Voyager
Telecommunications

Roger Ludwig and Jim Taylor

March 2002

JPL DESCANSO

Deep Space Communications and Navigation Systems
Center of Excellence

Design and Performance Summary Series

DESCANSO Design and Performance Summary Series

Article 4

Voyager Telecommunications

Roger Ludwig and Jim Taylor
Jet Propulsion Laboratory,
California Institute of Technology
Pasadena, California

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

March 2002

This research was carried out at the
Jet Propulsion Laboratory, California Institute of Technology,
under a contract with the
National Aeronautics and Space Administration.

Voyager: The Interstellar Mission

After exploring the outer planets—Jupiter, Saturn, Uranus, and Neptune—the Voyager spacecraft are seeking the edge of the solar system and heading toward their final destination: interstellar space.

These words acknowledge the Voyager mission's proud planetary past and introduce the interstellar challenge ahead. We chose *"Leaving Home"* as the cover image for the Voyager Interstellar Mission because it portrays the Voyager 2 spacecraft as it leaves the solar system and embarks on its exploration of the dark and mysterious environment of interstellar space. The Voyagers returned science data from Jupiter in 1979 and from Saturn, Uranus, and Neptune in the 1980s. The Interstellar Mission began in January 1990 and is planned to continue through 2020. The spacecraft on the cover looks very much like the full-scale model displayed in von Kármán Auditorium at the Jet Propulsion Laboratory.

Not farewell,
But fare forward, voyagers
T.S. Eliot[1]

This article was originally published on the website, DESCANSO: Deep Space Communications and Systems Navigation, http://descanso.jpl.nasa.gov/index_ext.html

[1] From *The Dry Salvages* (1941), excerpted in [5]. Also referenced in http://president.ua.edu/talks/looking.html and http://www.anglicancommunion.org/acns/lambeth/lc117.html

DESCANSO DESIGN AND PERFORMANCE SUMMARY SERIES

Issued by the Deep-Space Communications and Navigation Systems
Center of Excellence
Jet Propulsion Laboratory
California Institute of Technology

Joseph H. Yuen, Editor-in-Chief

Previously Published Articles in This Series

Article 1—"Mars Global Surveyor Telecommunications"
Jim Taylor, Kar-Ming Cheung, and Chao-Jen Wong

Article 2—"Deep Space 1 Telecommunications"
Jim Taylor, Michela Muñoz Fernández, Ana I. Bolea Alamañac, and Kar-Ming Cheung

Article 3—"Cassini Telecommunications"
Jim Taylor, Laura Sakamoto, and Chao-Jen Wong

Table of Contents

List of Figures

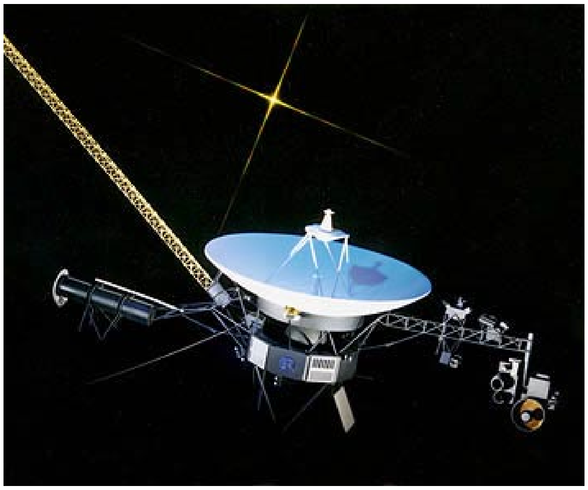
List of Tables

Foreword

This Design and Performance Summary Series, issued by the Deep Space Communications and Navigation Systems Center of Excellence (DESCANSO), is a companion series to the DESCANSO Monograph Series. Authored by experienced scientists and engineers who participated in and contributed to deep-space missions, each article in this series summarizes the design and performance for major systems, such as communications and navigation, for each mission. In addition, the series illustrates the progression of system design from mission to mission. Lastly, it collectively provides readers with a broad overview of the mission systems described.

Joseph H. Yuen
DESCANSO Leader

Preface



This article describes how the two Voyager spacecraft and the Deep Space Network (DSN) ground systems receive and transmit data. The primary purpose of this article is to provide a reasonably complete single source from which to look up specifics of the Voyager radio communications.

The description is at a functional level, intended to illuminate the unique Voyager mission requirements and constraints that led to the design of the Voyager spacecraft communications system in the 1970s and the upgrade of flight software and the ground communication system in the 1980s. The article emphasizes how the end-to-end communication system continues to serve the Voyager Interstellar Mission (VIM) that began in the 1990s. This article will be updated when needed as the mission progresses.

The Voyager spacecraft were designed and constructed at the Jet Propulsion Laboratory (JPL) in Pasadena, California. The flight team is also located at JPL.

Acknowledgements

Much of the telecom design information in this article was obtained from original Voyager prime mission design documentation: the design control document for the telecommunications links [1], the functional description of the telecommunications system [2], and the hardware design requirement for the modulation demodulation subsystem (MDS) [3]. Much of the mission and operational information was obtained from the Voyager Operational Handbook [4], the Voyager Neptune Travel Guide [5], and the Voyager website, Enrique Medina Webmaster [6]. The cover image was created by Pat Rawlings[1] and is courtesy of the National Aeronautics and Space Administration (NASA).

The authors are especially grateful to Dave Bell, Kar-Ming Cheung, and Ed Massey for their advice, suggestions, and helpful information.

[1] NASA artwork by Pat Rawlings/SAIC. Caption: About nine billion miles from Earth, Voyager 2 leaves the influence of Sol and enters interstellar space. http://www.challenger.org/gallery/misc/images/LeavingHome3.jpg

Section 1

Voyager Interstellar Mission Description

The two Voyager spacecraft are on a unique 43-year (1977-2020) exploratory mission. They are now traversing regions of space never before encountered, building on the legacy of NASA's* most successful and productive interplanetary exploration endeavor [7].

Voyager 1 and Voyager 2 were launched in 1977, within the 3-year period that occurs once every 176 years when a unique alignment of Earth, Jupiter, Saturn, Uranus and Neptune presents the opportunity for a "Grand Tour." Both spacecraft had close encounters with Jupiter and Saturn. Voyager 1 (launched second) arrived at Saturn first and successfully scanned the scientifically interesting and high-priority moon Titan, then passed somewhat "beneath" Saturn and was deflected "up," north of the ecliptic plane at an angle of approximately 35 deg. This freed the later-arriving Voyager 2 (launched first) from the Titan obligation, allowing it to be targeted on to Uranus and Neptune. Voyager 2 departed Neptune and the ecliptic heading approximately 48 deg south. Voyager flight paths are displayed in Figure 1-1.

The remainder of this section focuses on the Voyager Interstellar Mission (VIM), the current mission phase,[1] which began in January 1990. The VIM is critical for meeting certain science objectives most recently defined in NASA's Space Science Enterprise 2000 Strategic Plan.[2] One objective is to "understand our changing Sun and its effects throughout the solar system." The Voyager mission is the only one currently exploring the outer heliosphere. The Voyagers are ideally situated to contribute to our understanding of events occurring within and eventually beyond the farthest reaches of the immense region carved out of the interstellar medium by the Sun.

Other Strategic Plan objectives are to "Learn how galaxies, stars, and planets form, interact, and evolve" and to "Use the exotic space environments within our solar system as natural

[1] Earlier mission phases included launch and Earth-Jupiter cruise and the planetary mission (Jupiter, Saturn, Uranus, and Neptune encounters). See [6], particularly http://vraptor.jpl.nasa.gov/voyager/voyager_fs.html

[2] The Strategic Plan is available at http://spacescience.nasa.gov/admin/pubs/strategy/2000/index.html

*Look up this and other abbreviations and acronyms in the list that begins on page 45.

