required to prevent data sidebands from interfering with the receiver’s carrier tracking loop. PCM/PM modulation is recommended whenever the data rate is high enough with respect to the receiver tracking loop bandwidth to ensure that whatever data products fall within the tracking bandwidth do not significantly degrade the loop signal to noise ratio.

2.1 Data Waveforms

A data sequence where a logical “one’ is represented by one level and a logical “zero” is represented by another level is referred to as Non-Return to Zero-Level (NRZ-L) data. NRZ-L data is the easiest to process but the transmission format creates an ambiguity as to what phase constitutes a logical one and what phase constitutes a logical zero. This ambiguity must be resolved through data processing techniques such as recognition of a synchronization marker within the data. The ambiguity can be resolved during the reception process by employing one of two forms of *differential encoding*. The Non-Return to Zero-Mark (NRZ-M) data waveform uses a transition to indicate a one and the lack of a transition to indicate a zero. Thus, the logical value is implicit within the received waveform. The opposite convention is adopted for the Non-Return to Zero-Space data waveform where a transition indicates a zero and lack of a transition indicates a one. As is the case with NRZ-M data, the logical value is implicit in the NRZ-S waveform.

Each of these three waveforms has a bi-phase equivalent. Bi-phase data uses a transition from one level to another to indicate a one and a transition in the opposite direction to indicate a zero. Thus, every symbol period contains at least one transition. This is useful to maintain symbol synchronization during transmission of long strings of ones or zeroes. Another advantage is that there is no data power at the carrier frequency. However, a bi-phase waveform consumes twice the bandwidth of the equivalent NRZ waveform and its use is normally limited to low data rates where null in data power at the carrier frequency is beneficial. The 26-m subnet supports the data waveforms illustrated in Figure 1.

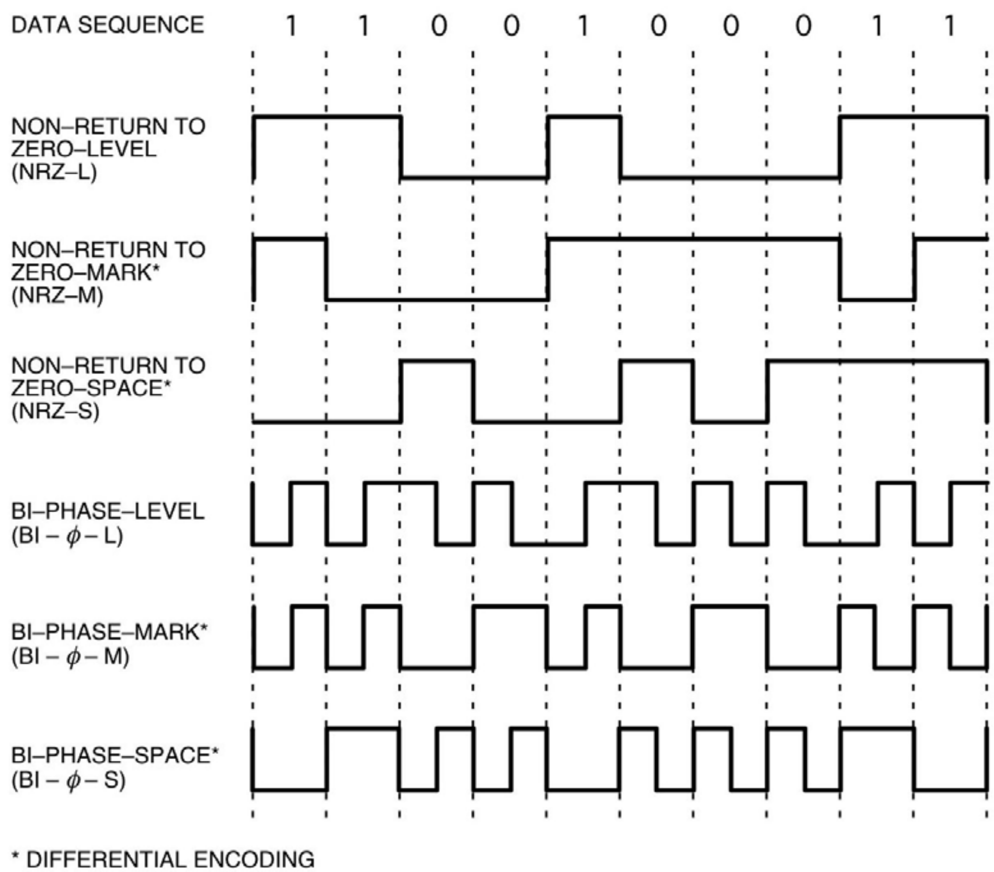

Figure 1. Pulse Code Modulation Data Waveforms.

Where a data waveform other than NRZ-L is selected, the conversion is done immediately prior to transmission and following reception. However, when convolutional encoded data (described below) is used, the conversion from NRZ-L to the alternate waveform is done prior to the input of the convolutional encoder and at the output of the convolutional decoder. This enables the coding gain to be used to improve the symbol recognition process.

2.2 Modulation Index

In any residual carrier modulation system it is important to properly allocate power between the carrier and the data. When a subcarrier is employed, it is assumed that the subcarrier is fully suppressed so, if only a single channel of telemetry modulation is present, all power is accounted for by the allocation between the carrier and the data channel.

This allocation must consider many factors including bit rate, the carrier loop bandwidth selected to accommodate signal dynamics, the coding scheme, an allowance for receiver detection losses, and sources of increased phase noise such as spacecraft oscillator instability and solar phase noise. The following observations can be made about modulation index selection.

- When calculations suggest a modulation index in excess of 80-degrees, 80-degrees should be used because higher indices are difficult to maintain and do not provide a significant increase in data power.
- Uncoded data requires a higher modulation index (more data power) than coded data because of the lack of coding gain in the data channel.
- A lower modulation index (more carrier power) will be required if spacecraft dynamics are such as to require a wider carrier loop bandwidth.
- At low data rates, there is sufficient energy in each received symbol or bit to permit additional power to be allocated to the carrier.

The carrier power P_C and data power P_D are given by

$$P_C = \begin{cases} P_T \cos^2 \theta, & \text{no subcarrier or squarewave subcarrier} \\ P_T \, \mathrm{J}_0^2(\theta), & \text{sinewave subcarrier} \end{cases} \tag{1}$$

$$P_D = \begin{cases} P_T \sin^2 \theta, & \text{no subcarrier or squarewave subcarrier} \\ P_T \, 2\mathrm{J}_1^2(\theta), & \text{sinewave subcarrier} \end{cases} \tag{2}$$

where θ is the peak modulation index and J_0 and J_1 are Bessel functions of the first kind of orders zero and one. In the case of a sinewave subcarrier, only the power in the fundamental harmonics (upper and lower) of the subcarrier is recoverable and the power in the higher-order harmonics is not used. In this case, P_D represents the power in just these harmonics.

If ranging modulation is present on the downlink carrier, then the equations for residual-carrier power and data power need to be adjusted to reflect the fact that some of the downlink power is being allocated to ranging signal and noise that is present in the transponder ranging channel.

A telecommunication link is normally successful when the link designer has selected a modulation index that provides a carrier signal-to-noise ratio (SNR) of at least 13 dB (see module 204) and an input energy per bit to noise spectral density ratio (bit SNR) that allows at least a 3-dB margin above that required by the selected coding scheme after allowing for all losses (see Section 4 of this module). The bit SNR is defined as

$$\frac{E_b}{N_0} = \frac{P_D}{N_0 R_{BIT}} \qquad (3)$$

where R_{BIT} is the bit rate (before encoding).

2.3 Coding

Coding takes a continuous sequence of information digits and either converts them to a greater number of symbols or augments them with additional symbols generated by the coding process, or both. When the coded information sequence is received, the decoder uses the additional symbols to enhance recognition of the information digits. Coding always results in a bandwidth expansion however, in the regime where available spacecraft transmitter power prevents filling the available bandwidth, coding improves the bandwidth utilization and increases the amount of data that can be returned.

The 26-m subnet stations can support short constraint-length, Rate 1/2, convolutional coding, Reed-Solomon coding, and concatenated coding using the Rate 1/2, convolutional as the inner code and Reed-Solomon coding as the outer code.

