206, Rev. B
Telemetry General Information

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Prepared by:

Approved by:

A. Kwok   10/29/09
A. Kwok   Date

T. T. Pham   10/30/09
T. T. Pham   Date
DSN Chief System Engineer

Released by:

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Change Log

Rev	Issue Date	Affected Paragraphs	Change Summary
Initial	10/7/2004	All	All
Rev. A	9/19/2008	Many	Added 34-m and 70-m array information originally planned for inclusion in module 215. Deleted references to portions of AMMOS that are responsibility of projects and to the GDSCC 26-m antenna that has been decommissioned. Added Near-earth 26 GHz support and revised proposed capabilities
Rev. B	10/31/2009	Many	Removed all references related to the 26-m stations.

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 is intended to provide Deep Space Network (DSN) customers with an overview of DSN telemetry capability and to direct telecommunications designers with specific concerns to the appropriate portions of this handbook. This module also contains brief descriptions of future enhancements to telemetry capability that are in the design or early implementation phases and of capabilities that are being maintained for legacy customers using the previous generation of telemetry equipment.

1.2   *Scope*

This module describes the Telemetry Service as currently implemented in the DSN. It includes high-level definitions, equations, functional descriptions, and capabilities to provide the telecommunication designer with an introduction to the more detailed information in the other modules of this handbook. Some characteristics are extracted from these modules for the readers' convenience and information relating to telemetry reception that does not conveniently fit in the major divisions of this handbook is included. Schedules for proposed implementation or the removal of any legacy support are not included. All questions relating to schedule must be directed to the DSN Mission Commitments Program Office.

1.3   *Relation to Other 810-005 Material*

The information necessary to properly design a telemetry link is distributed across many modules of this handbook. The following paragraphs discuss these modules and describe the parameters contained in them that should be of interest to a telecommunications link designer.

1.3.1   *Telecommunications Interface Modules*

Modules 101, 102, 103, and 104 contain the radio frequency (RF) characteristics of the Deep Space Network (DSN) antennas. These characteristics include the frequencies of operation, antenna sensitivity (antenna gain to system noise temperature ratio), beamwidths, and polarization capability. A block diagram of each antenna's microwave equipment is also included.

1.3.2   *Environmental Effects*

Module 105 provides the attenuation effects of the Earth's atmosphere on the telecommunications link. Statistics are provided from which a confidence level for link performance can be derived. Limited information on wind effects is provided as a guide for estimating when the antennas may not be available. The module also includes information on solar, lunar, and planetary noise that will be experienced when the antenna beam is in their vicinity when tracking spacecraft.

Module 106 provides information on additional effects caused by the solar wind or corona when the antenna beam passes near the sun.

1.3.3   Receiver Performance

The telemetry receiver used in the 34-m and 70-m stations is described in module 207. This module provides information on the types of telemetry modulation that can be accommodated and recommendations on carrier loop bandwidth, subcarrier frequency, modulation index, and data rate for each modulation type. Also included is a discussion of system losses for each modulation type.

The 34-m and 70-m stations may make use of the open-loop Radio Science receiver to record an appropriate segment of the received spectrum for post-pass processing. The characteristics of this receiver are described in module 209, however the process of extracting telemetry from radio science receiver recordings is not a standard DSN Service and is not covered in this handbook.

1.3.4   Arraying

The 34-m antennas at each complex can be combined into an array with or without the co-located 70-m antenna. The capabilities of such an array are discussed in paragraph 2.3.4.

1.3.5   Telemetry Decoding

Telemetry decoding capability for the 34-m and 70-m stations is covered in module 208.

1.3.6   Other Factors

Although not of primary interest, the telemetry link designer may be interested in coverage limits presented in module 301 and antenna mechanical performance, including open-loop beam positioning, presented in module 302. Test support provided by the DSN may also be of interest and is described in module 305.

2   General Information

Telemetry service support is available from the three Deep Space Communication Complexes (DSCCs) located in Goldstone, California, USA (GDSCC), near Canberra, Australia (CDSCC), and near Madrid, Spain (MDSCC). Telemetry support is also available from the DSN development and test facility, DTF-21, near JPL, the Merritt Island Launch Area at the Kennedy

Space Center (MIL-71), and the transportable Compatibility Test Trailer, CTT-22. CCSDS (Consultative Committee for Space Data Communications) Space Link Extension (SLE) data is available from the station at which it is received or from JPL. All other data types are routed by the Ground Communications Network (GCN) to JPL before delivery to the users. Figure 1 shows

the DSN equipment used for telemetry service support. The items shown on the figure are discussed below.

In general, telemetry service support requires one antenna, at least one receiver, and telemetry processing equipment for each spacecraft. Additional receivers and telemetry processing equipment can be added for spacecraft with multiple downlinks or for redundancy. In addition, the DSN is capable of tracking two spacecraft per antenna (MSPA) if they both are within the scheduled antenna's beamwidth.

The DSN makes every attempt to provide the same functions in every instantiation of the Telemetry Service (TLM). There is one exception for historical reasons. There are only two copies of the long constraint length convolutional decoder at each complex as it was originally implemented to support a specific mission. Missions that require this decoder must schedule its use and be aware of the potential for conflicts.

Table 1 summarizes the DSN telemetry service support available from each complex.