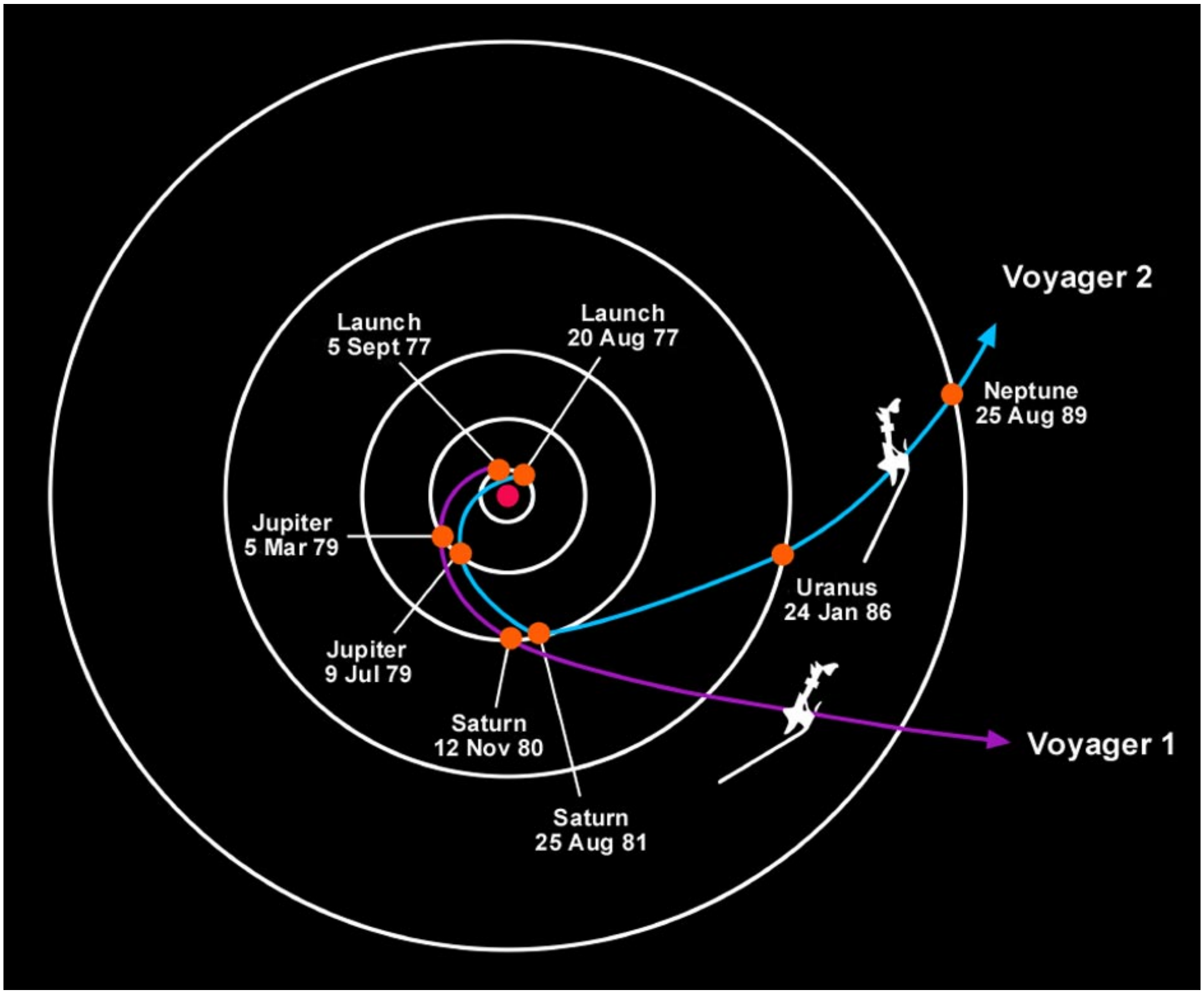


Fig. 1-1. Voyager flight paths.

science laboratories and cross the outer boundary of the solar system to explore the nearby environments of our galaxy." The Voyager spacecraft are the only spacecraft in position to carry out these goals. The longevity of the Voyagers makes them ideal platforms for studying long-term solar wind variations. Their distance makes them ideal for studying the evolution of the solar wind, shocks, and cosmic rays. The interpretation of Voyager data is greatly enhanced by the ability to compare it with data from Earth-orbiting spacecraft (IMP 8, WIND, ACE, SAMPEX) and Ulysses.

The Voyagers and Pioneers 10 and 11, launched four and five years earlier, will be the first four spacecraft to escape the gravity of our solar system on their journeys into the Milky Way. Due to better launch dates and a speed advantage, the Voyagers are now outdistancing the Pioneers and achieving certain milestones first. Voyager 1 crossed Pluto's orbit in 1988 before Pioneer 10 at about 29 astronomical units (AU), when Pluto's orbit was inside Neptune's. Although Pioneer 11 crossed Uranus' orbit just before Voyager 2's 1986 encounter, Voyager 2 encountered Neptune in 1989 before Pioneer 11 crossed Neptune's orbit.

The Voyagers, depicted in Figure 1-2, each carry the following instruments:[3]

- Plasma spectrometer (PLS) measures velocity, density, and pressure of plasma ions
- Low-energy charged particles (LECP) experiment measures electrons, protons, and heavier ions in the tens of KeV to MeV range
- Cosmic ray system (CRS) measures cosmic ray electron and nuclei energies in the 3 to 30 MeV range
- Triaxial fluxgate magnetometer (MAG) measures the strengths of planetary and interplanetary magnetic fields
- Plasma wave system (PWS) observes low-radio-frequency electron-density profiles and plasma wave-particle interactions
- Planetary radio astronomy (PRA) experiment studied radio-emission signals from Jupiter and Saturn
- Ultraviolet spectrometer (UVS) measures atmospheric properties in the ultraviolet spectrum
- Imaging science system (ISS) includes one narrow-angle, long-focal-length camera and one wide-angle, short-focal-length camera
- Photopolarimeter system (PPS), to collect emission intensity data, includes a polarizer and a filter for one of eight bands in the 220- to 730-nm spectral region
- Infrared interferometer spectrometer (IRIS) and radiometer measures local and global energy balance and vertical temperature profiles of the planets, satellites, and rings.

The spacecraft and instruments are generally in good health. With two exceptions, the instruments work well and all have the sensitivity to continue observations in the environments expected beyond the termination shock and heliopause. The PLS on Voyager 1 no longer returns useful data. The Voyager 2 MAG experiment has had a continuing problem with noise generated by the spacecraft and other instruments making reliable analysis very difficult, but the increase in magnetic field strength as solar maximum approached in 2001 made that problem more tractable.

The VIM consists of three distinct phases: termination shock, heliosheath exploration, and interstellar exploration. Today, both spacecraft are searching for the termination shock. They operate in an environment controlled by the Sun's magnetic field with plasma particles dominated by those contained in the expanding supersonic solar wind. They sample the interplanetary/interstellar media and solar wind, observe ultraviolet sources among stars, and sense for first signs of the termination shock wave.

The exact location of the wave is not known; however, most of the current estimates time the Voyager 1 termination shock to be seen between 2002 and 2005 at a distance of 90 ±5 AU. At the termination shock wave, the solar wind slows from supersonic to subsonic speed (from an average of about 400 km/s near the Earth's orbit to 20 km/s), and large changes in plasma

---

[3] Figure 1-2 shows these instrument locations on the spacecraft. For more information on the instruments and experiments, see http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1977-084A&ex=* .

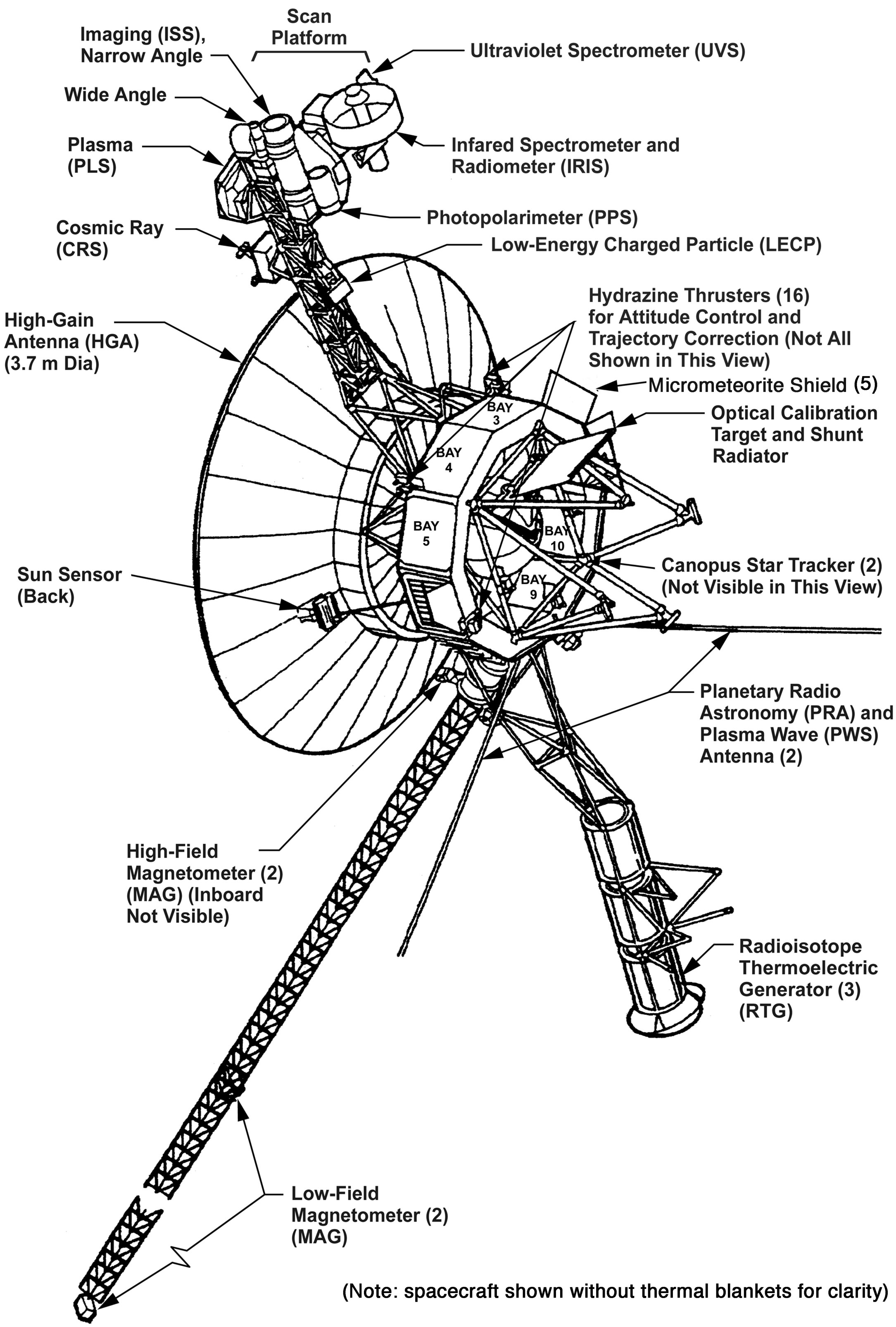


Fig. 1-2. Voyager spacecraft and science instruments.