2.3.1 Short Constraint Length Convolutional Code

The supported short constraint-length convolutional code is the CCSDS standard rate 1/2, constraint-length 7 code created by an encoder having the block diagram shown in Figure 2. The code produced is a member of that class of codes referred to as *transparent codes*, that is, codes where inversion of the input bit stream simply results in inversion of the output symbol stream. This is valuable if NRZ-L or Bi-phase-L modulation is used with its inherent sign ambiguity as it permits the decoding to be accomplished before the sign ambiguity is resolved. The decoder at the 26-m stations will also decode codes where the C1, C2 symbol order is interchanged, and the inversion of either or both of the C1 and C2 symbols are optional.

2.3.2 Frame Synchronization

Frame synchronization is an optional capability for all telemetry streams and must be established prior to operation of an RS decoder or, when no outer code is being used, before processing information contained in transfer frames. When it is not being used, the received or

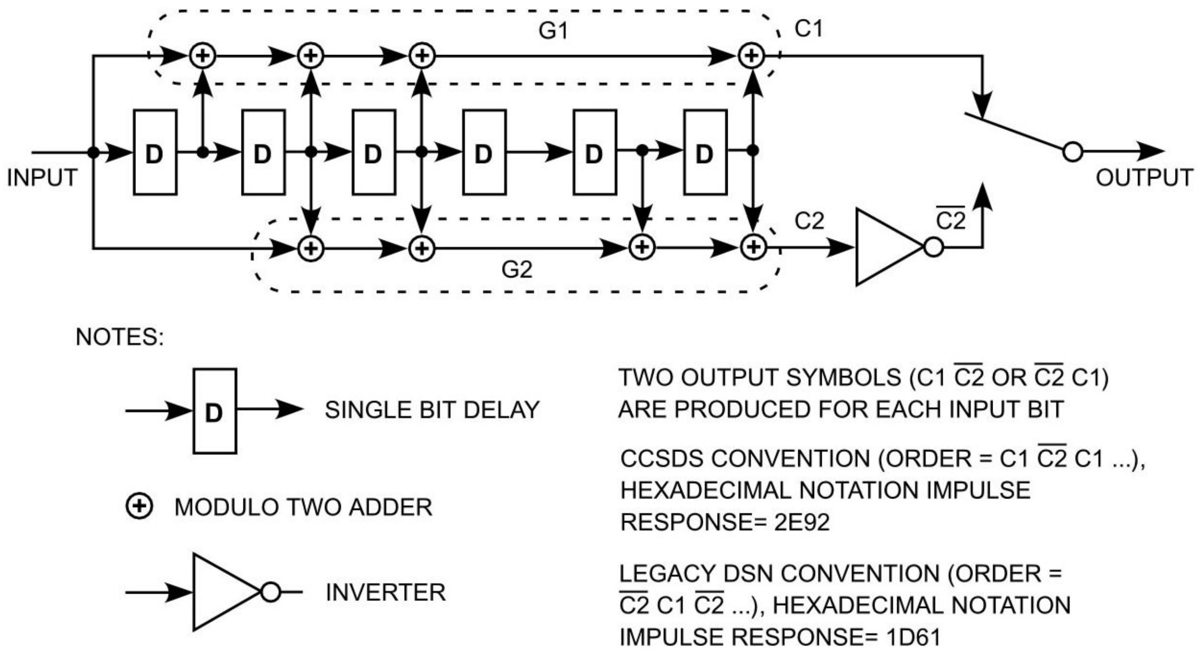

Figure 2. Constraint Length 7, Rate 1/2 Connection Vector Schematic.

received-and-decoded bits are placed into telemetry transport blocks in the order received and annotated in the block header with status data consisting of mode identifiers and data quality indicators.

Synchronization is accomplished by preceding each codeblock or transfer frame with a fixed-length Attached Synchronization Marker (ASM). This known bit pattern can be recognized to determine the start of the codeblocks or transfer frames. It also can be used to resolve the phase ambiguity associated with NRZ modulation. The CCSDS has adopted a 32-bit ASM with a pattern represented in hexadecimal as 1ACFFC1D and illustrated in Figure 3. The 26-m telemetry equipment can accommodate other ASM patterns with lengths up to 64 bits.

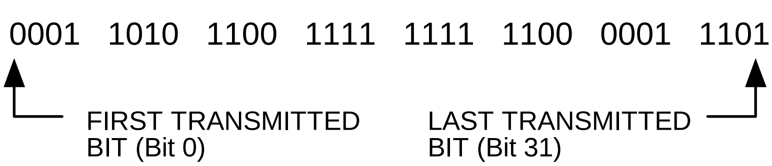

Figure 3. CCSDS 32-bit Attached Synchronization Marker.

The parameters required by the frame synchronizer are frame length, frame length tolerance, the ASM, the number of bit errors permissible for recognizing the ASM, the number of frames required to verify synchronization, and the number of frames that may be missed before loss of synchronization is declared.

The synchronizer processes the data stream in one of four states as depicted by the state diagram shown in Figure 4. Initially in the SEARCH state, the input data stream is searched for an acceptable sync pattern of either polarity and all data are discarded. Once an acceptable pattern is found, the CHECK or LOCK states are entered depending on the programmed number of check frames. At this point, the polarity is switched, if required, and the data are accumulated in a frame buffer. If an unacceptable frame is received while in the CHECK state, the SEARCH state is re-entered. The LOCK state is entered after the specified number of consecutive, acceptable frames are received.

The LOCK state is maintained as long as consecutive, acceptable frames are received. If an unacceptable frame is received, FLYWHEEL or SEARCH states are entered depending on the specified number of flywheel frames. When the specified number of consecutive, unacceptable frames are received while in the FLYWHEEL state, the SEARCH state is entered. If an acceptable ASM is recognized while in the FLYWHEEL state, the LOCK state is re-entered. This method of operation ensures that the LOCK state will be maintained even when the received data stream is corrupted by random errors.

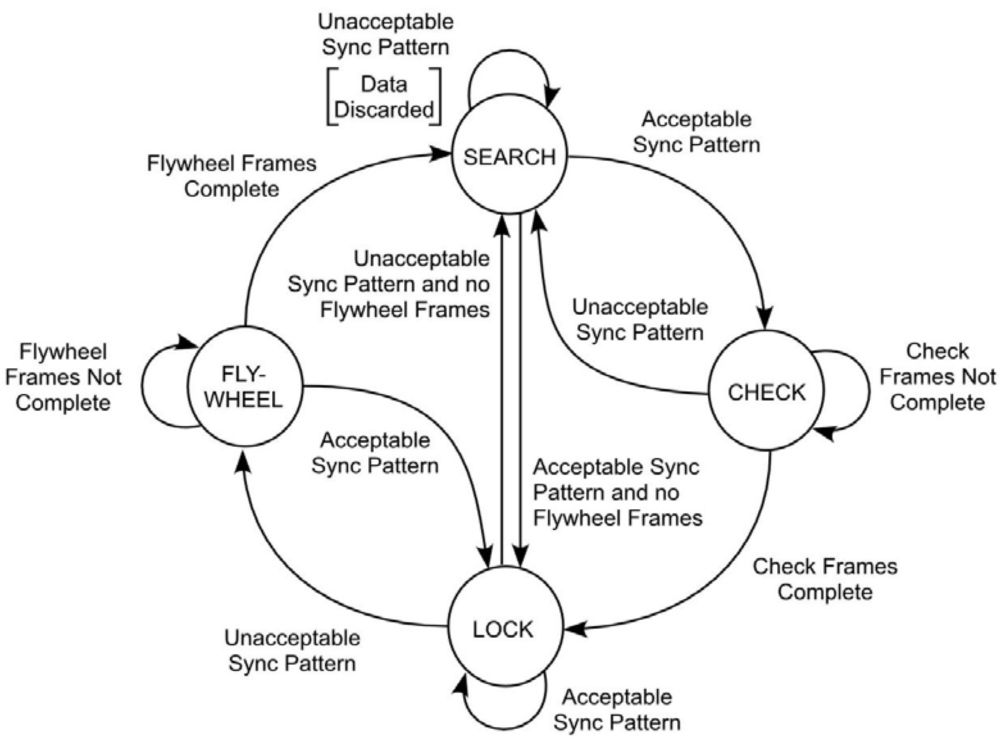

Figure 4. Frame Synchronizer State Diagram.