Table 1. Telemetry Support Capability

| Capability	Value	Remarks
Number of simultaneous spacecraft tracks per complex	GDSCC = 7 CDSCC = 5 MDSCC = 6	Based on the number of antennas plus one for MSPA
MSPA	One antenna per complex	MSPA is presently limited to two spacecraft but can be increased to four if needed
Frequency bands supported	S, X, and Ka	Depends on antenna.
Polarization	Right-hand circular (RCP) or left-hand circular (LCP)	Simultaneous RCP and LCP is available on some antennas
Arraying	All 34-m and 70-m antennas within one complex	Uses full-spectrum combining. See paragraph 2.3.4
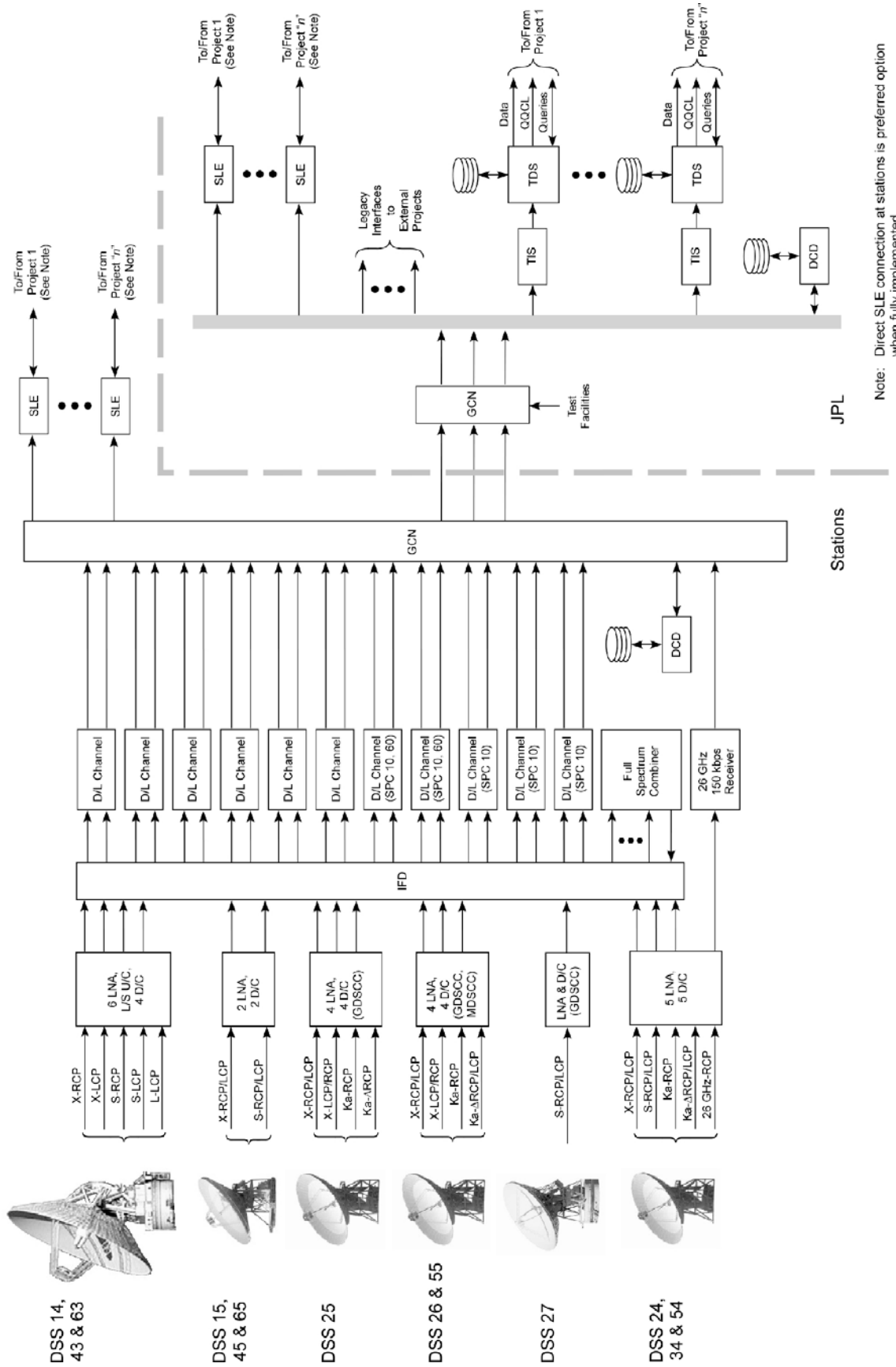
Figure 1. DSN Telemetry Equipment for Spacecraft Support.

2.1   *Telemetry Services*

Two distinct types of telemetry service are available. The first of these is the traditional return link from a spacecraft that may carry engineering or science data as one of several forms of telemetry modulation including residual-carrier or suppressed-carrier binary-phase-shift keying (BPSK), quadrature-phase-shift keying (QPSK), or offset QPSK (OQPSK). The second is the beacon mode service that is intended to monitor the high-level state of a spacecraft during periods when insufficient link margin prevents the reception of telemetry.

2.2   *Facilities and Equipment*

2.2.1   *Antennas*

Each Deep Space Communications Complex contains one 70-m, from two to five 34-m antennas. There are two types of 34-m antennas. The first is the so-called high-efficiency (HEF) antennas that have their feed, low-noise amplifiers, and transmitter located on the tilting structure of the antenna. These antennas were named when a less-efficient 34-m antenna was in use by the DSN and the name has survived. The efficiency of all DSN 34-m antennas is now approximately the same. The second type of 34-m antenna is the beam waveguide (BWG) antenna where the feeds, low noise amplifiers and transmitters are located in a room below the antenna structure and the radio frequency energy is transferred to and from the antenna surface by a series of mirrors encased in a protective tube. All antennas that are designed to receive S- or X-band can receive either RCP or LCP in these bands. Antennas with two low noise amplifiers (LNAs) and downconverters in either of these bands can receive simultaneous RCP and LCP. All antennas that receive in 26 GHz or 32 GHz (Ka) bands are designed to receive RCP. Four of the five antennas that receive 32 GHz can receive LCP provided that autotrack capability is not required.