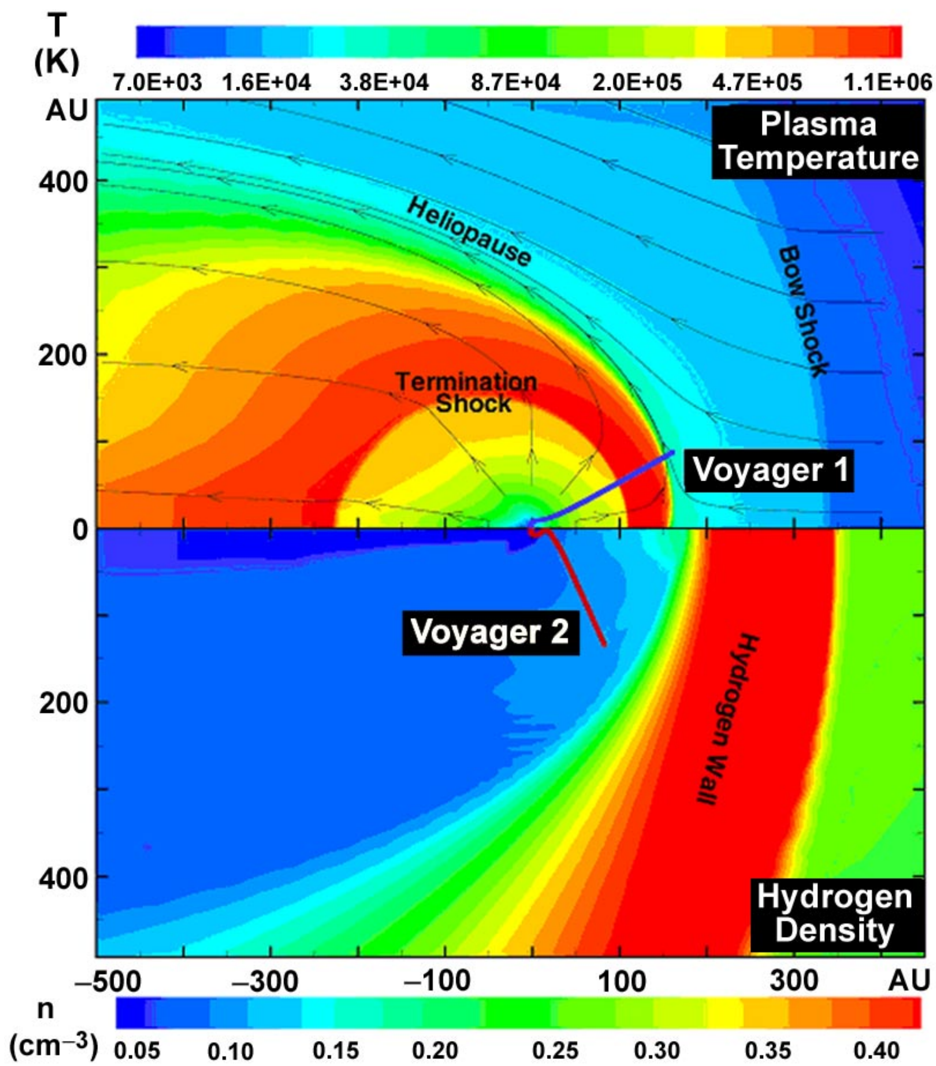


Fig. 1-3. Simulation of plasma and neutral environments explored by the Voyager Interstellar Mission, May 2001.

flow direction and magnetic field orientation occur. Multiple cycles, in which a spacecraft overtakes the shock wave only to be retaken by it, may occur.

Heliosheath exploration will begin after final passage through the termination shock. The heliosheath is dominated by the magnetic field of the Sun and by particles contained in the subsonic solar wind. The thickness of the heliosheath is uncertain and could be tens of AU thick, taking several years to traverse.

Heliosheath exploration ends with passage through the heliopause, the outer extent of the magnetic field of the Sun and the solar wind, marking a transition to an environment dominated by interstellar wind and the start of interstellar exploration.

The VIM engineering challenges are to reach the heliopause with operational spacecraft and to return the first-ever science observations from that region.

Figure 1-3 shows a simulation of the plasma and neutral environments being explored by the VIM as of May 2001. The top panel shows contours of plasma temperature as indicated by the color bar and streamlines of plasma flow. The bottom panel shows density contours of neutral hydrogen. The X- and Y-axes in AU and the spacecraft trajectories show the distance from the Sun [8].

The duration of the VIM is limited primarily by the decreasing spacecraft electrical power (from the two radioisotope thermoelectric generators [RTGs]) and telemetry link capability. Table 1-1 provides life estimates for electrical power, telecommunications, and hydrazine (for attitude control). With Voyager 2 now far south of the ecliptic, it is not visible from the northern hemisphere stations. The table shows telemetry data rate limits for two Deep Space Station sizes at Goldstone, California for Voyager 1 and near Canberra, Australia for Voyager 2. Limits for the third site, near Madrid, Spain, are similar to those at Goldstone for Voyager 1.

Voyager continously reviews, updates, and consolidates processes in order to increase efficiency and improve its return on public investment. During VIM, Voyager has reduced its flight team staffing by 97%, from approximately 300 in 1989 to 10 in 2002. Reduced staffing increasingly constrains VIM in the areas of non-routine activity planning, execution and analysis, and anomaly response.

The allocations of VIM telemetry rate to types of data are as follows. At 160 bps or 600 bps, the different data types are interleaved.

- 7200, 1400 bps tape recorder playbacks
- 600 bps real-time fields, particles, and waves; full UVS; engineering
- 160 bps real-time fields, particles, and waves; UVS subset; engineering
- 40 bps real-time engineering data.

Table 1-1. Spacecraft lifetime estimates in calendar years.

	Voyager 1	Voyager 2
Electrical power	2023	2023
Telemetry link capability		
7200 bps, 70-/34-m HEF[a] array	1994	1998
1400 bps, 70-m antenna	2007	2011
600 bps, 70-m antenna	2026	2030
600 bps, 34-m HEF antenna	2003	2007
160 bps, 34-m HEF antenna	2024	2029
40 bps, 34-m HEF antenna	2050	2057
Hydrazine for attitude control	2040	2048

[a] High efficiency.

Section 2

Overview of Telecom Functional Capabilities

This section describes telecom system capabilities that existed at launch. Figure 2-1 is an overview of the functions of the spacecraft and DSN* telecom system. Some functions, such as S-band downlink and the spacecraft low-gain antenna, are no longer used. Section 7, **Operational Scenarios**, describes the combinations of capabilities being used in the VIM.*

2.1 Uplink

2.1.1 Uplink Carrier

The Deep Space Station (DSS) transmits an uplink carrier frequency[1] of 2114.676697 MHz to Voyager 1 and 2113.312500 MHz to Voyager 2. The carrier may be unmodulated or modulated with command (CMD) or ranging (RNG) data or both. Phase lock to the uplink carrier is provided. When the transponder[2] receiver (RCVR) is phase locked, its voltage-controlled oscillator (VCO) provides a frequency reference to the exciter to generate a downlink carrier that is two-way coherent with the uplink.

[1] These frequencies are DSN Channel 18 and Channel 14, respectively. The specific values are the defined channel center frequencies. The DSN channels are defined in [10], module 201, *Frequency and Channel Assignments*.

[2] A transponder, like a transceiver, includes a receiver and an exciter. An exciter is the part of a radio transmitter that produces the downlink carrier frequency. A transponder differs from a transceiver in that a transponder has the capability to make the downlink carrier frequency coherent in phase with the uplink carrier frequency.

*Look up this and other abbreviations and acronyms in the list that begins on page 45.