2.3.3 Randomization

The alternate symbol inversion used with convolutional codes provides a sufficient density of symbol transitions to ensure adequate symbol synchronizer operation in most applications. However, it is possible to create symbol streams with symbol transition densities less than the 125 per 1000 symbols recommended by the CCSDS. In these cases, with uncoded data, or with NRZ data using direct modulation (no subcarrier), the telemetry should be randomized prior to coding or transmission by combination with a standard pseudo-random sequence. This sequence begins at the first bit of the Codeblock or Transfer Frame after the ASM and repeats every 255 bits until the end of the Codeblock or Transfer Frame

The 26-m telemetry equipment supports the pseudo-noise sequence recommended by the CCSDS and generated by the polynomial given as equation (4). Figure 5 illustrates one possible generator for this sequence.

$$h(x) = x^8 + x^7 + x^5 + x^3 + 1 \qquad (4)$$

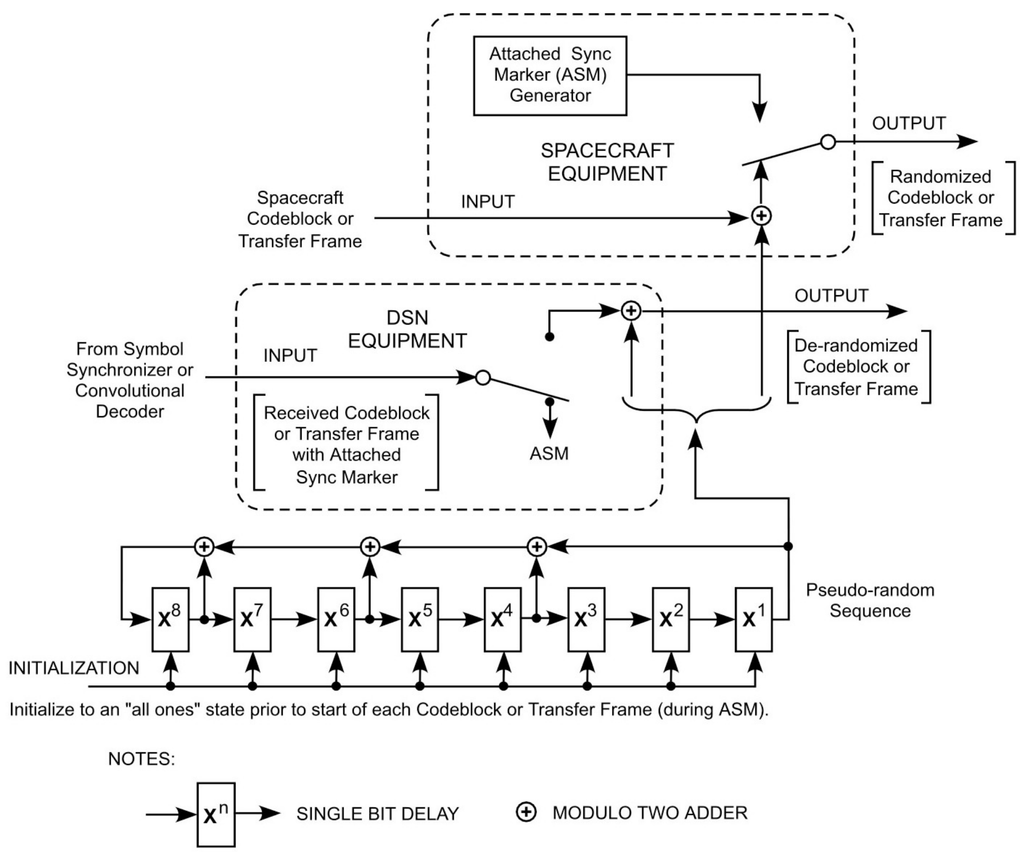

Figure 5. Pseudo-Randomizer Implementation.

2.3.4 Frame Error Control Field

A frame error control field or cyclic redundancy check (CRC) is the recommended method to detect errors that may have been introduced into a transmission frame by the communications channel or by the data handling process when other methods of error detection, such as the Reed-Solomon coding discussed below, are not used. The CRC recommended by the CCSDS and supported by the 26-m telemetry processing equipment is 16 bits long and requires that the shift register used to hold the intermediate calculations of the CRC be initialized to all ones at the start of each frame.

The CRC is implemented by designing the data portion of the telemetry frame to be 16 bits shorter than the transmitted frame to allow the insertion of the CRC at its end. The equation for the CRC is

$$\mathrm{CRC} = \left[X^{16} \cdot M(X) \oplus X^{(n-16)} \cdot L(X) \right] \text{ modulo } G(X) \tag{5}$$

where

n is the length of the transmitted frame (including the CRC)

$M(X)$ is the (n – 16) bit message to be encoded expressed as a polynomial with binary coefficients.

$L(X)$ is a polynomial of all ones of order 15

$\oplus$ is the modulo 2 addition operator (Exclusive OR)

$G(X)$ is the polynomial

$$G(X) = X^{16} + X^{12} + X^{5} + 1 \tag{6}$$

The $X^{(n\text{-}16)} \cdot L(X)$ term has the effect of presetting the shift register used to hold the intermediate calculations to all ones prior to the start of each CRC calculation.

2.3.5 Reed Solomon Coding

Reed Solomon coding provides excellent error correction capability with minimal bandwidth expansion in channels where burst noise is the principal source of errors. Under these conditions, it provides an extremely low undetected error rate. This means that the decoder can reliably indicate that successful decoding was accomplished without the need for a CRC. The supported Reed–Solomon code takes the input data and divides it into 8-bit sequences to form symbols. The RS encoder creates 32 parity symbols from the data that enable the decoder to correct any combination of 16 or fewer symbol errors per RS codeword. The output of the RS encoder is a *systematic* code (one in which the input symbols are contained in the output) containing 223 information symbols followed by 32 parity symbols and is referred to as the RS (255,223) code.

Reed-Solomon coding, by itself, cannot guarantee sufficient channel symbol transitions to keep a receiver symbol synchronizer in lock. Therefore, the Pseudo-Randomizer defined in Paragraph 2.3.3 is required unless the system designer verifies that sufficient symbol transition density is assured by other means when the randomizer is not used.

2.3.6 Interleaving with Reed-Solomon Codes

As data rates increase, it becomes probable that a noise burst will exceed the 16 RS symbol (128-bit) error correction capability of the code. The effects of burst errors can be spread across several RS codewords through a technique referred to as *interleaving*. The functional operation of a Reed-Solomon interleaver is depicted in Figure 6.

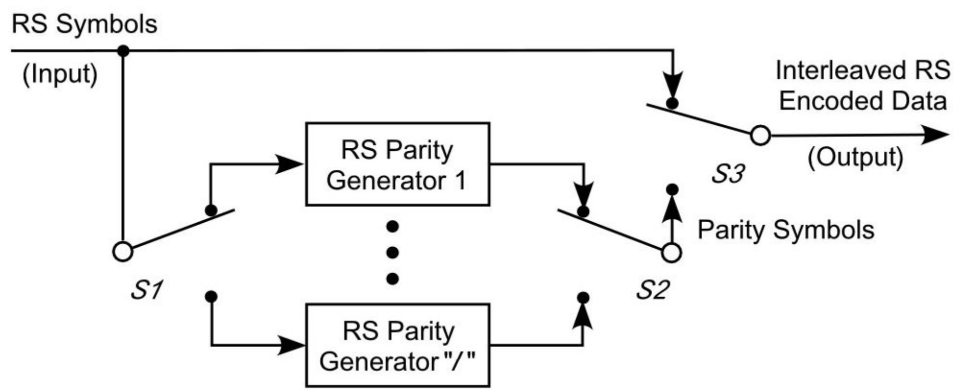

Figure 6. Functional Operation of Reed-Solomon Interleaver.

As Reed-Solomon data symbols are generated they are both passed to the next stage of telemetry data encoding (typically, addition of the ASM) and distributed across a set of *I* RS Parity Generators, where *I* is the *interleave factor*, by the action of *S1* which advances to the next parity generator after each symbol. When 223*I* symbols have been dispatched, the *I* Parity Generators will be full and *S3* is used to append the parity symbols to the input symbols. *S2* selects the first parity symbol from Parity Generator 1 followed by the first symbol from each parity generator until Parity Generator *I* is reached. Then, the process repeats for the second parity symbol until all parity symbols have been dispatched. Thus, the code remains systematic but the effects of burst errors are distributed across the entire 32*I* length of the parity space.