The capabilities of each antenna type and of the individual Beam Waveguide (BWG) antennas are different and must be considered in designing a return link. The selection of antenna will depend on the downlink frequencies it supports and the gain it can provide. Table 2 lists the uplink and downlink frequency ranges for each antenna type and the sensitivity, expressed as the ratio of antenna gain to system temperature, at the time this module was published. The modules referred to above should be consulted for current values and other parameters. The telecommunications link designer is cautioned against making designs dependent on the 70-m antenna as there is only one per complex and it subject to severe scheduling constraints.

The DSN has entered into an agreement with the Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO) to use the Australia Compact Telescope Array (ATCA) at Narrabri as a backup for the one antenna at the DSN Canberra complex with Ka-band capability and has provided CSIRO with a set of standard DSN telemetry processing equipment. The agreement requires the ATCA to provide sufficient aperture to equal or exceed the performance of the DSN 34-m antenna at Ka-band however the details of this performance are beyond the scope of this document.

Table 2. Frequencies Covered and Sensitivity of DSN Antennas for Telemetry

Antenna type	Downlink Frequency Ranges (MHz)	Sensitivity (G/T, dB) (See Note 1)	GDSCC	CDSCC	MDSCC
70-m	2270 – 2300	48.3 – 51.3	1	1	1
	8400 – 8500	61.0 – 61.7			
34-m HEF (Note 2)	2200 – 2300	39.1 – 39.9	1	1	1
	8400 – 8500	53.0 – 54.8			
	8200 – 8600	51.2 – 52.4			
34-m BWG S/X/26 GHz (Note 3)	2200 – 2300	40.8 – 41.7	1	0	0
	8400 – 8500	52.2 – 53.6			
	25500 – 27000	58.8			
34-m BWG S/X/26 GHz/ Ka (Note 4)	2200 – 2300	40.6 – 41.9	0	1	1
	8400 – 8500	52.4 – 54.2			
	25000 – 27000	56.1 – 57.2			
	31800 – 32300	58.4 – 59.7			
34-m BWG X/Ka (Note 5)	8400 – 8500	52.8 – 54.7	2	0	1
	31800 – 32300	59.2 – 61.9			
34-m HSB	2200 – 2300	34.6	1	0	0

Notes:

1. Range covers best performing antenna with 95% weather (see module 105) at band center and 45-degrees elevation in highest sensitivity configuration (usually one band, downlink only) to worst performing antenna at band center and peak gain point in lowest sensitivity configuration (usually dual band downlink or backup LNA with uplink in one band). See appropriate telecommunications interface module for complete performance envelope and module 105 for atmospheric effects.

2. The 8200 – 8600 MHz (VLBI) band uses a wideband LNA with lower performance that is available as an amplifier for telemetry in the 8400 – 8500 MHz allocation. See module 103.

3. 26 GHz capability will be added to the GDSCC S/X station in the near future. Performance values are estimates. 26 GHZ implementation includes a special low G/T mode for high signal level conditions.

4. 26 GHz capability will be added to the CDSCC and MDSCC S/X/Ka stations in the near future. Performance values are estimates. Wide range of 26 GHz and 32 GHz performance results from present reduced antenna efficiency and higher atmospheric contribution at MDSCC. 26 GHZ implementation includes a special low G/T mode for high signal level conditions.

5. Does not include backup X-band LNA for DSS 25 that has significantly lower performance. See module 104. Wide range of Ka-band performance results from much lower atmospheric contribution at GDSCC than at MDSCC Wide range of X-band performance results from use of cooled common aperture X and Ka feed at DSS 26 and DSS 55 that is not available at DSS 25.

2.2.2   Telemetry Receivers

All DSN antennas employ a receiver architecture where one or both circular polarizations of the received spectrum are amplified by an LNA and translated to an intermediate frequency by a downconverter (D/C) before being routed to the control room where the desired signal is extracted. The 70-m stations have an L-band reception capability that was installed for Very-long Baseline Interferometry support. L-band is not available for telemetry because its frequency range is not within an authorized space-to-Earth telemetry allocation. The antennas are designed to receive extremely weak signals and can be overloaded by signals in excess of –90 dBm. Antennas supporting 26 GHz have a special low-gain mode that permits operation up to – 50 dBm with degraded G/T. Missions must be careful to not exceed these limits when designing the near-Earth phase or phases of their mission.

Each S-, X-, and Ka-band intermediate frequency from the 34-m and 70-m stations is made available to from one to four sets of receiving and telemetry processing equipment in the SPC however software limitations restrict the number of spacecraft that can be tracked from a single antenna to one or two. The additional receivers can be used to provide redundancy or reception for additional return links from the supported spacecraft. Additional redundancy can be obtained at S-band and X-band from stations with simultaneous RCP and LCP capability by setting both downconverters to the same polarization. However, the two spacecraft per antenna limit is maintained.

The intermediate frequency from the 26 GHz downconverter at the BWG stations is connected directly to a high-rate telemetry receiver in the SPC with a second receiver available for backup. The following is a brief discussion of the DSN telemetry receivers. Their characteristics are summarized in Table 3.

Each receiver for the S-, X-, and Ka- bands at the 34-m and 70-m antennas is contained in an assembly referred to as a *Downlink Channel.* The receiver utilizes a closed-loop digital super-heterodyne receiver with a selectable carrier tracking loop bandwidth to produce an 8-bit estimated symbol value as its output. Alternatively, these receivers can be used to detect the presence or absence of one of four subcarriers referred to a beacon tones. A complete discussion of the capabilities of this receiver is contained in module 207 of this handbook.

The receiver for 26 GHz is part of a special Downlink Channel containing a wideband telemetry processor. The receiver is preceded by a fixed-frequency downconverter in the antenna and a step-tunable downconverter in the control room. The capabilities of this receiver are discussed in module 215 of this handbook.

2.2.3   Telemetry Processing

Telemetry processing at the 34-m and 70-m is available for both CCSDS and non-CCSDS (legacy) spacecraft. A summary of the capabilities for these stations is provided in Tables 3.