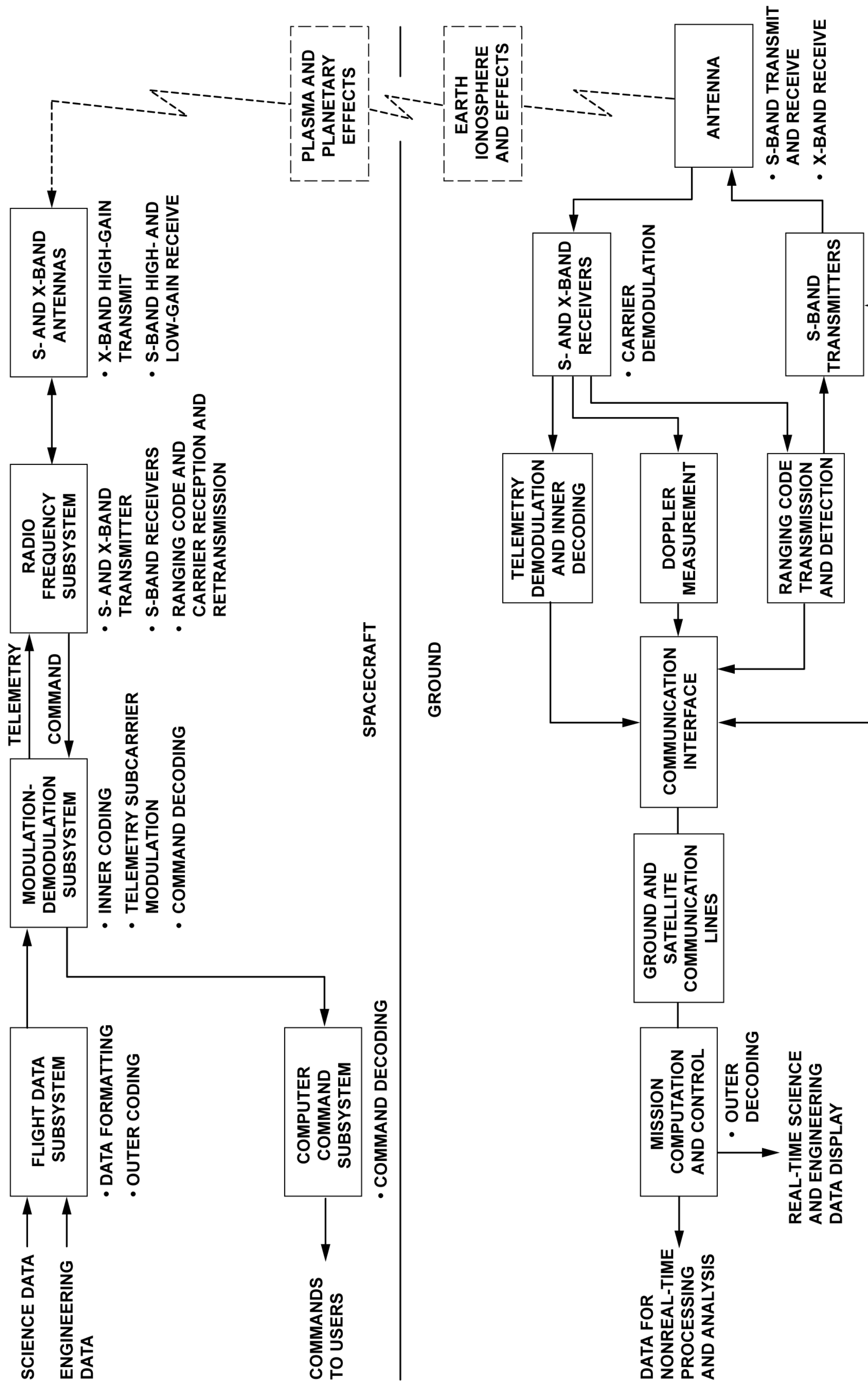


Fig. 2-1. Overview of spacecraft and ground telecommunications functions for Voyager.

2.1.2 Ranging Modulation

Voyager uses standard DSN turnaround sequential ranging modulation.[3] The spacecraft transponder has the capability to demodulate the uplink ranging data from the uplink carrier and modulate it on the S-band[4] downlink carrier, the X-band downlink carrier, or both downlink carriers simultaneously. For the ranging acquisitions to be valid, the transponder must be configured (set) for two-way coherent operation.

2.1.3 Command Demodulation

Voyager receives and demodulates the command signal[5] from the uplink carrier. The signal consists of 16-bps, Manchester-encoded commands, bi-phase modulated onto a squarewave subcarrier frequency of 512 Hz.

2.2 Downlink

2.2.1 Downlink Carriers

When the transponder is set to the two-way coherent tracking mode and is locked to an uplink carrier, the received carrier frequency is used to generate phase and frequency coherent downlink carriers. The ratio between downlink frequency and uplink frequency is 240/221 for the S-band downlink and 880/221 for the X-band downlink.

The transponder may also be set to a mode in which the receiver may be locked to an uplink, but the downlink carrier is not coherent with that uplink carrier.[6] In this mode, or when the receiver is not locked to an uplink carrier, an onboard frequency source generates the downlink carrier frequencies.

2.2.2 Transmit Frequencies

Table 2-1 contains the downlink carrier frequencies and associated DSN channel numbers that Voyager 1 and Voyager 2 produce in the coherent and non-coherent modes.

2.2.3 Downlink Polarizations

Table 2-2 defines the downlink polarization produced at S-band (from either power amplifier) and X-band (from the selected traveling wave tube amplifier (TWTA).

---

[3] "Turnaround" means the ranging modulation on the uplink carrier is demodulated by the spacecraft receiver and remodulated on the downlink carrier. "Sequential" means that a series of ranging codes are transmitted one after the other, allowing for both sufficient resolution in range and elimination of ambiguity in range. The DSN ranging modulation is described in [10], module 203, *Sequential Ranging*.

[4] For spacecraft in the deep space frequency bands, S-band refers to an uplink frequency of about 2115 MHz and a downlink frequency of about 2295 MHz. X-band refers to a downlink frequency of about 8415 MHz.

[5] The DSN command modulation is described in [10], module 205, *34-m and 70-m Command*.

[6] The described mode is "two-way non-coherent on," or "TWNC on." Voyager is one of many JPL Deep Space missions that have two transponder modes called "TWNC on" and "TWNC off." TWNC is pronounced "twink." The TWNC on mode means the downlink frequency cannot be coherent with an uplink frequency. The TWNC off mode means the downlink will be coherent with the uplink when the transponder's receiver is in lock.

Table 2-1. Voyager 1 and Voyager 2 downlink frequencies and channels.

Spacecraft	Coherent Downlink Frequency (MHz)	Channel	Non-Coherent Downlink Frequency (MHz)	Channel
Voyager 1	2296.481481	18	2295.000000	14
Voyager 2	2295.000000	14	2296.481481	18
Voyager 1	8420.432097	18	8415.000000	14
Voyager 2	8415.000000	14	8420.432097	18

Table 2-2. S-band and X-band downlink polarizations.

Link	Polarization
S-band	Right circular
X-band TWTA-1	Left circular
X-band TWTA-2	Right circular

2.2.4 Telemetry Modulation

The telemetry comes to the telemetry modulation unit (TMU) separately as a “low-rate” channel and a “high-rate” channel. Low rate is 40 bps only and its routing through the TMU is such that it can only be downlinked as uncoded bits. High rate, one of a set of rates between 10 bps and 115.2 kbps, is downlinked as coded symbols. The TMU encodes the high rate data stream with a convolutional code having constraint length of 7 and a symbol rate equal to twice the bit rate (k=7, r=1/2).

Either modulator can bi-phase-modulate the telemetry symbols onto either a 22.5-kHz or a 360-kHz subcarrier. A subcarrier is a symmetrical square wave signal derived from a TMU crystal oscillator that has a nominal frequency of 2.88 MHz. The 360-kHz subcarrier is required for bit rates greater than 7.2 kbps. The TMU has one modulator for the S-band downlink and another for X-band downlink. The modulated subcarrier goes to the S- or X-band exciter.[7]

[7] DSN telemetry data bit, symbol, and subcarrier waveform requirements are defined in [10], module 207, *34-m and 70-m Telemetry Reception.*

Section 3

Spacecraft Telecom System Design

3.1 Spacecraft Telecom System Overview

The telecom system consists of three subsystems, as detailed in Table 3-1. The table shows the subsystem acronyms for reference.

Table 3-1. Voyager spacecraft telecom subsystems and their components.

Subsystem/Component	Quantity
Radio frequency subsystem (RFS)	
S-band receiver (S-RCVR)	2
S-band exciter (S-EXC)	2
X-band exciter (X-EXC)	2
S-band traveling wave tube amplifier (S-TWTA)	1
S-band solid-state amplifier (SSA)	1
X-band traveling wave tube amplifier (X-TWTA)	2
Ultrastable oscillator (USO)	1
Modulation demodulation subsystem (MDS)	
Command detector unit (CDU)	2
Telemetry modulation unit (TMU)	2
S/X-band antenna subsystem (SXA)	
High-gain antenna (HGA)	1
Low-gain antenna (LGA)	1

[a] The pairs of components, such as S-RCVRs, are identical to one another, providing redundancy for the function. In each case, one and only one of the components is operative (powered on) at a time.

*Look up this and other abbreviations and acronyms in the list that begins on page 45.

Figure 3-1 is a functional block diagram of the Voyager telecom system.[1] The telecom system is housed in equipment bays 1, 9, and 10 of the spacecraft bus. The bus is a decagonal structure, with each of the ten sides making up the external surface of one equipment bay, as shown in Figure 1-2.

The radio frequency subystem is designed to perform as a command receiver, a phase-coherent ranging transponder, and a telemetry transmitter. Final X-band amplification is provided by redundant traveling-wave tube amplifiers; final S-band amplification by a traveling-wave tube amplifier or solid state amplifier, working as a redundant pair. Microwave components provide RF filtering and switching for connecting the transmitters and receivers to the high-gain or low-gain antenna.

The modulation demodulation subsystem has redundant command detector units and telemetry modulation units.

The S-/X-band antenna subsystem consists of a low-gain antenna and a high-gain antenna that receive S-band signals and transmit S-band and X-band signals to and from the Deep Space Network.

The telecom system receives control instructions from the computer command subsystem (CCS) and the flight data subsystem (FDS) to select its operating modes. The primary modes are:

- S-band TWTA/SSA high power
- S-band TWTA/SSA low power
- S-band ranging on
- S-band ranging off
- X-band TWTA high power
- X-band TWTA low power
- X-band ranging on
- X-band ranging off
- HGA select for transmitting and receiving
- LGA select for transmitting and receiving
- TWNC on
- TWNC off
- USO on
- USO off

Table 3-2 displays typical configurations used by Voyager for each mission phase.

[1] The numbered triangular markers in the block diagram indicate capabilities that are no longer available in VIM, including those lost due to hardware failures or other circumstances. The Voyager 2 receiver problems (flags 3 and 4) still require special procedures as described in Section 7, **Operational Scenarios**.