2.3.7 Virtual Fill with Reed-Solomon Codes

Reed-Solomon coding may be used with frame lengths less than 223*I* symbols (1784*I* bits), where *I* is the interleave factor, through a technique called *virtual fill*. Because the RS code is a block code, the parity symbols must be calculated on the entire block. However, if a portion of this block is known to contain all-zero symbols at both the transmitting and receiving ends of a link, there is no need for these symbols to be transmitted – as long as all 32 parity symbols are transmitted. The convention that has been adopted by the CCSDS is that the virtual fill is inserted at the beginning of each code block, between the ASM and the significant symbols. It should be noted that once a decision to use virtual fill is established, it must be used for all blocks within the data stream. This is because the frame synchronizer cannot operate with blocks of varying length. A diagram of the virtual fill implementation is shown in Figure 7.

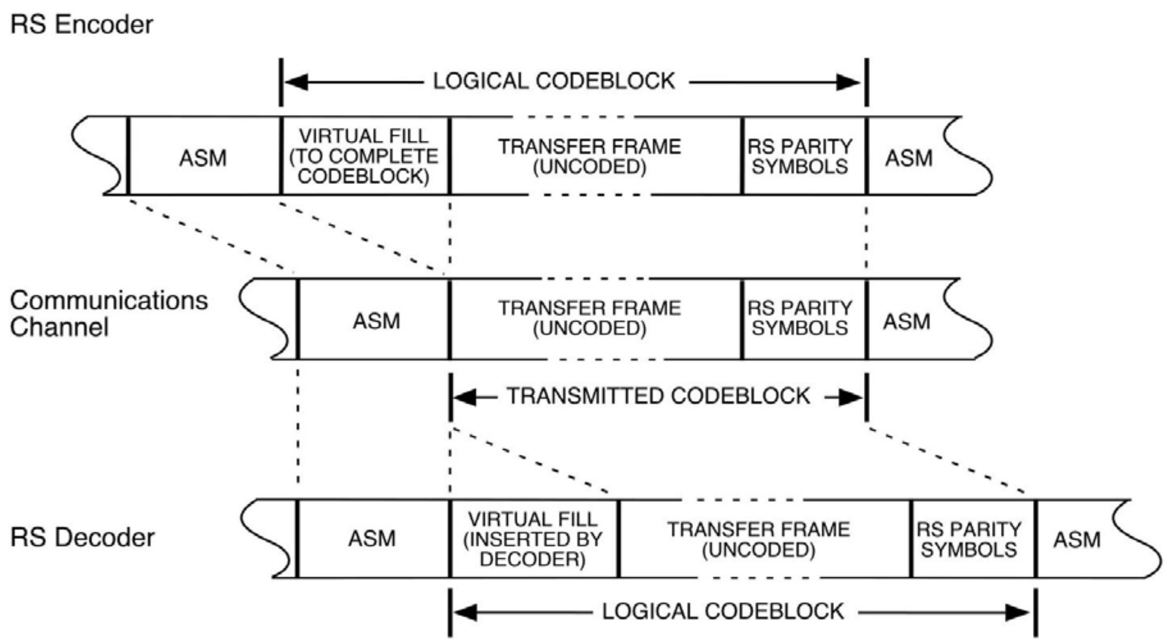

Figure 7. Virtual Fill

If a CRC is employed with Reed-Solomon coding, it is placed as the last two data symbols before the start of the parity symbols. The CRC is calculated and compared before Reed-Solomon decoding so reported CRC errors may be corrected by the Reed-Solomon decoder. The CRC's location with respect to the start of an RS codeblock can be calculated by the expression

$$\text{Location} = \text{Transmitted Codeblock Length} - 32I - 2 \qquad (7)$$

where I is the interleave factor.

2.3.8 Concatenated Convolutional and Reed-Solomon Code

In power-limited channels, it is beneficial to use the gain available from convolutional coding. However, as threshold is approached, a convolutional coder will tend to become unlocked for several constraint lengths before it re-synchronizes – creating the appearance of burst noise at its output. Concatenating Reed-Solomon and convolutional coding provides an effective mechanism to ameliorate this with little additional bandwidth. Used this way, the Reed-Solomon code is the *outer code* (furthest from the communications channel), while the convolutional code is the *inner code* (closest to the communications channel).

2.4 Time Tagging

The frame synchronization process includes the capability to attach a time-stamp to the first or last bit of each synchronized frame. The delay between the point of application of the time stamp and the input of the low noise amplifier (LNA) is calibrated after any significant change in the equipment that could affect this value. The time delay between the LNA input and the antenna reference point (intersection of the antenna axes) is not significant.

2.5 Data Structure

The 26-m telemetry processing equipment can process unstructured, time-division multiplexed (TDM) data and CCSDS structured data. The only requirements on TDM data are that it be divided into frames of 8 to 4096 bytes separated by ASMs. The content of the frames may be randomized and may contain a CRC as their last two bytes. Upon receipt, these frames are time stamped, annotated with data quality information, formatted, and delivered to the user.

CCSDS data consists of Transfer Frames or Virtual Channel Data Units (VCDUs). VCDUs are referred to as Coded Virtual Channel Data Units (CVCDUs) when RS coding is used. Both of these terms refer to the fixed-length frame prior to it being prefixed by an ASM. These two structures are also referred to as CCSDS Version 1 frames (Transfer Frames) or CCSDS Version 2 frames (VCDUs or CVCDUs) because of the version identifier that forms the first two bits of the frame header. The 26-m telemetry processing equipment can be set to restrict processing to the specified type of frame or to automatically recognize and process either type of frame.

Both types of CCSDS frames support the concept of *virtual channels*. Virtual Channels (VCs) are a mechanism whereby a single physical channel is shared between different users by creating multiple and apparently parallel paths through the channel. Each virtual channel is identified by a Virtual Channel ID in the range of 0 to 63 and the data in each frame is identified by this ID. Figure 8 provides an example of telemetry data flow when virtual channels are being used with CCSDS Version 1 frames.

The 26-m telemetry processing equipment has the capability of extracting up to 8 virtual channels from the 64 possible. Each channel is annotated with accountability information appropriate for the virtual channel (as opposed to the physical channel) and delivered to the user as a separate data stream.

2.6 Virtual Channel Stripping

As shown in Figure 8, the contents of a virtual channel may be created by combining packets from multiple sources. The packets from each source will be identified by a header that includes an Application Process ID (APID) and a packet length. The TCP is capable of creating a virtual telemetry stream containing packets from a single process based on customer-supplied APID. Since the packet header fields within the VC are not protected from errors, virtual channel stripping can only be provided when the spacecraft data is Reed-Solomon encoded.