At the 34 and 70-m stations, the digital symbol output of the telemetry receiver is coupled to a Telemetry Processor (TLP) within the Downlink Channel assembly that performs time-tagging, optional decoding and frame synchronization, virtual channel extraction, and formatting of the data for delivery to the customer. Decoding and frame synchronization are discussed in module 208 of this handbook. Data delivery formats are beyond the scope of this handbook but are available to qualified users through the DSN Mission Commitments Program Office.

Real-time data delivery may have to be limited to critical data at times. The remainder will be delivered non real-time within an agreed timeframe.

2.2.4 *Ground Communications Network*

The GCN uses communications circuits provided by the NASA Integrated Services Network (NISN) to connect the stations to JPL Central and users. The communication lines are shared with all users and, while DSN makes every effort to supply sufficient bandwidth.

2.2.5 *DSN Data Delivery*

The DSN provides CCSDS SLE data delivery directly from the station at which it is received or through the DSN central facility at JPL. Data storage, buffering against line outages, access, retrieval, and query are provided at all locations. Data delivery for additional telemetry functions such as packet extraction and CCSDS File Delivery Protocol (CFDP) file processing is from the DSN central facility where these functions are performed.

2.3 *Concepts Used in Estimating Telemetry Performance*

The following concepts are important to understanding telemetry performance. Additional discussion of these concepts is contained in module 207B of this handbook.

Table 3. 34-m and 70-m Telemetry Reception Characteristics

Parameter	S-, X-, and Ka-band Characteristics	26-GHz (Near Earth) Characteristics
Receiver Type	Digital	Digital
Closed-loop Carrier Loop Bandwidth (1 sided)	0.2 Hz – 200 Hz	0.1% of symbol rate
Carrier Tracking	Residual Carrier or Suppressed Carrier	Suppressed Carrier

Table 3. 34-m and 70-m Telemetry Reception Characteristics (Continued)

Parameter	S-, X-, and Ka-band Characteristics	26-GHz (Near Earth) Characteristics
Pre-digitization Bandwidth	36 MHz	400 MHz
Modulation Types	Residual Carrier BPSK with or without subcarrier, Suppressed Carrier BPSK, QPSK, OQPSK	Suppressed Carrier BPSK, QPSK, OQPSK, UQPSK
Subcarrier Frequencies	500 Hz – 2.0 MHz	Not Available
Subcarrier Data Rate (Residual Carrier)	4 s/s – 0.67 X fsubcarrier (s/s)	Not Available
Subcarrier Data Rate (Suppressed Carrier)	20 X loop B/W (s/s) – 0.67 X fsubcarrier (s/s)	Not Available
Direct Modulation (Residual Carrier)	10 ks/s – 26 Ms/s (NRZ) 100 s/s – 13 Ms/s (Bi-f)	Not Available
Direct Modulation (Suppressed Carrier)	20 X loop B/W (s/s) – 26 Ms/s (NRZ) 20 X loop B/W (s/s) – 13 Ms/s (Bi f)) 40 ks/s – 26 Ms/s (QPSK or OQPSK)	1 Ms/s to 350 Ms/s
Beacon Mode	1 of 4 tones, SNR > 5 dB-Hz	Not Available
Data Formats	NRZ (-L, -M, -S) Bi-f (-L, -M, -S)	NRZ (-L, -M, -S) Bi-f -L
Available Decoding	Short and long Constraint Convolutional, Reed-Solomon, Concatenated Convolutional and Reed-Solomon, Turbo	Short Constraint Convolutional, Reed-Solomon, Concatenated Convolutional and Reed-Solomon
Short Constraint Convolutional Decoding	k=7, r=1/2 CCSDS or DSN Connection, Optional De-randomization and alternate symbol inversion 10 Ms/s (max)	k=7, r=1/2 CCSDS Connection, Optional De-randomization 350 Ms/s (max)

Table 3. 34-m and 70-m Telemetry Reception Characteristics (Continued)

Parameter	S-, X-, and Ka-band Characteristics	26-GHz (Near Earth) Characteristics
Long Constraint Convolutional Decoding (1 station per complex)	k=3 – k=15 r=1/2 – r=1/6 6.6 Ms/s (max)	Not Available
Frame Synchronization	CCSDS and non-CCSDS, 6 Mb/s (max)	CCSDS, 350 Ms/s (Max)
Reed-Solomon Decoding	RS (255, 223), Interleave = 1 – 8	RS (255, 223), Interleave = 1 – 8
Turbo Decoding Frame Size Code Rate and Data Rate	CCSDS 1784, 3568, 7136, 8920 1/2 (1.6 Mb/s, max) 1/3 (1.6 Mb/s, max) 1/4 (TBD Mb/s, max) 1/6 (1.0 Mb/s, max)	Not Available

2.3.1 *Relative Power of Telemetry Signal Components*

It is possible to share the available downlink power between more than one type of modulation when using residual carrier power modulation schemes. The functions $\alpha(\theta)$ and $\beta(\theta)$, as shown in Table 4, are used to describe the allocation of downlink power between two or more modulation types.

The equations below provide the component to total power relationships for any combination of the modulating signals identified at Channels 1 through 4 although it is rare that more than two types of modulation will be used. Power not accounted for by these equations is distributed as inter-modulation products and is not available to the communications process. The modulation indices, ϕ, for all equations must be in units of radians, peak, and the modulation index for the unused channels should be set to zero.

Table 4. Definition of $\alpha(\theta)$ and $\beta(\theta)$ for θ in radians, peak

Telemetry type	$\alpha(\theta)$	$\beta(\theta)$	Remarks
squarewave subcarrier or data only	$\cos(\theta)$	$\sin(\theta)$	$\beta(\theta)$ includes data power in all harmonics
sinewave subcarrier	$J_0(\theta)$	$\sqrt{2}J_1(\theta)$	$\beta(\theta)$ only includes data power in fundamental harmonics

(1)   Channel 1 data ($D1$) directly modulates the carrier with modulation index ϕ_1.