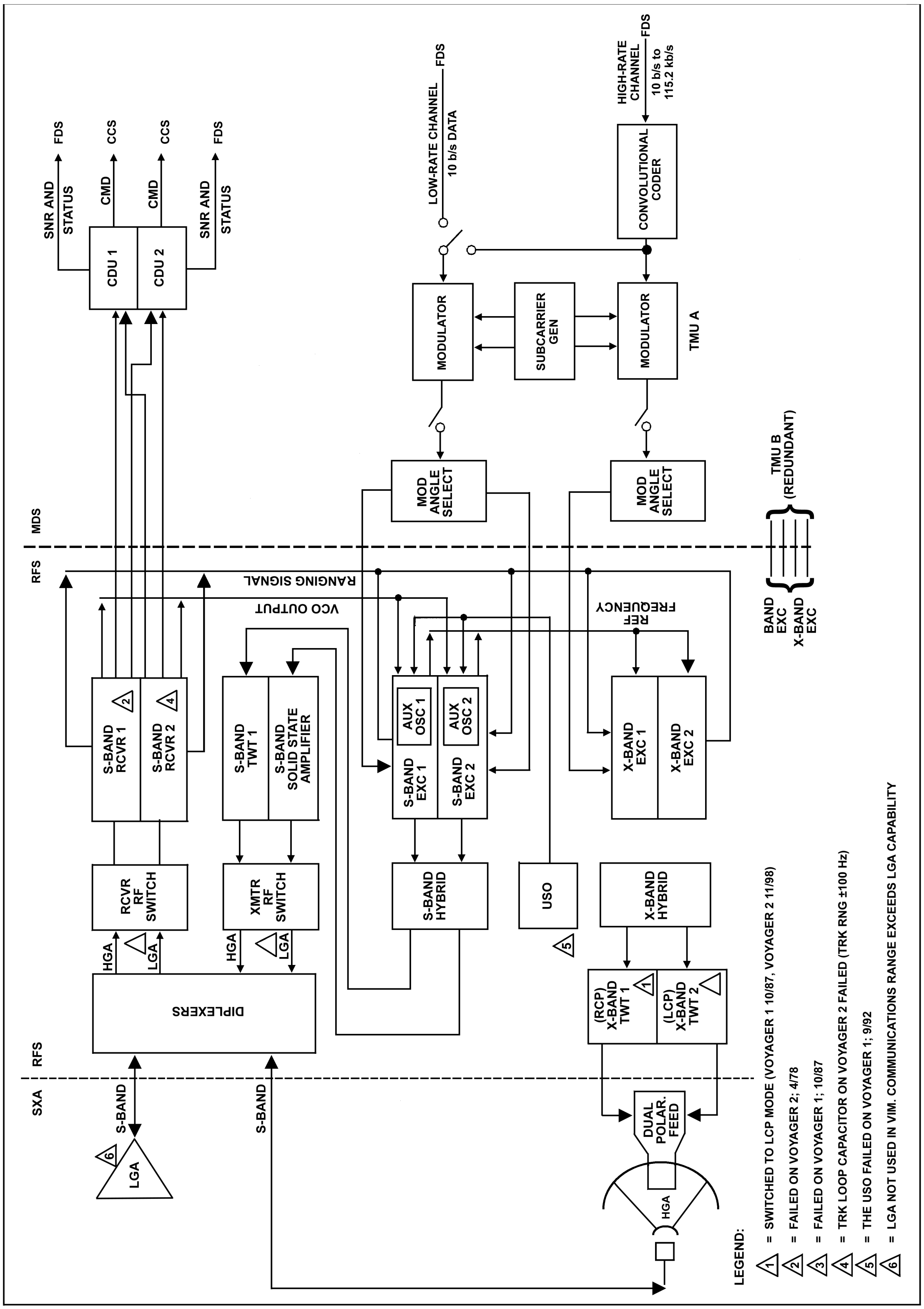


Fig. 3-1. Voyager spacecraft telecom functional block diagram.

Table 3-2. Typical Voyager telecom configurations.

	Transmitter power			Ranging		Subcarrier freq (kHz)		Link data rates and coding		RFS tracking
Mission phase	S	X	Antenna	S	X	S	X	S (bps)	X (bps)	configuration
Launch	Low	Off	LGA	Off	Off	22.5	Off	1200[a]	Off	One-way
First 80 days	High	Off	LGA	Off	Off	22.5	Off	10–2560[a]	Off	Two-way coherent
Planetary cruise	Off	Low	HGA	Off	On	Off	22.5	Off	10–2560[a]	Two-way coherent
Planetary playback	Low	High	HGA	On	On	22.5	360	40[c]	7.2 k–115.2 k[b]	Two-way coherent
VIM cruise	Off	Low	HGA	Off	Off	Off	22.5	Off	160[b]	One-way
VIM playback	Off	High	HGA	Off	Off	Off	22.5	Off	1.4 k–7.2 k[b]	One-way

[a] Convolutionally coded.
[b] Convolutionally coded with Golay or Reed-Solomon.
[c] Uncoded.

3.2 Modulation Demodulation Subsystem

3.2.1 Command Detector Units

The CDU demodulates the command subcarrier from the radio frequency subsystem (RFS) receiver, synchronizes its internal clock to the received command bit rate, and detects the command bits.

The CDU outputs to the CCS the detected command bits and a clock signal derived from the command bit rate. The CDU outputs status signals to the FDS.

3.2.2 Telemetry Modulation Units

The TMU can receive both high- and low-rate, non-return-to-zero (NRZ), serial digital data from the FDS. Refer to Figure 3-1 for the most commonly used set of modes of processing of telemetry data through the TMU, including how either the low-rate or high-rate data may be transmitted on the S-band downlink. CCS control inputs determine low-rate/high-rate data routing, subcarrier frequency selection, modulation index value, and the input of the modulated subcarrier to the S-band and X-band exciter. The low-rate data is not coded; the high-rate data is convolutionally coded. High-rate data is always available for the X-band downlink.

3.3 Radio Frequency Subsystem

3.3.1 Receivers

The receiver is a narrow-band, double-conversion, super-heterodyne, automatic-phase-control design. The receiver has a coherent amplitude detector that detects and measures received signal strength and provides the receiver with an automatic gain control (AGC) function. Receiver AGC is telemetered as a primary uplink performance parameter.

When phase locked to an uplink signal, the receiver's phase detector will (1) control the phase and frequency of the transmitted downlink carriers if in two-way coherent mode, (2) demodulate the composite command signal, if present, and (3) demodulate the ranging signal if present. The ranging signal level is controlled by the ranging AGC.

The received carrier frequency controls the generation of the coherent downlink at both S- and X-band, at transmit/receive frequency ratios of 240/221 and 880/221, respectively (two-way tracking). The ranging signal is provided by independently switched paths to the S- and X-band exciters for modulation of the downlinks. The S- and X-band ranging channels are controlled by discrete commands from the spacecraft CCS, regardless of which receiver is powered.

3.3.2 S-Band Exciters

The S-EXC provides RF drive to the S-band power amplifier and a frequency reference to the X-EXC. One or the other S-EXC must be powered on at all times. The X-band downlink requires an S-EXC, an X-EXC, and an X-TWTA.

The S-EXC also phase modulated the S-band downlink carrier present in earlier mission phases with the composite telemetry signal (modulated subcarrier) from the TMU and with the ranging signal detected by the receiver when the S-band ranging channel was controlled on.

Each S-EXC has a crystal-controlled auxilliary oscillator (aux osc) that can generate the D/L in the TWNC-on mode or when there is no U/L. Although the USO (Section 3.3.6) is preferred as the D/L source in these cases, the aux osc can take over if the USO fails[2] or is switched off.

3.3.3 S-Band Power Amplifiers

Only one S-band power amplifier, either the S-TWTA or the SSA, may be powered at a time, or both may be off when no S-band downlink is required. Both power amplifiers have two RF output power levels available.[3] A CCS control instruction (high power/low power) establishes the power level in both units, with a separate control input to turn the selected power amplifier on or off.

[2] The Voyager 1 USO failed in September 1992, as flagged by legend item 5 in Figure 3-1. The exciter aux osc has generated the 1-way downlink since then. Use of the less stable aux osc restricts Voyager 1 to transmitting downlink in the residual carrier mode only.

[3] From [2], the low-power and high-power RF levels to the HGA for the S-TWTA are 6.5 W and 19 W. For the S-SSA, they are 6 W and 15 W.

3.3.4 X-Band Exciters

The X-band exciter converts the frequency at the output of the S-band exciter to X-band to drive the X-band TWTA. Comparable to the S-band exciter function, the X-band exciter phase modulates the RF signal with the composite telemetry signal from the TMU and, if the X-band ranging channel is on, the ranging signal detected by the receiver.

3.3.5 X-Band Power Amplifiers

Only one X-TWTA can be powered at a time. Further, a control input from the CCS ensures that the X-TWTA is powered off when the X-exciter is off. As is the case for S-band, whether powered on or not, the X-TWTA power level is selected to either of two levels[4] by CCS control input.

In October 1987, the Voyager 1 X-TWTA-2 failed, as annotated in Figure 3-1, legend item 3. The primary downlink was switched to X-TWTA-1. In November 1998, Voyager 2 switched from X-TWTA-2 to X-TWTA-1 [6].[5] For both spacecraft, legend item 1 in the figure flags the changes from X-TWTA-2's right hand circular polarized downlink to X-TWTA-1's left hand circular polarized downlink.[6]

3.3.6 Ultrastable Oscillator

The RFS has one USO. The USO provides the most stable frequency reference available for the downlink in the non-coherent mode of operation. The USO has short-term stability of 12×10^{-12} MHz and lifetime stability of $\pm 2 \times 10^{-6}$ MHz. The USO on/off state is via control input from the CCS. When the USO is turned off, the aux osc in the powered S-band exciter is consequently turned on, and vice versa.

3.4 S/X-Band Antenna Subsystem

The S/X-band antenna (SXA) consists of an S-band low-gain antenna (LGA) and an S-band and X-band high-gain antenna (HGA). For the HGA, the SXA has a 3.66-m diameter main reflector, a frequency selective surface (FSS) subreflector, and S-band and X-band feeds. Axially in front of the main reflector are, in order, the X-band feed, the FSS, the S-band feed, and the LGA (farthest from the spacecraft).