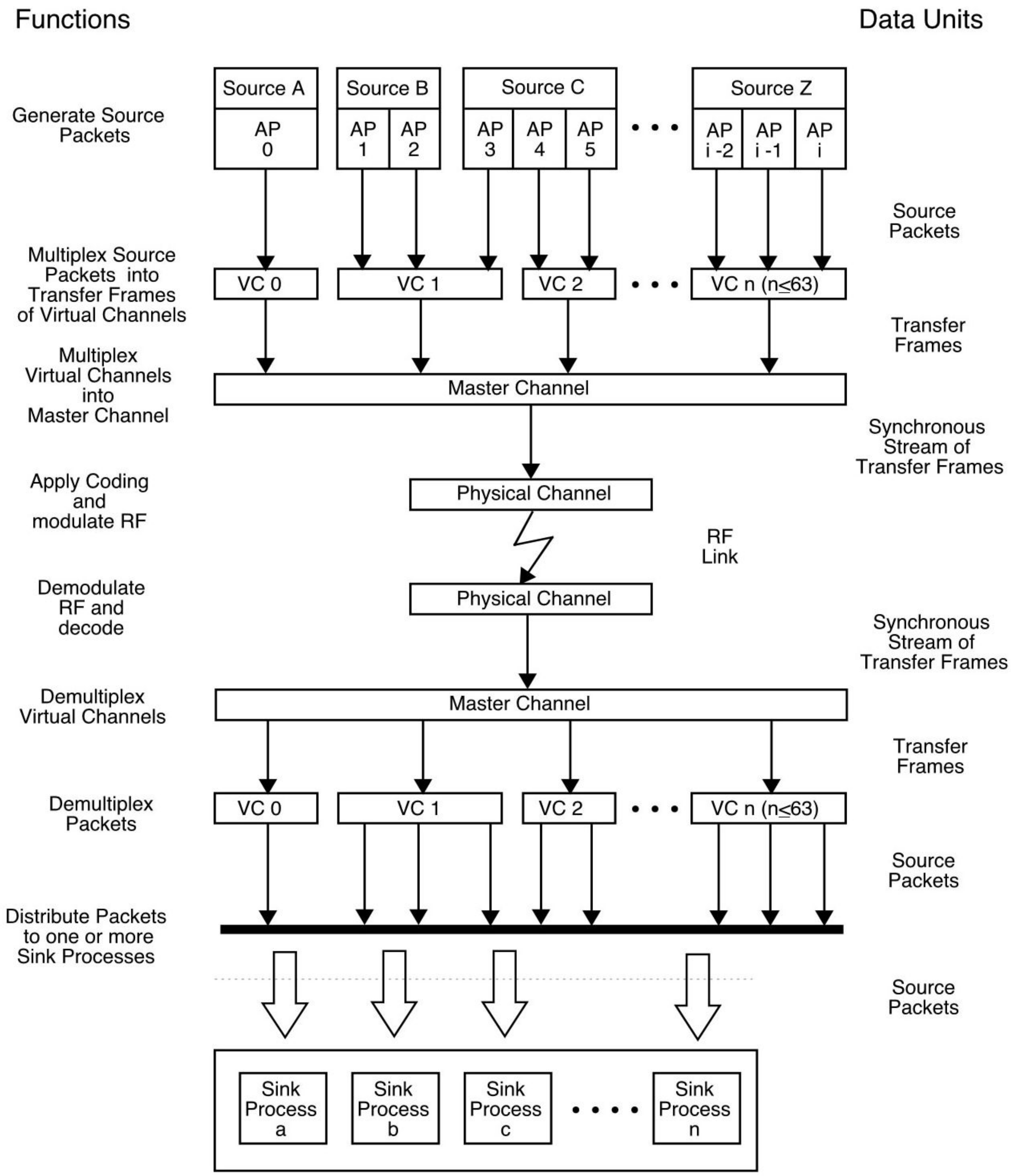

Figure 8. Example of Telemetry Data Flow using CCSDS Version 1 Frames.

2.7 Data Formatting

The 26-m telemetry processing equipment includes many options for formatting its output data. The selection is negotiated between the DSN and users and documented as external user interface specifications. The normal data format is one or more streams of Standard Formatted Data Units (SFDUs). A telemetry SFDU is a self-identifying, self-delimiting data structure that is used to encapsulate a portion of the telemetry data acquired from a spacecraft for delivery to a mission. Typically, each SFDU encapsulates one telemetry frame. A given sequence of telemetry SFDUs may encapsulate one physical channel from a spacecraft, or it may encapsulate only a part of a physical channel (e.g., a virtual channel). Each SFDU also contains additional information related to the telemetry data encapsulated in the SFDU (including the quantity of data, the station and spacecraft identification, and the Earth Received Time).

2.8 Data Recording

All telemetry data is recorded within the telemetry processing equipment for protection against failures of other station equipment. Provisions are made to record 30 minutes of data at a maximum data rate of 2.2 Mb/s for up to 15 passes. Files remain on the storage device for up to 24 hours or until a file-transfer confirmation is received. The contents of the storage device is purged based on the file time stamps at an interval determined by JPL.

Automatic playback occurs at the available data rate when the received data rate exceeds the station bandwidth. Post-pass data playback is available at normal or reduced rates provided the user has scheduled the activity. Post-pass playback is not available when the telemetry processing equipment is being used for another activity.

3 Equipment Description

A functional block diagram depicting the major assemblies of the three 26-m stations that form the 26-m subnet is shown in Figure 9 with the telemetry data flow indicated by the heavy lines. RF energy is received by the antenna, amplified, and fed to three MFRs that are part of the Receiver, Exciter, and Ranging (RER) equipment. The baseband output of the two receivers is fed to the two TCPs where the telemetry information is extracted, processed, and formatted for delivery to the user. The formatted data flows to users via the Signal Processing Center (SPC) local area network (LAN), the Ground Communications Routers (GCRs) at the stations and at JPL, and the Special Function Gateway (SFG) at JPL. Telemetry data are also archived by the Central Data Recording Assembly (CDR) at JPL.

Although not involved in telemetry reception, Figure 9 also shows other significant elements of the 26-m stations including the transmitter (TXR), the Antenna Interface Unit (AIU), the Metric and Pointing Assembly (MPA), the Sequential Ranging Assembly (SRA), the Link Monitor Processor (LMP) and the Monitor and Control Processor (MCP). It also identifies the other elements of the RER including the S-band Exciters (SBEs), and the tone Ranging Equipment (RE) assembly.

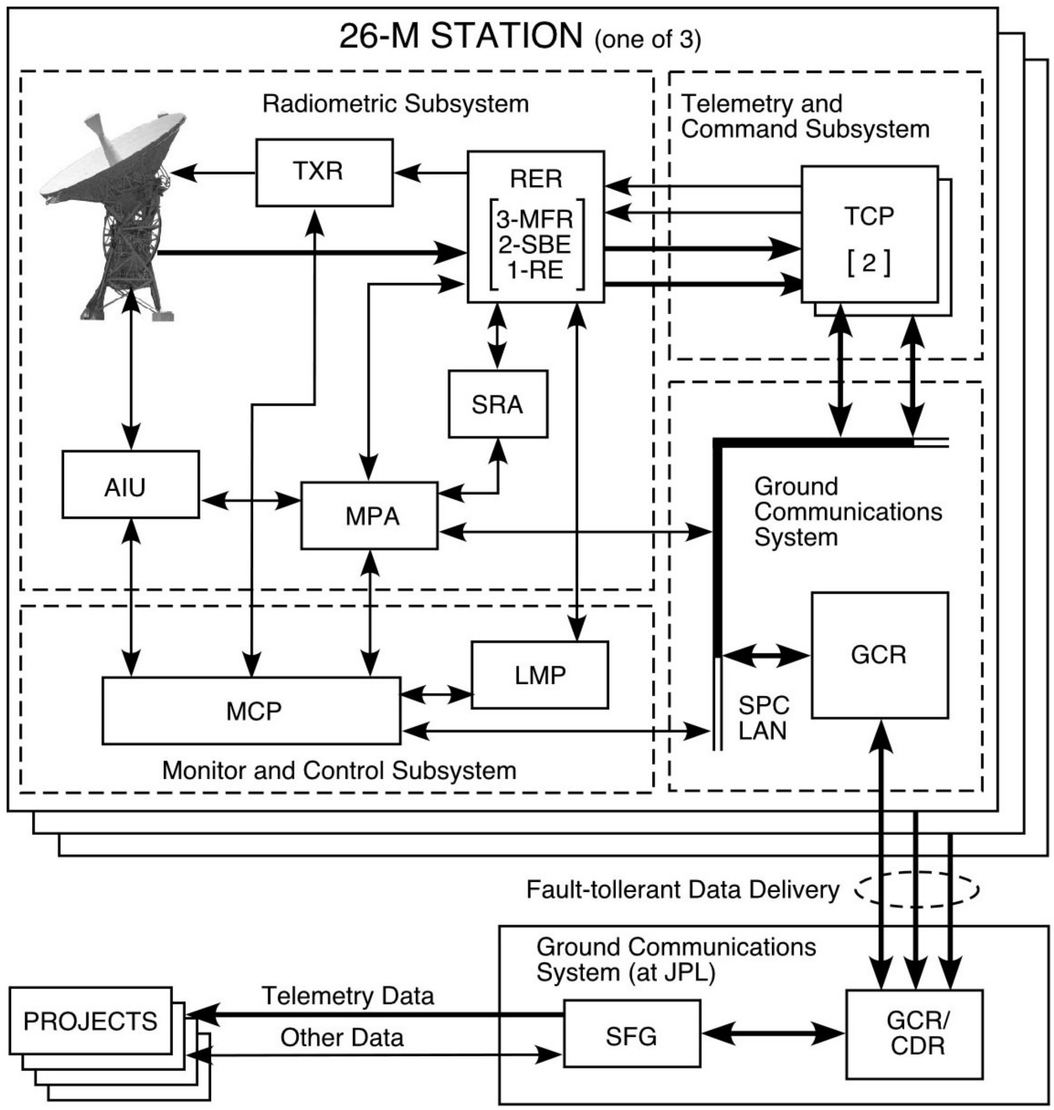

Figure 9. 26-m Subnet Functional Block Diagram.