(2)   Channel 2 data ($D2$) bi-phase modulates a square-wave or sine-wave subcarrier that is used to modulate the carrier with modulation index ϕ_2.

(3)   Channel 3 data ($D3$) bi-phase modulates a square-wave or sine-wave subcarrier that is used to modulate the carrier with modulation index ϕ_3.

(2)   Channel 4 data ($D4$) is a square-wave or sine-wave ranging signal that directly modulates the carrier with modulation index ϕ_4.

The carrier suppression is

$$\frac{P_C}{P_T} = \left[\cos(\phi_1)\cdot\alpha(\phi_2)\cdot\alpha(\phi_3)\cdot\alpha(\phi_4)\right]^2. \tag{1}$$

The ratio of the available data power to total power for each of the data streams is

$$\frac{P_{D1}}{P_T} = \left[\sin(\phi_1)\cdot\alpha(\phi_2)\cdot\alpha(\phi_3)\cdot\alpha(\phi_4)\right]^2, \tag{2}$$

$$\frac{P_{D2}}{P_T} = \left[\cos(\phi_1)\cdot\beta(\phi_2)\cdot\alpha(\phi_3)\cdot\alpha(\phi_4)\right]^2, \tag{3}$$

$$\frac{P_{D3}}{P_T} = \left[\cos(\phi_1)\cdot\alpha(\phi_2)\cdot\beta(\phi_3)\cdot\alpha(\phi_4)\right]^2, \tag{4}$$

$$\frac{P_{D4}}{P_T} = \left[\cos(\phi_1)\cdot\alpha(\phi_2)\cdot\alpha(\phi_3)\cdot\beta(\phi_4)\right]^2. \tag{5}$$

2.3.2 Definition of ST_B/N_O and ST_{SY}/N_O (dB)

Telemetry signal-to-noise ratios (SNRs) are expressed as bit SNR (represented as either ST_B/N_O or E_B/N_O) or symbol SNR (represented as either ST_{SY}/N_O or E_S/N_O). The distinction between symbols and bits is that when the telemetry data are encoded prior to transmission, channel bits (information bits plus overhead such as frame sync and parity bits) are the input to the encoder and symbols are the output. When coded data are processed after receipt on the ground, the telemetry stream consists of symbols until converted to bits again by the decoder at which time any overhead bits are discarded. The relationship between ST_{SY}/N_O and ST_B/N_O is:

$$ST_{SY}/N_0 = \frac{1}{r} \cdot ST_B/N_0 \qquad (6)$$

where

$$
\begin{array}{lll}
S & = & \text{the data power as defined in equations (1), (2), or (3);} \\
T_B & = & \text{the bit period,} \\
T_{SY} & = & \text{the symbol period,} \\
N_O & = & \text{the one-sided noise spectral density,} \\
r & = & \text{the number of symbols per bit.}
\end{array}
$$

Some typical values for r include:

1 for uncoded data,

2 for rate 1/2 convolutionally coded or turbo coded data,

6 for rate 1/6 convolutionally coded or turbo coded data,

255/223 for Reed-Solomon coded data,

$2 \times (255/223)$ for concatenated Reed-Solomon and rate 1/2 convolutionally coded data.

2.3.3 Carrier Loop SNR

The DSN Telemetry provides the user with an estimate of E_S/N_O. This can be used to calculate a value for Carrier Loop SNR that includes system losses. This provides both a way to validate link design and a way to determine the system loss in a controlled environment. The following equations provide the Carrier Loop SNR where B_L is the carrier loop bandwidth.

$$\rho_L = \frac{E_S/N_0}{\tan^2 \phi \cdot T_S \cdot B_L} \qquad \text{for squarewave and direct modulation.} \qquad (7)$$

$$\rho_L = \frac{(E_S/N_0) \cdot J_0^2(\phi)}{2J_2^2(\phi) \cdot T_S \cdot B_L} \qquad \text{for sinewave subcarrier modulation.} \qquad (8)$$

When using these relationships with more than one data stream modulating the carrier, care should be taken to use the values of E_S/N_O, T_{SY}, and ϕ that all pertain to the same data stream.

2.3.4   *Arraying*

The DSN Telemetry can combine the intermediate frequencies from the 70-m and 34-m antennas at each complex by full spectrum combining. The output of the Full Spectrum Combiner appears to be another IF spectrum that can be selected by from one to four receivers.

Ideally, the combined telemetry SNR is:

$$\left(\frac{E_b}{N_0}\right)\!\Sigma \ = \sum_{i=1}^{n}\left(\frac{E_b}{N_0}\right)_i \qquad (9)$$

where

$$\left(\frac{E_b}{N_0}\right) \ = \qquad \text{the telemetry SNR at the input of the } i\text{th receiver for the non-arrayed case}$$

$$n \quad = \qquad \text{the number of streams combined.}$$

The ratio of the array sum E_b/N_0 to the E_b/N_0 of the master antenna (usually the antenna with the highest individual E_b/N_0) is the array gain. The individual SNRs are proportional to the ratios of antenna gain to system noise temperature. G/T, at each of the contributing antennas. Table 5 is a tabulation of G/T ratios relative to a 34-m and 70-m antenna for individual antennas and for combinations of arrayed antennas. The antenna performance values used to calculate the values in this table are those of the average antenna for each antenna type listed in Table 2 at its peak gain elevation angle. Relative aperture will approach the ratio of the antenna areas at low elevation angles where the high atmospheric temperature component becomes dominant over the LNA temperature.