The main reflector, X-band feed, and the FSS (reflecting at X-band) form a Cassegrain radiator. The main reflector, FSS (transparent at S-band), and S-band feed form a prime focus radiator. The LGA is mounted on the back of the S-band feed structure. The SXA also includes an X-band waveguide, an S-band coaxial cable, and RF power probes for each frequency.

Figure 3-2 sketches the relative patterns of the HGA and LGA, with the angles not to scale. The figure also lists the gain and beamwidth values. As the figure indicates, the LGA and

[4] The low-power and high-power RF levels to the HGA for the X-TWTA are 12 W and 18 W.

[5] The switch to the backup X-TWTA is in status report http://vraptor.jpl.nasa.gov/voyager/pressrel/vg981117.html

[6] The relationship between X-TWTA selection and the resultant polarization of the X-band downlink is described in the SXA section that follows.

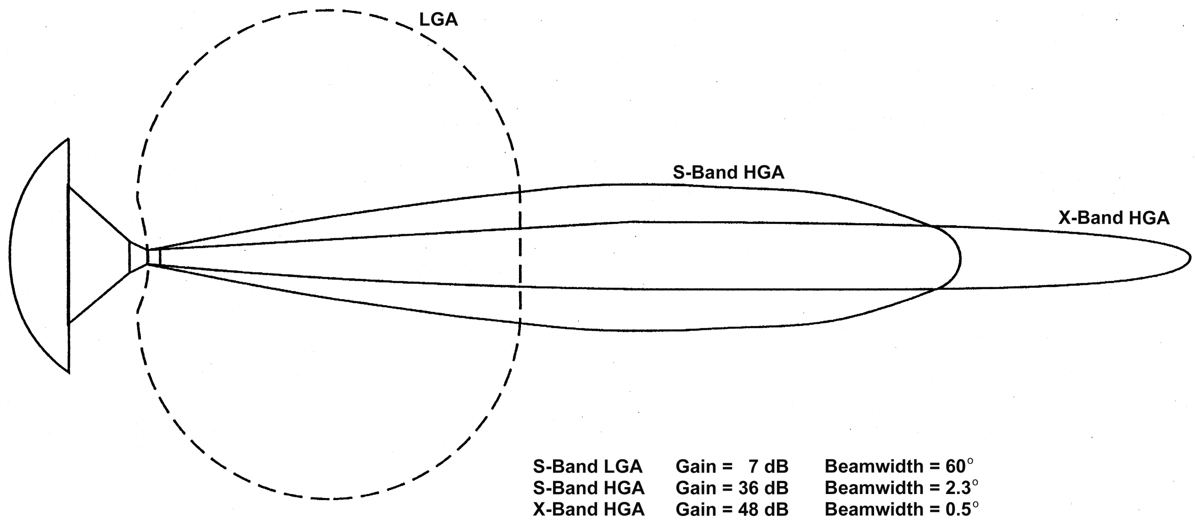


Fig. 3-2. Voyager SXA patterns and beamwidths.

HGA boresights are aligned with each other. The LGA has a broad S-band pattern about its boresight; the HGA has narrower S-band and X-band patterns as determined by the main reflector's diameter.

3.4.1 High-Gain Antenna

In the VIM, communication to and from the spacecraft is through the HGA. The HGA consists of S- and X-band feeds backed by a circular parabolic reflector. S-band gain is approximately 36 dBi; X-band gain is approximately 48 dBi.

The HGA is right-hand circularly polarized at S-band. At X-band it uses a dual-polarized Cassegrain feed that produces a right-hand or left-hand circularly polarized wave, depending on which of the two X-TWTAs is driving the feed. A left-hand circularly polarized downlink comes from X-TWTA-1; a right-hand circularly polarized downlink comes from X-TWTA-2.

3.4.2 Low-Gain Antenna

The spacecraft also carries an S-band-only LGA. The LGA consists of a right hand circularly polarized radiator. The radiation pattern is approximately a cardioid of revolution. The gain of the LGA is approximately 7 dBi.

The LGA, used immediately following launch, was also available for emergency communications until margin for LGA links was exhausted in the 1980s.

3.5 Telecom System Input Power and Mass

Table 3-3 summarizes the steady-state spacecraft input power to the major telecom system units for both high-power and low-power modes, as applicable. The table also summarizes the masses of components of the system.

Table 3-3. Voyager spacecraft input power and mass summary.

	No. of Units	Input power (W)[a]	Mass (kg)[b]
RFS			44.0
Transponder	2		4.7
Receiver		4.3	
S-band exciter		2.4	
ACIS[c]		0.9	2.5
S-TWTA	1	33.0/86.4[a]	5.1
S-band SSA	1	35.7/91.2[a]	5.0
X-TWTA	2	48.3/71.9[a]	5.8
USO	1	2.7	2.0
Diplexer	2		1.4
Receiver RF switch			1.2
Transmitter RF switch			0.9
Other microwave			3.5
Cabling			2.3
MDS			8.4
TMU	2	5.7	2.2
CDU	2	5.4	2.0
SXA			53.0
SXA coax, waveguide			2.1
SXA structure, including main reflector			50.9
Mass Total			105.4

[a]Low power/high power values do not include turn-on or turn-off transients.
[b]The stated mass is for one unit; for example, each X-TWTA weighs 5.8 kg.
[c]Antenna control and interface system.

Section 4

Telecom Ground System Description

The DSN* is an international network of ground stations (antennas, transmitters, receivers, and associated systems) that operates intensively at S-band and X-band, with a Ka-band capability being developed.[1] The DSN supports interplanetary spacecraft missions and radio and radar astronomy observations for the exploration of the solar system and beyond. The DSN consists of three deep-space communications complexes located approximately 120 deg from each other at Goldstone, in California's Mojave Desert; near Madrid, Spain; and near Canberra, Australia. Each complex has one 70-m antenna, two or more 34-m antennas, and one 26-m antenna (not used for Voyager).

Specific DSN numerical parameters for Voyager are defined in *DSN Operations Plan for the Voyager Interstellar Mission* [9]. The *Deep Space Mission Systems Telecom Link Design Handbook* [10] includes functional capability descriptions of each antenna type for the purpose of modeling link capability between a spacecraft and station.[2,3]

---

[1] See http://deepspace.jpl.nasa.gov/dsn/brochure/index.html, an online "brochure" about the DSN, including its history, the three deep space communications complexes, and brief descriptions of the DSN's antennas, receivers, station arrays, and telemetry decoding.

[2] [10] is 810-005 (Rev. E), released January 2001. The Voyager spacecraft was originally designed to work with ground systems defined in previous versions of the Handbook. This description of 70-m station antenna and microwave systems, receivers, command processing, and telemetry processing is consistent with 810-005, Rev. E.

[3] See http://www.jpl.nasa.gov/basics/bsf18-3.html for a general description of uplink and downlink data flow at a Deep Space Communications Complex.

---

*Look up this and other abbreviations and acronyms in the list that begins on page 45.

4.1 Uplink and Downlink Carrier Operation

Voyager uses an S-band uplink, X-band primary downlink, and S-band secondary downlink.[4] Command uplinks and maneuver and tape-recorder-playback downlinks require the 70-m antennas. The 34-m antennas are limited to reception of the relatively low-rate 160 bps cruise data.

Figure 4-1 shows the antenna and microwave sections of a 70-m station. The following paragraphs describe Voyager-related functions of that type of station. Refer to [10] for corresponding figures and descriptions of the other types of DSN stations.

4.1.1 Uplink

The uplink signal produced by the 20-kW S-band transmitter goes through an S-band diplexer, orthomode junction, and polarizer to the S-band feed. The signal then passes through an S-/X-band dichroic reflector, subreflector, and main 70-m reflector before radiation to the spacecraft. Voyager has no plan to use the 400-kW S-band transmitter.

4.1.2 Downlink

The X- and S-band downlinks from the main (70-m) reflector and the subreflector are both focused at the S/X dichroic reflector. A dichroic is reflective at one frequency band and transparent at another, thus allowing S-band frequencies to be separated from X-band frequencies. This dichroic reflector reflects the S-band (on the path shown by the thick line in Figure 4-1) to the S-band feed and passes the X-band through to the X-band feed with very low loss.

From the diplexing junction, the X-band signal goes to a polarizer that selects the right circular polarization output for both spacecraft. The output from the polarizer is amplified by the X-band high-electron-mobility field-effect transistor (HEMT) preamplifier and frequency-downconverted for input to the block V receiver (BVR).

The S-band downlink signal shares a common path with the uplink signal between the feed and the S-band diplexer. The diplexer routes the downlink to the S-band low-noise preamplifier (S-band maser). After further routing and downconversion similar to the X-band downlink, the S-band downlink is input to the BVR.

4.2 Command Processing

Voyager command files are transferred to the station minutes in advance of transmission in a store-and-forward system. At the station, the command processor assembly (CPA) and the command modulator assembly (CMA) clock out the command bit stream, modulate the command subcarrier, and provide the subcarrier to the station's exciter for modulation of the RF uplink carrier. Bit rates, the command subcarrier frequency, and the command modulation index (suppression of the uplink carrier) are controlled through standards and limits tables.

---

[4] The X-band downlink was designated "primary" to return science data because it has greater telecom performance than the S-band link via the HGA. The S-band link was designated "secondary" because it will be used if the X-band link fails or antenna pointing angle requires the LGA.

The JPL Voyager Spacecraft Mission Controller, referred to as the ACE, operates the multimission command system from a workstation in the mission support area. Just prior to a command session, the ACE directs the station to turn command modulation on and selects the 16-bps command rate and a calibrated "buffer" in the station's CMA. The CMA produces the command subcarrier, which produces a 512-Hz squarewave to match the subcarrier-tracking-loop best-lock frequency in the Voyager CDU. As the ACE sends the spacecraft commands, the CMA modulates the command-bit waveform onto the subcarrier. When finished, the ACE directs the station to turn command modulation off.