3.1 Antenna and Microwave

The 26-m antenna uses fixed-focus, Cassegrain optics to capture S-band energy and direct it to a feed that separates the energy into right circular polarization (RCP) and left circular polarization (LCP) components. Each component is amplified by a High Electron Mobility Transistor (HEMT) amplifier, downconverted to a 400 MHz to 500 MHz intermediate frequency, and distributed to the three receivers. The feed includes monopulse channels for angle tracking of spacecraft where pointing predicts are unavailable or uncertain. Additional details of the microwave equipment can be found in module 102. Information on the antenna tracking performance can be found in module 302. Orbital coverage for the antennas is provided in module 301.

Two small reflectors containing monopulse feeds – one for S-band and one for X-band – are mounted on the dish structure to provide broad-beam tracking for spacecraft acquisition. The S-band acquisition antenna can be switched into the normal S-band downconverters so telemetry is available during acquisition. The X-band acquisition antenna is part of a dedicated acquisition system that does not provide telemetry detection. However, tracking offsets from the 26-m antenna can be used to position a 34-m BWG or HEF antenna and use its telemetry receivers (provided that tracking rates are within the limits of the 34-m antenna as discussed in module 302). Under these conditions the reception and telemetry processing capability would be as discussed in modules 202, 207, and 208.

3.2 Telemetry Processing

Telemetry processing at each 26-m station is provided by two redundant strings of equipment. At any time, each string contains one of the MFRs and one TCP. The two telemetry strings are normally configured in a hot backup configuration but can be operated independently.

3.2.1 Multifunction Receiver

The multifunction receivers are designed to receive residual carrier phase modulation or frequency modulation however frequency modulation is no longer used by the DSN. There are three MFRs at each station that can be independently switched to the outputs of the RCP or LCP downconverters. Thus, they can be used redundantly on one polarization or to receive simultaneous RCP and LCP signals. The receivers can be operated in either an open-loop or a closed-loop mode using a third-order tracking loop with selectable loop bandwidths. See module 204 for a complete discussion of receiver operation and performance.

The receivers take the 400 to 500 MHz signal from the antenna and downconvert it, first to a 110 MHz fixed intermediate frequency (IF) and then to a 10 MHz fixed IF. Each of the IFs has a selectable predetection bandwidth and a telemetry detector with a selectable video bandwidth. Under normal tracking conditions the video bandwidth is set to twice the bit rate plus the subcarrier frequency for NRZ codes and four times the bit rate plus the subcarrier frequency for Bi-phase codes. The predetection bandwidth is set to closest available setting that is at least twice the selected video bandwidth. Therefore,

$$BW_V \geq \begin{cases} 2R_{BIT} + f_{SC}\text{, NRZ PCM Code} \\ 4R_{BIT} + f_{SC}\text{, Bi-}\phi\text{ PCM Code} \end{cases} \tag{8}$$

and

$$BW_P \geq 2BW_V. \tag{9}$$

Available telemetry predetection and video bandwidths are provided in Table 1. The video output of the selected telemetry detector provides the input to the TCP.

Table 1. MFR Predetection and Video Bandwidths.

Narrowband (10 MHz) Telemetry Detector		Wideband (110 MHz) Telemetry Detector	
Predetection BWs	Video BWs	Predetection BWs	Video BWs
10 kHz, 30 kHz, 60 kHz, 100 kHz, 300 kHz, 600 kHz, 1 MHz, 1.5 MHz, 3 MHz	1.5 kHz, 5 kHz, 15 kHz, 30 kHz, 75 kHz, 150 kHz, 300 kHz, 500 kHz, 750 kHz, 1.5 MHz	6 MHz, 10 MHz, 20 MHz	3 MHz, 5 MHz, 10 MHz

3.2.2 Telemetry and Command Processor

The Telemetry and Command Processor is assembled from commercial satellite terminal components. It employs digital signal processing techniques to provide subcarrier demodulation, symbol synchronization, short constraint-length convolutional decoding, frame synchronization, Reed-Solomon decoding, and data formatting. The equipment specifications are provided in Table 2.

If the telemetry was modulated on a subcarrier, it is shifted to baseband by complex multiplication with an internal oscillator steered by feedback from a digital Costas loop employing a second-order loop filter. Symbols are detected by a symbol tracking loop employing a sampling error detector and a second-order loop filter to derive the frequency correction for the symbol clock generator. The output of the symbol detector is either hard-decision symbols for uncoded or Reed-Solomon (only) data or 3-bit, soft-decision symbols for convolutionally coded data.

The default bandwidths of the subcarrier and symbol tracking loops are set at 1% of the symbol rate for symbol rates in excess of 5,000 sps (2,500 bps for bi-phase coding). Default bandwidths for symbol rates below 5,000 sps are provided in Table 3.

Table 2. Telemetry and Command Processor Capabilities.

Parameter	**Value**	**Remarks**
Subcarrier Demodulator		
Subcarrier Frequency	1 kHz to 15 MHz	
Waveform	Sinewave or Squarewave	
Modulation Type	BPSK	
Symbol Rate	100 s/s to 2.1 Ms/s	

Table 2. Telemetry and Command Processor Capabilities (Continued)

Parameter	Value	Remarks
Bit Synchronizer		
Data Rates	100 s/s to 10 Ms/s	
PCM Codes	NRZ-L, M, S; Bi-phase-L, M, S	
Output Quantization	3-bit	
Viterbi Decoder		
Supported Code	Constraint Length (*k*) = 7, Rate (*r*) = 1/2	Complies with CCSDS Recommendation 101.0-B-3
Connection Vectors	G1 (1ST Symbol) = 1111001 G2 (2ND Symbol) = 1011011	G1/G2 order may be reversed
Symbol Inversion	Output of G2	Optional
Input	3-bit soft symbols	
Symbol Input Rate	100 s/s – 10 Ms/s	
Frame Synchronizer		
Sync Marker Length	Up to 32 bits	Automatic Polarity Correction
Acceptable Marker Bit Errors	0 to 15	
Acceptable Marker Bit Slip	0 ± 3 bits	
Number of Check Frames	0 to 7	
Flywheel Duration	0 to 7 frames	
Word Size	4 to 16 bits	
Frame Length	≤ 8192 words	
Derandomizer	Optional	Complies with CCSDS Recommendation 101.0-B-3
Reed-Solomon Decoder		
Code Supported	CCSDS (255, 223)	
Virtual Fill	Supported	
Interleave	1 to 8	

Table 3. Default Subcarrier and Symbol Loop Bandwidths.

Symbol Rate or 2 x Bi-phase bit rate (sps)	Subcarrier Loop Bandwidth (% of rate, Hz)	Symbol Loop Bandwidth (% of rate, Hz)
≤50	10	12
≤250	7	10
≤750	5	7
≤2,500	3	5
≤5,000	1	2

4 Performance

Many tests have been conducted to assess the 26-m telemetry performance. In most of the tests reported here, the bandwidth of the MFR carrier tracking loop was set to 100 Hz (one-sided). It is assumed that the bandwidth values for the subcarrier tracking and symbol synchronization loops were the default values (see Table 3) as these values are not contained in the default operational displays and are not normally changed.

Figure 10 displays representative plots of BER versus E_b/N_0 for subcarrier modulation of uncoded data at data rates from 512 b/s to 10 kb/s while Figure 11 displays plots of direct modulation for uncoded data rates from 100 kb/s to 2.5 Mb/s. Figure 12 illustrates the performance of convolutionally coded telemetry for direct modulation at data rates from 105 kb/s to 2.5 Mb/s. Two of the curves in Figure 11 appear to meet or exceed theory. This is obviously not true but the curves have retained illustrate the quality of data that have been obtained. The wide spread in telemetry performance among curves of similar data rates is due, mostly, to uncertainties in the actual E_b/N_0 values at which each test was run. The 26-m subnet does not contain instrumentation for accurately measuring operating system temperature and setting E_b/N_0. As a result, design values are commonly used for N_0 and these values may differ from reality on the order of 1 dB or more.