The values in the table must be considered to be approximations as they do not take into consideration the particular antennas being arrayed, the effects of varying elevation, and the selected support configuration (polarization, diplexed vs. non-diplexed, etc.). The "Equivalent (dB)" column has been reduced by 0.3 dB to accommodate the typical combining loss. Thus, the combination of one S-band 34-m antenna with the 70-m antenna is not listed as the combining loss is approximately equal to the array gain.

Table 5. Relative Telemetry Aperture

Practical Arrays [Best Antenna, Arrayed Antenna(s)]	G/T Ratio Relative to Reference Antenna	Equivalent (dB) Less Combining Loss
Relative to 34-m BWG Antenna		
S-band, 34-m BWG & 34-m HEF	1.66	1.90
X-band, 2 34-m (BWG or HEF)	2	2.71
X-band, 3 34-m (BWG or HEF)	3	4.47
X-band, 3 34-m BWG and HEF	4	5.72
Ka-band, 2 34-m BWG	2	2.71
Relative to 70-m Antenna		
S-band, 70-m, 34-m BWG & 34-m HEF	1.23	0.60
X-band, 70-m, 1 34-m (BWG or HEF)	1.18	0.42
X-band, 70-m, 2 34-m (BWG or HEF)	1.36	1.03
X-band, 70-m, 3 34-m (BWG or HEF)	1.53	1.55
X-band, 70-m, 3 34-m BWG and HEF	1.70	2.01

3 Typical Performance

Figures 2 and 3 provide the expected performance at X-band and Ka-band using a reference spacecraft having the characteristics listed in Table 6. Spacecraft antenna size and transmitter power have been made equal to provide a fair comparison. These figures illustrate that, all other factors being the same, the performance of the 34-m BWG antennas at Ka-band is essentially the same as the 70-m antennas at X-band. It is also evident that use of Ka-band omni-directional antenna for emergency purposes is not practical for most spacecraft.

4 Recommendations for Mission Design

4.1 Operating Frequency

The DSN supports telemetry reception in the S-, X-, and Ka-bands. The trend in deep space communications (Category B spacecraft) has been towards the higher frequencies. Near-Earth (Category A) spacecraft have used S-band exclusively but are adopting 26 GHz for high data rate applications.
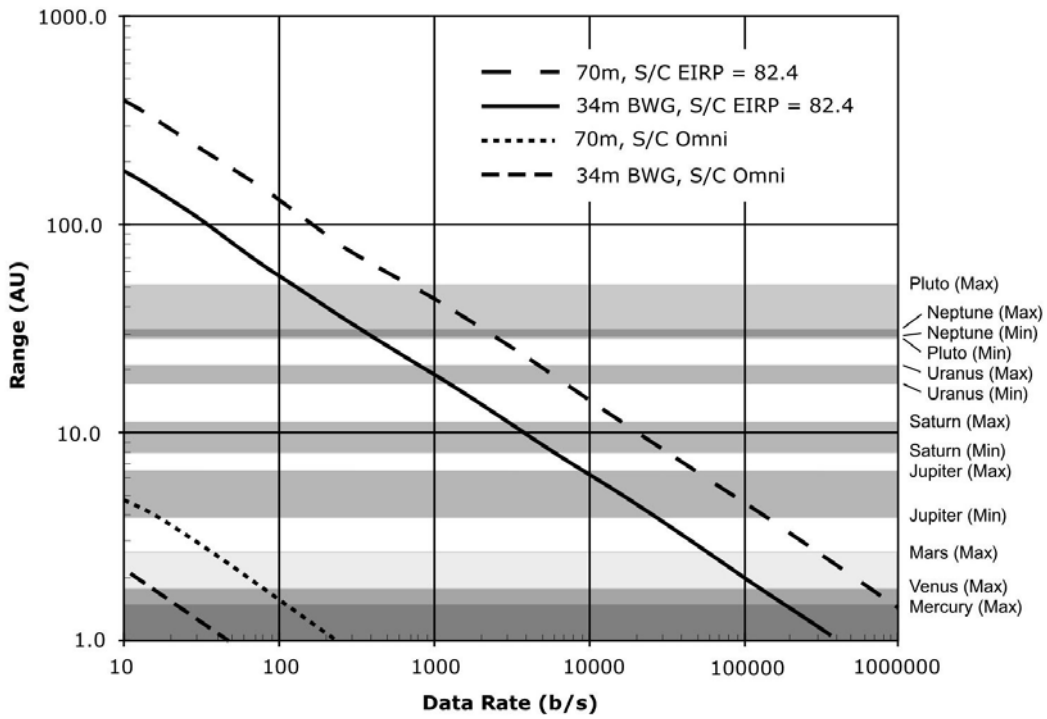
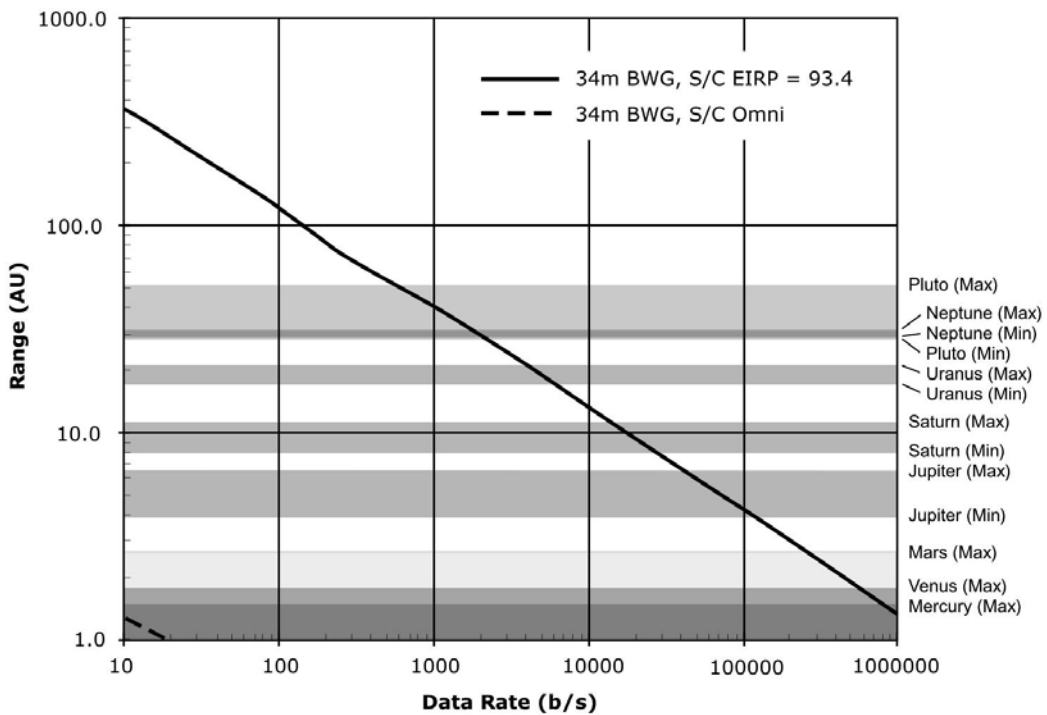Figure 2.   X-band Telemetry Performance with Reference Spacacecraft