4.3 Telemetry Processing

Two BVRs are assigned to a project's tracking pass. Each BVR has phase-locked loops for acquiring and tracking the carrier, telemetry subcarrier, and telemetry symbol stream. Voyager generates a 22.5-kHz subcarrier for use with bit rates less than or equal to 7.2 kbps and a 360-kHz subcarrier for use with bit rates greater than 7.2 kbps. In the residual carrier mode, the X-band carrier modulation index settings vary from 51 deg for the lowest data rate (10 bps) to 80 deg for the highest (115.2 kbps).[5]

The BVR delivers telemetry symbols to the maximum likelihood convolutional decoder (MCD). Voyager can use either the Block 2 or Block 3 MCD (MCD2 or MCD3)[6] to process the (7,1/2) convolutional code. The MCD outputs decoded telemetry bits to the frame synchronizer subsystem (FSS).

An MCD/FSS pair make up a telemetry channel assembly (TCA). The telemetry group controller governs the operation of TCA1 (with MCD3) and TCA2 (with MCD2). After the MCD achieves lock, the FSS requires recognition of a minimum of two successive frame-sync words to output telemetry to the project. Validation requires recognition of a third sync word. The number of allowable miscompares (between received and expected bit values) in each frame-sync word recognized by the synchronizer can be set in the software.

---

[5] A modulation index of 90 deg puts all of the power in the sidebands and therefore produces a suppressed carrier mode. Suppressed carrier mode is used during VIM to extend Voyager 2 playback data rate capability. See Section 6, **New Telecom Technology**.

[6] See [10], module 208, *Telemetry Data Decoding*, for a description of the Block 2 and Block 3 MCDs. Block 3 refers to a later DSN equipment implementation than Block 2, and has been available for operational use beginning in 1997.

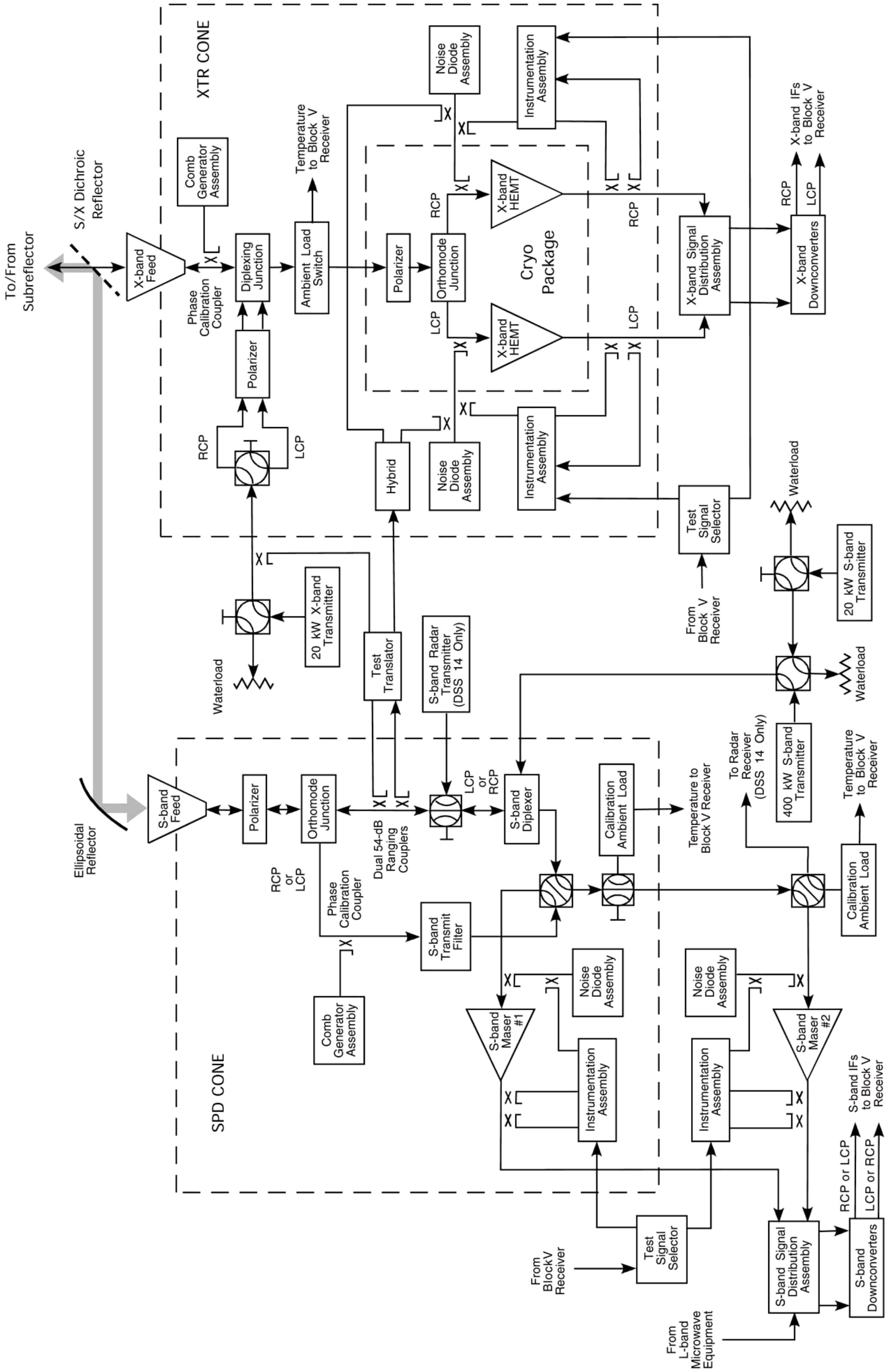


Fig. 4-1. DSS-14 and DSS-43 microwave and transmitter block diagram.

Section 5

Sample Telecom System Performance

The Voyager spacecraft receives an S-band uplink from the Earth and transmits S- and X-band downlinks to the Earth, compatible with DSN* station configurations and performance defined in [9] and [10].

The telecommunications system is capable of simultaneous commanding, telemetry processing, and radiometric tracking using any combination of the available uplink and downlink frequency bands. See [1] for planned telecom configurations and predicted uplink and downlink performance during Voyager's prime mission.[1]

The Voyager communication link margins are computed using the link budget techniques and statistical criteria defined in *Deep Space Telecommunications Systems Engineering* [11].

The four VGR telecom functions are carrier tracking (Doppler), command, telemetry, and ranging. The performance of each function is expressed as an SNR, as shown in Table 5-1.

Each SNR is expressed in terms of N_0, which is noise spectral density. The "signal" part of the SNR is P_c (carrier power), E_b (energy per command bit), E_s (energy per telemetry symbol),

Table 5-1. VGR telecom link functions and signal-to-noise ratios.

Function	SNR Definition
Carrier	P_c/N_0
Command	E_b/N_0
Telemetry	E_s/N_0
Ranging	P_r/N_0

[1] This section is limited to a summary of the telemetry performance during VIM.

*Look up this and other abbreviations and acronyms in the list that begins on page 45.

or P_r (downlink ranging power). Each function has a minimum SNR, the threshold, at which the quality of the link meets the criteria defined by the project.

5.1 Design Control Tables

Link performance is book-kept using a design control table (DCT), sometimes called a link budget. When used for planning future capability, Voyager link predictions are based on a criterion of positive margin under the following conditions:

- Command: mean minus 3-sigma
- Telemetry: mean minus 2-sigma.

Sigma refers to the standard deviation of the command E_b/N_0 and telemetry E_s/N_0.

The DCTs on the next three pages predicted Voyager 2 telecom performance at DSS-43, the Canberra, Australia, 70-m station on January 1, 1996 at time 00:00 [12].

- Table 5-2: S-band uplink carrier
- Table 5-3: X-band low-power downlink carrier
- Table 5-4: X-band downlink 160 bps telemetry channel.

A DCT includes numerous link parameters and their tolerances, but applies to only one point in time. For planning and analyzing performance during flight, the project may prefer tabulations, such as Table 5-5, of a few of the most important parameters incremented by time.

Table 5-2. Voyager 2 uplink carrier design control table.