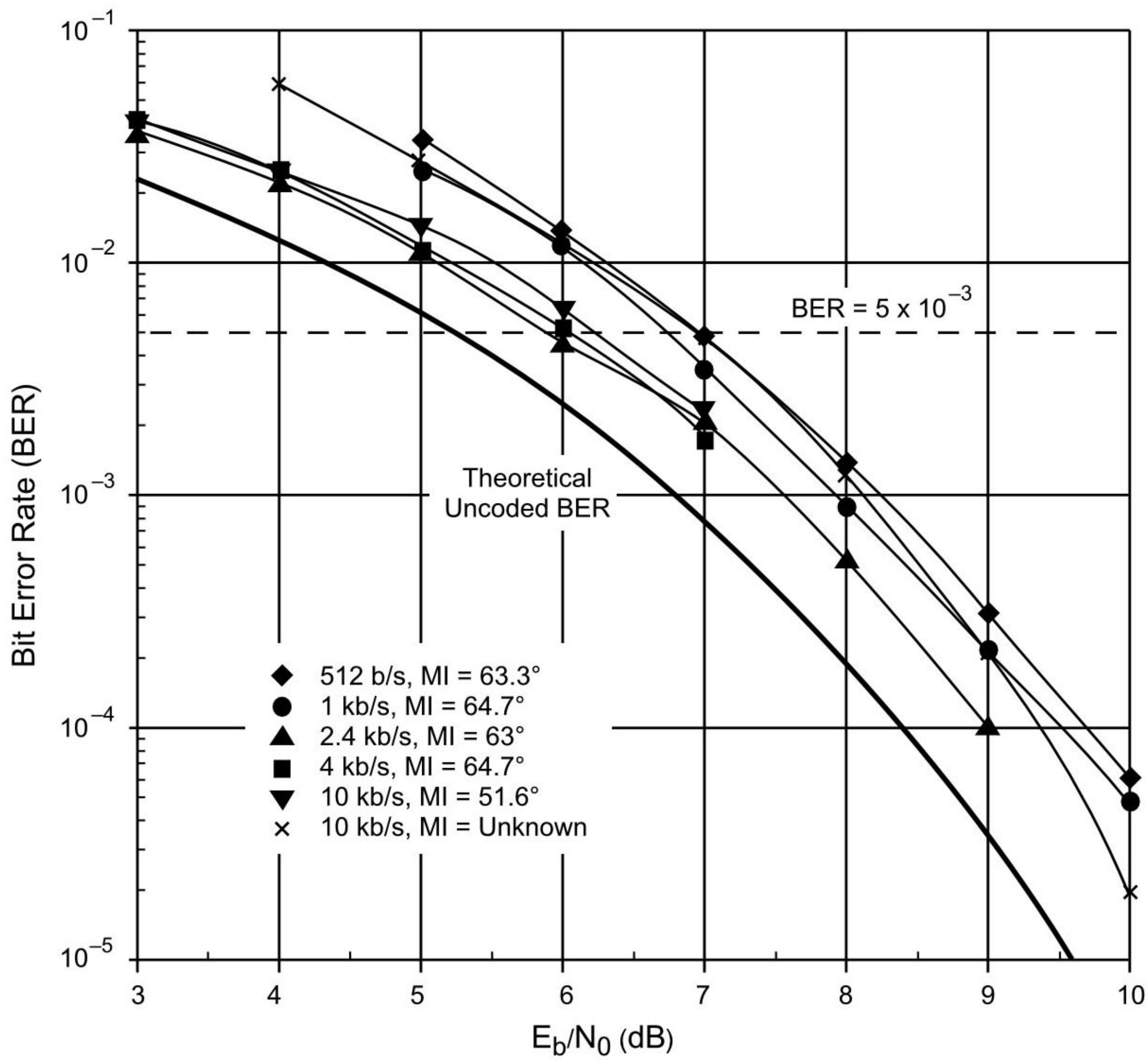

Figure 10. Uncoded Telemetry Performance, Subcarrier Modulation.

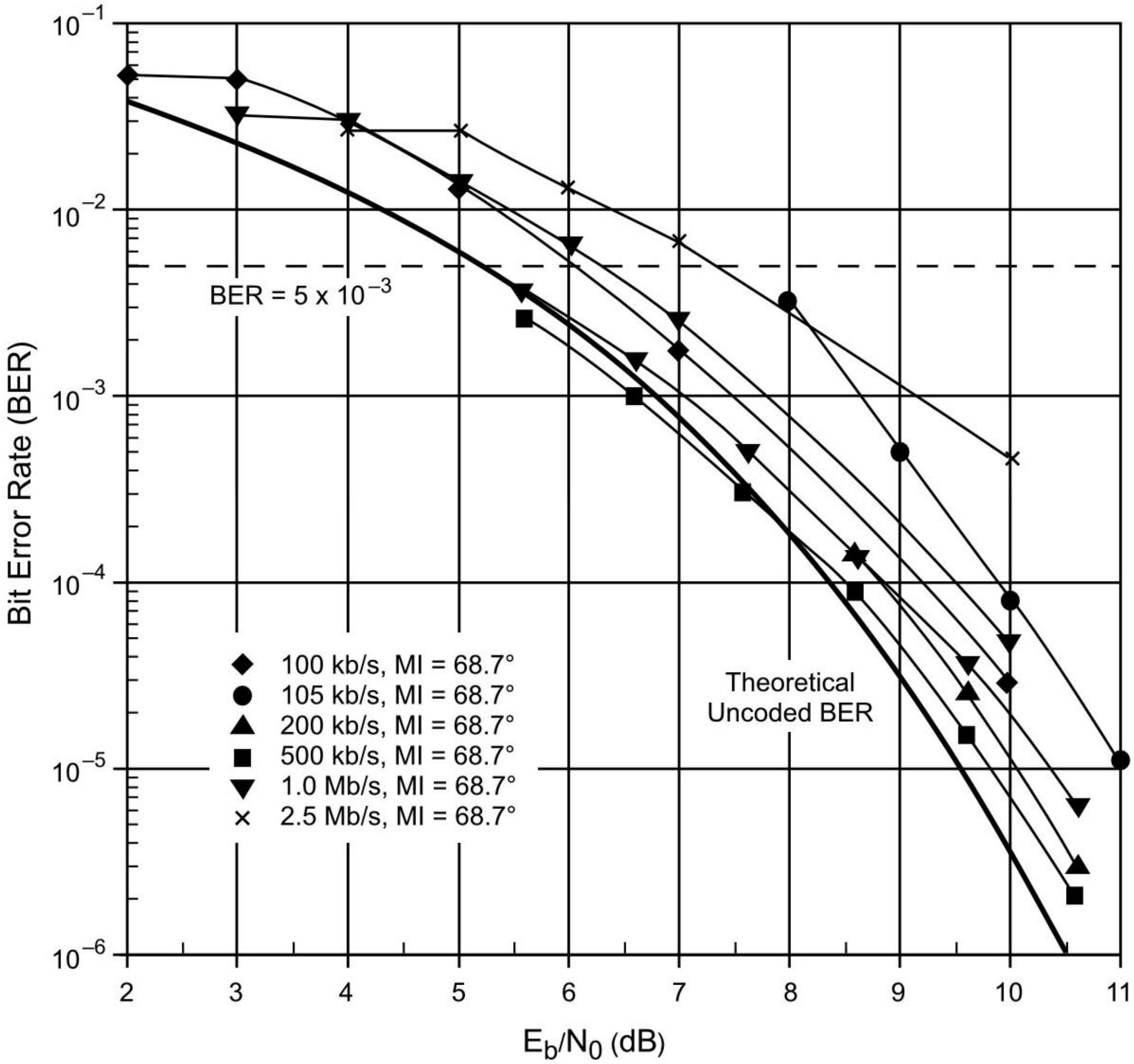

Figure 11. Uncoded Telemetry Performance, Direct Modulation.