Figure 3.   Ka-band Telemetry Performance with Reference Spacecraft

Table 6. Reference Spacecraft Characteristics

Parameter	X-band	Ka-band
Transmitter Power	35 W	35 W
Circuit Loses	2 dB	2 dB
Hi-gain Antenna (S/C HGA)	39 dB	50 dB
Pointing Loss (S/C HGA)	0.5 dB	1.5 dB
Coding	1784, r=1/3 Turbo	1784, r=1/3 Turbo
Weather	CD = 50	CD = 50
DSN Vacuum G/T	55.3 dB (34-m), 63.0 dB (70-m)	65.5 dB
Pointing Loss (DSN)	0.1 dB	0.1 dB
Margin	3 dB	3 dB

4.1.1   *S-band*

S-band has been the frequency of choice for near-Earth spacecraft where link performance is relatively easy to obtain and the mass of spacecraft components is not as critical as with deep space spacecraft. Other advantages include the availability of low-cost spacecraft components and ground resources along with compatibility with the Goddard Spaceflight Center (GSFC)-managed Tracking and Data Relay Satellite System (TDRSS). The principal disadvantage of S-band for Category A spacecraft is that the total allocation bandwidth is 90 MHz. This creates a significant possibility of interference between spacecraft.

The principal advantage of S-band for deep space (Category B) spacecraft is low space loss that may be important for applications where there is little or no antenna gain at the transmitting (space) end of the link. Its disadvantages include larger spacecraft components, a limited channel bandwidth of 370 kHz, and significant link degradation when the link must pass near the sun. While it is possible to use more than one channel, the total S-band allocation bandwidth is only 10 MHz.

4.1.2   *K-band (25.5 – 27.0 GHz)*

K-band is available for high data-rate, Category A (near-Earth) missions in combination with S-band for command and engineering telemetry. It provides an advantage over an S-band for spacecraft with equivalent specifications of approximately 20 dB. Its principal disadvantage is degradation from adverse weather but this can be ameliorated by a combination of on-board data storage, weather forecasting, and an adaptive downlink data rate strategy.

4.1.3   X-band

X-band is presently the most heavily used allocation for deep space missions. It is the highest frequency band in which uplink is currently supported making it possible to have a single-band spacecraft with a moderately high telemetry rate. The standard telemetry channel bandwidth at X-band is 1.4 MHz and, while missions may use more than one channel, the total X-band allocation bandwidth is only 50 MHz and the use of bandwidth-efficient modulation is preferred over multiple channel use.

4.1.4   Ka band (31.8 – 32.3 GHz)

Ka-band is recommended for high data-rate missions in combination with X-band for command and engineering or emergency telemetry. It has no defined channels as its total allocation of 500 MHz cannot be accommodated with a single turn-around ratio from S- or X-bands. It provides an advantage over an X-band for spacecraft with equivalent specifications of approximately 9 dB and is the least susceptible to solar effects. Its principal disadvantages are degradation from adverse weather, high space loss that precludes use of an omni-directional antenna for emergency transmission, and somewhat greater spacecraft pointing requirements. Adverse weather effects can be ameliorated by a combination of on-board data storage, weather forecasting, and an adaptive downlink data rate strategy.

4.2   Telemetry Modulation

The DSN supports a wide range of telemetry modulation schemes. Some advantages and disadvantages of the various schemes are discussed in the following paragraphs.

4.2.1   Residual-Carrier BPSK

Residual carrier BPSK using a squarewave subcarrier is the modulation scheme that has been most commonly employed for deep space telemetry. There are historical reasons for this but it remains a good choice in many applications. A residual carrier provides the ability to share downlink power to support additional functions such as two-way ranging and Delta-differential One-way Ranging (ΔDOR). The ability of a spacecraft to provide an un-modulated carrier is also useful for Radio Science investigations. Residual carrier tracking tolerates a lower carrier loop SNR before experiencing cycle slips and is not subject to the more damaging half-cycle slips that are possible with suppressed carrier tracking. The subcarrier keeps the data sidebands away from the residual carrier in the frequency domain so the carrier can be tracked without interference. Use of a subcarrier occupies more spectrum than direct modulation however, the occupied bandwidth is typically not an issue for low data-rate telemetry.

Sinewave subcarriers have been used for Category A (near Earth) missions where relatively high power and wide antenna beamwidths make spectrum conservation essential. The higher-order harmonics of a sinewave subcarrier fall off faster with the result being that less bandwidth is occupied than by a squarewave subcarrier of the same frequency. The disadvantage of sinewave subcarriers is that the receiver can recover only the power in the fundamental

harmonics. Data power transmitted in the higher-order harmonics is lost. This is contrasted to squarewave subcarriers where all data power within the bandwidth of the receiver is recovered.

Direct carrier modulation is a good choice for medium and high-rate telemetry when other considerations require a residual carrier. The baseline performance of this scheme is the same as that when using a squarewave subcarrier and spectral occupancy is no more than half that of the equivalent squarewave subcarrier system.

4.2.2   *Suppressed-Carrier BPSK*

Suppressed-carrier BPSK provides approximately the same performance at high data rates as residual-carrier BPSK and improved performance at some medium data rates. The bandwidth occupancy is the same as residual-carrier BPSK without a subcarrier. A disadvantage of suppressed-carrier BPSK is that telemetry must be disabled in order to perform DSN ranging or ΔDOR.

4.2.3   *QPSK and OQPSK*

QPSK and Offset QPSK offer better bandwidth efficiency than BPSK. For a given binary symbol rate, a QPSK or OQPSK carrier occupies only half the bandwidth of a BPSK-modulated carrier (with no subcarrier). QPSK and OQPSK have the same disadvantage as suppressed-carrier BPSK in that that telemetry must be disabled in order to perform DSN ranging or ΔDOR.

The baseline telemetry performance of QPSK and OQPSK is the same as suppressed-carrier BPSK at high data rates. When shaped data pulses are used, there is some advantage to OQPSK, relative to QPSK, which accounts for the popularity of OQPSK in satellite communications; however, for unshaped data pulses, the performance and spectral occupancy of QPSK and OQSPK are the same.

4.3   *Coding Schemes*

Selection of coding scheme is independent of modulation scheme and involves the tradeoff of four considerations. These are coding gain, bandwidth, latency, and error floor. In general, coding gain increases with bandwidth and latency. The following coding schemes are supported by the DSN.

4.3.1   *Uncoded*

Uncoded data requires the least bandwidth and has the lowest latency. Its primary use is for transfer of extremely high data rates in bandwidth-limited situations when adequate link margin is available.

4.3.2   Reed-Solomon Code

The (255,223) Reed-Solomon (RS) code used by the DSN is capable of correcting up to 16 symbol errors out of each 255, corresponding to a bit error rate (BER) at the input of the decoder of 6.2×10^{-2}. A failure to decode is declared at BERs greater than this. An SNR of approximately 3-dBs is required when system losses are taken into consideration. It has a modest bandwidth expansion but the lack of performance near threshold limits its use to high E_B/N_O conditions.

4.3.3   Short Constraint Length, Rate 1/2 Convolutional Code

Short constraint length ($k = 7$), rate 1/2 convolutional code is a low-latency code that requires twice the bandwidth of uncoded data but provides coding gain for any input SNR. Its low latency makes it a good choice for low rate, emergency communications when recovery of data in real-time may outweigh the coding gain of higher-latency codes.

4.3.4   Concatenated Reed-Solomon and Rate 1/2 Convolutional Codes

When Reed-Solomon encoded spacecraft data is rate 1/2 convolutionally encoded before transmission, the resultant code has a slightly greater bandwidth expansion but significantly better performance at all SNRs than either of its components. This is because the convolutional decoder improves the input symbol error rate to the Reed-Solomon decoder at low SNRs while the RS decoder improves the output error rate for all SNRs above its input threshold. As convolutional decoders tend to produce bursts of errors as they near their threshold, they can overwhelm the correction capability of the RS decoder. This can be alleviated by a technique called *interleaving* (See module 208) that trades improved performance for increased latency.

4.3.5   Long Constraint-Length, Higher-Rate Convolutional Codes

Long constraint-length convolutional codes with rates up to 1/6 can be processed on one link at a time at each complex. These codes offer significant improvements over the k=7, r=1/2 code but at the expense of bandwidths expansions of from 3 to 6. As is the case with short constraint-length codes, they can be concatenated with Reed-Solomon coding for better performance. Use of these codes is discouraged because of their limited support within the DSN.

4.3.6   Turbo Codes

Turbo codes provide near Shannon-limit performance with bandwidth expansions from slightly more than 2 to slightly more than 6. Block sizes of 1784, 3568, 7136, and 8920 symbols are accommodated. The smaller block sizes are intended for lower data rates while using larger block sizes as the data rate increases reduces coding overhead. Their principal disadvantages are the amount of processing that must be done to decode them and the presence of an error floor at a Frame Error Rate of about 10^{-6}. The decoding complexity results in increased latency and limits the rate to that established by number of frames that can be in-process at any time and the processing time for each frame.

5 *Proposed Capabilities*

The following paragraphs discuss capabilities that have not yet been implemented by the DSN but have adequate maturity to be considered for spacecraft mission and equipment design. Telecommunications engineers are advised that any capabilities discussed in this section cannot be committed to except by negotiation with the DSN Mission Commitments Program Office.

5.1 *Low-density Parity-Check Codes*

Low-Density Parity-Check codes conforming to the code family specified in Section 3 of the CCSDS Experimental Specification 131.1-O-2 are under consideration as a complement to codes currently implemented in the DSN.

5.2 *Bandwidth-efficient Modulation*

Several bandwidth-efficient modulation schemes are under consideration to permit the maximum amount of data to be returned within the allocated frequency bands. The most likely candidate for implementation is Gaussian minimum-shift keying (GMSK).

5.3 *Weather-related Service Management*

New operational methods will be implemented to maximize the data return at Ka-band where atmospheric effects are much greater than at S- or X-band. The anticipated link performance at a specified confidence level, based on both historical models and near-term forecasts, will be made available to projects. An optimum data rate or the two optimum data rates for a pass will also be provided based on the expected weather and the range of required elevation angles for the pass. The project will be given the option to uplink the appropriate commands to their spacecraft in time to adapt the downlink data rate to the optimum value(s) for the expected weather.