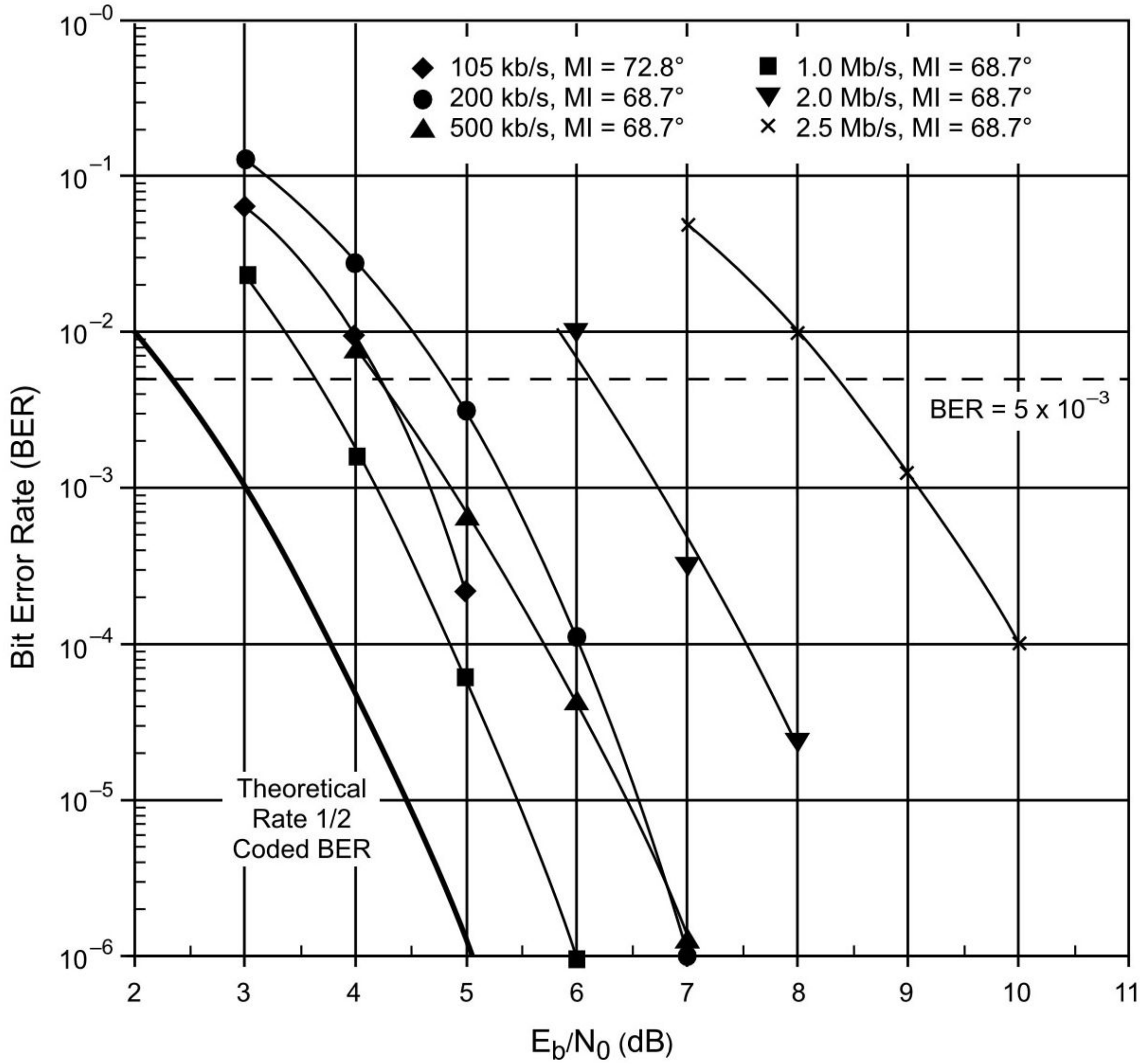

Figure 12. Convolutionally Coded Telemetry Performance, Direct Modulation.

Figures 13 and 14 illustrate the measured performance in a different manner. The data are taken from the complete set from which the representative curves were extracted and both figures include both coded and uncoded data. In this case, only the points where E_b/N_0 = 6 dB are presented. These curves illustrate that the scatter in the measurements hides the improvement in performance that would be expected when E_b/N_0 is maintained constant while the symbol rate increases. It has been proposed that undetected video band limiting in the receiver may be responsible for a decrease in performance at the higher symbol rates but this is unsubstantiated and the telecommunications designer is encouraged to make allowances for the relatively unpredictable performance in the link design.

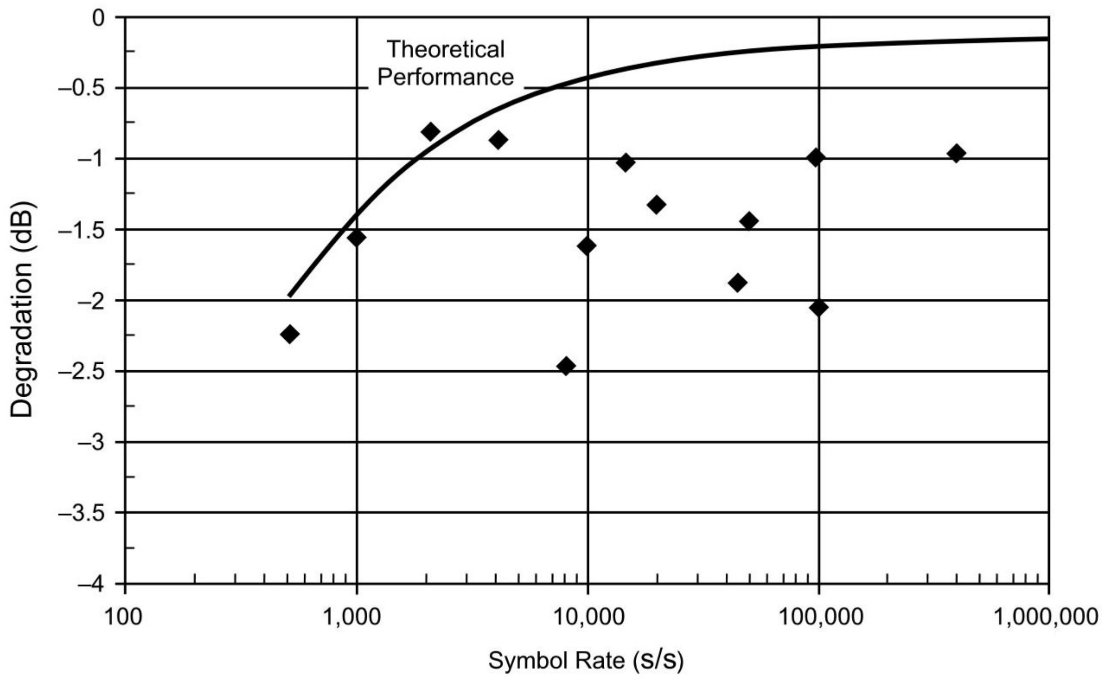

Figure 13. Scatter in Subcarrier Modulation Telemetry Performance Measurements

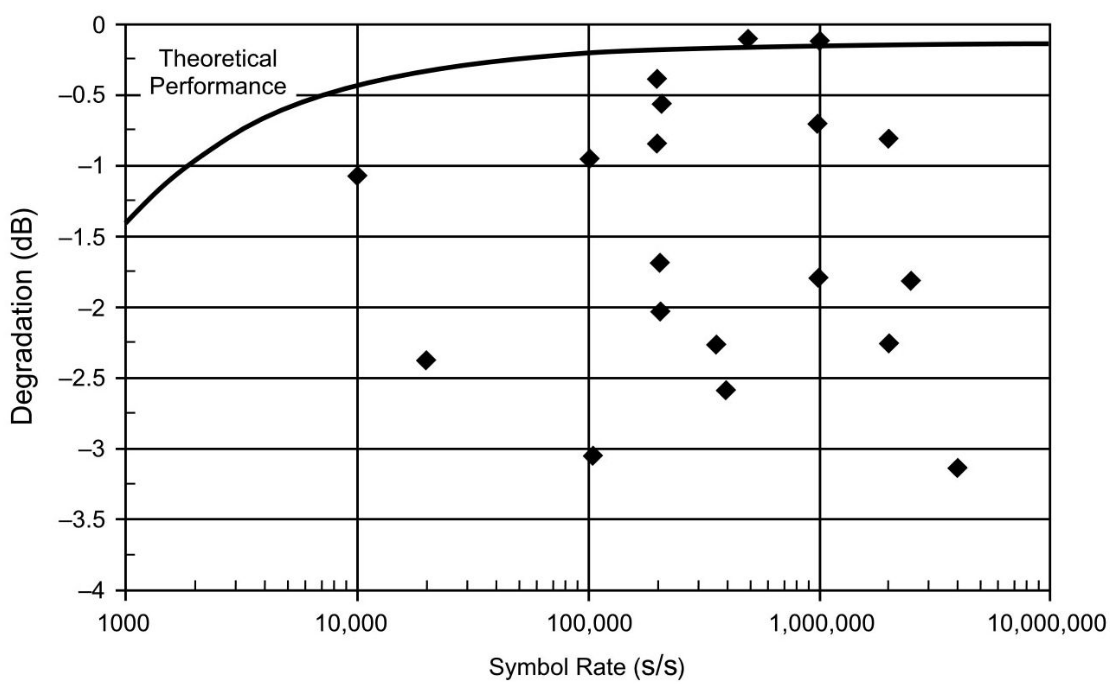

Figure 14. Scatter in Direct Modulation Telemetry Performance Measurements