Voy 2 (JSX), 70m/18 kW/12 Hz, 0 dB Rng, 0 dB Cmd, Clr Wthr X-Band TWT LP, HGA/NLC, 160 bps Coded, 2-Way Radio Losses					
Spacecraft 2	Station 43				
Time in Mission 96/001/00/00	Time from Epoch 35065 00:00				
	Design	Fav Tol	Adv Tol	Mean	Variance
Transmitter Parameters					
1) RF Power, dBm	72.55	0.50	–0.50	72.6	0.04
Power Output = 18.0 kW					
Transmit Circuit Loss, dB	0.00	0.00	0.00	0.0	0.00
2) Antenna Gain, dBi	62.10	0.30	–0.70	61.9	0.08
Elev Angle = 58.01 deg					
3) Pointing Loss, dB	–0.03	–0.03	–0.03		
Path Parameters					
4) Space Loss, dB	–296.18			–296.2	0.00
Freq = 2113.31 MHz					
Range = 7.273+09 km					
= 48.62 AU					
5) Atmospheric Attenuation, dB	–0.04	0.00	0.00	0.0	0.00
Receiver Parameters					
6) Polarization Loss, dB	–0.12	0.12	–0.18		
7) Antenna Gain, dBi	34.60	0.39	–0.39	34.5	0.03
8) Pointing Error, dB	–0.10	0.10	–0.10	–0.1	0.00
Limit Cycle, deg	0.05	–0.05	0.00		
Angular Errors, deg	0.00	0.00	0.00		
9) Rec Circuit Loss, dB	0.00	0.00	0.00	0.0	0.00
10) Noise Spec Dens, dBm/Hz	–166.71	–0.10	0.16	–166.7	0.00
Operating Temp, K	1545.00	–34.00	59.00		
Hot Body Noise, K	0.00	0.00	0.00		
11) Carr Thr Noise, BW, dB-Hz	12.72	–0.24	0.23	12.7	0.01
Power Summary					
12) Rcvd Power, P_t, dBm				–127.4	0.16
(1+2+3+4+5+6+7+8+9)					
13) Rcvd P_t/N_0, dB-Hz (12–10)				39.2	0.16
14) Ranging Suppression, dB	0.00	0.00	0.00	0.0	0.00
15) Command Suppression, dB	0.00	0.00	0.00	0.0	0.00
16) Carr Pwr/Tot Pwr, dB (14–15)				0.0	0.00
17) Rcvd Carr Pwr, dBm (12+16)				–127.4	0.16
18) Carr SNR in 2BLO, dB (17–10–11)				26.5	0.17
				2.0S =	0.80

Table 5-3. Voyager 2 downlink carrier design control table.

Voy 2 (JSX), 70m/18 kW/12 Hz, 0 dB Rng, 0 dB Cmd, Clr Wthr X-Band TWT LP, HGA/NLC, 160 bps Coded, 2-Way Radio Losses					
Spacecraft 2 Time in Mission 96/001/00/00	Station 43 Time from Epoch 35065 00:00				
	Design	Fav Tol	Adv Tol	Mean	Variance
Transmitter Parameters					
1) RF Power to Antenna, dBm				40.9	0.04
Transmitter Power, dBm	40.90	0.50	–0.50	40.9	0.04
Transmit Circuit Loss, dB	0.00	0.00	0.00	0.0	0.00
2) Antenna Circuit Loss, dB	0.00	0.30	0.00	0.0	0.00
3) Antenna Gain, dBi	48.20	0.26	–0.26	48.2	0.01
4) Pointing Error, dB	–0.10	0.10	–0.10	–0.1	0.00
Limit Cycle, deg	0.05	–0.05	0.00		
Angular Errors, deg	0.00	0.00	0.00		
Path Parameters					
5) Space Loss, dB	–308.19			–308.2	0.00
Freq = 8415.00 MHz					
Range = 7.273+09 km					
= 48.62 AU					
6) Atmospheric Attenuation, dB	–0.04	0.00	0.00	0.0	0.00
Receiver Parameters					
7) Polarization Loss, dB	–0.08	0.08	–0.11		
8) Antenna Gain, dBi	74.01	0.60	–0.60	73.7	0.14
9) Pointing Loss, dB	–0.20	0.20	–0.20		
10) Noise Spec Dens, dBm/Hz	–185.35	–0.97	0.80	–185.4	0.09
Total System Noise Temp, K	21.12	–4.24	4.24		
Receiver Temperature, K	13.20	–3.00	3.00		
Ground Contribution, K	2.88	–3.00	3.00		
Galactic Contribution, K	2.68	0.00	0.00		
Atmospheric Contrib, K	2.36	0.00	0.00		
Hot Body Noise, K	0.00	0.00	0.00		
Elev Angle = 58.01 deg					
11) Carr Thr Noise, BW, dB-Hz	14.77	–0.46	0.41	14.8	0.03
Power Summary					
12) Rcvd Power, P_t, dBm (1+2+3+4+5+6+7+8+9)				–145.5	0.19
13) Rcvd P_t/N_0, dB-Hz (12–10)				39.9	0.28
14) Ranging Suppression, dB	–0.22	0.05	0.05	–0.2	0.00
15) Telemetry Suppression, dB	–6.02	0.16	–0.17	–6.0	0.00
16) Carr Pwr/Tot Pwr, dB (14+15)				–6.2	0.00
17) Rcvd Carr Pwr, dBm (12+16)				–151.7	0.20
18) Carr SNR in 2BLO, dB (17–10–11)				19.0	0.31
				2.0S =	1.10

Table 5-4. Voyager 2 telemetry channel design control table.

Voy 2 (JSX), 70M/18 kW/12 Hz, 0 dB Rng, 0 dB Cmd, Clr Wthr X-Band TWT LP, HGA/NLC, 160 bps Coded, 2-way Radio Losses					
Spacecraft 2	Station 43				
Time in MIssion 96/001/00/00	Time from Epoch 35065 00:00				
	Design	Fav Tol	Adv Tol	Mean	Variance
Data Channel Performance					
19) Data Bit Rate, dB	22.04	0.00	0.00	22.0	0.00
Bit Rate = 160.0 bps					
20) Data Pwr/Total Pwr, dB	–1.25	0.05	–0.06	–1.2	0.00
Tlm Mod Index = 60.0 deg					
21) Data Pwr to Rcvr, dBm (12+14+20)				–147.0	0.19
22) ST/N_0 to Rcvr, dB (21–19–10)				16.4	0.28
23) System Losses, dB	–0.72	0.06	–0.36	–0.8	0.01
Radio Loss, dB	–0.18	0.02	–0.02		
Demod, Detect Loss, dB	–0.36	0.04	–0.36		
Waveform Dist Loss, dB	–0.18	0.04	–0.03		
24) Data Bit Rate, dB (22+23)				15.6	0.29
25) Data Bit Rate, dB	2.34	0.00	0.00	2.3	0.00
26) Data Bit Rate, dB (24–25)				13.3	0.29
				2.0S =	1.10

5.2 Long-Term Planning Predicts

Often, plots are more compact and useful for displaying link performance than either a series of DCTs or a set of tabulations. Figure 5-1 summarizes predictions of downlink P_t/N_0[2] at one station (DSS-43) and one day of the year (January 30) for Voyager 2 from 1995 to 2020, one year per curve. The horizontal axis is a 24-hour period. The main shape of any of the curves is due to the increasing DSS-43 elevation angle to Voyager 2 (from 17:00 to 21:00) and the decreasing elevation angle (from 05:00 to 09:00). The figure's second curve from the top depicts the downlink P_t/N_0 predicts for 1996 from the Table 5-5 listing in the form of a plot versus time. All the other Figure 5-1 curves have similar shapes because the Earth's orbit around the Sun repeats from year to year. Though they have the same general shape, the other curves are offset from each other vertically because the communications distance between Voyager 2

[2] The quantity downlink P_t/N_0 is a convenient link parameter to plot for telemetry links. There is a fixed value of P_t/N_0 that represents threshold for each data rate. Performance of bit rates that extend over orders of magnitude (600 bps to 7.2 kbps in Fig. 5-1 and 160 bps to 1.4 kbps in Fig. 5-2) can be shown on a scale of 10 dB per decade. The difference between the thresholds for the 1.4 kbps data rate for Voyager 2 (Fig. 5-1) and Voyager 1 (Fig. 5-2) represents the additional 0.8 dB gain achieved by using suppressed carrier for that rate on Voyager 2 only. See Section 4.3 **Telemetry Processing** and Section 6.3 **Ground System Performance Improvements** for additional information regarding the suppressed carrier downlink.

and Earth increases steadily from year to year. Telemetry thresholds are displayed as horizontal lines per the legend at right. The plot is used for long-term mission planning purposes.

Telemetry link margin exhaustion dates can be estimated within about half a year for each spacecraft by comparing the annual performance predictions with the bit-rate thresholds on each chart. Threshold lines for 160 bps and 40 bps are not included because they fall below the vertical scale, except for Voyager 1 at 160 bps in low power mode. There is plenty of link margin at those rates to operate well beyond 2020.

In the same manner, Figure 5-2 displays 25 years of Voyager 1 day-of-year (DOY) 008 performance predictions and bit-rate thresholds at DSS-14.

Table 5-5. Voyager 2 telecom predictions, 1996 DOY 030.

DOY/Time	Elev	UL P_t	P_t	D P_t	SNT	P_t/N_0	Marg	TOL	ST/N_0
29 17 45	11.66	–127.59	–146.19	–152.43	33.6	36.93	10.32	0.97	12.66
29 18 00	13.96	–127.56	–146.09	–152.34	31.4	37.31	10.74	0.98	13.08
29 18 15	16.31	–127.54	–146.01	–152.25	29.8	37.63	11.08	0.99	13.42
29 18 30	18.72	–127.53	–145.94	–152.18	28.5	37.90	11.36	0.99	13.70
29 18 45	21.18	–127.51	–145.87	–152.11	27.4	38.13	11.61	1.00	13.95
29 19 00	23.69	–127.50	–145.81	–152.05	26.5	38.34	11.84	1.01	14.18
29 19 15	26.24	–127.50	–145.75	–151.99	25.7	38.54	12.04	1.01	14.38
29 19 30	28.83	–127.49	–145.70	–151.94	25.0	38.71	12.23	1.02	14.57
29 19 45	31.45	–127.48	–145.65	–151.89	24.4	38.86	12.39	1.03	14.73
29 20 00	34.11	–127.48	–145.62	–151.86	23.8	39.00	12.53	1.03	14.87
29 20 15	36.80	–127.48	–145.58	–151.83	23.3	39.12	12.65	1.04	14.99
29 20 30	39.52	–127.47	–145.55	–151.80	22.8	39.24	12.78	1.04	15.12
29 20 45	42.26	–127.47	–145.53	–151.77	22.4	39.34	12.88	1.05	15.22
29 21 00	45.02	–127.47	–145.51	–151.76	22.1	39.43	12.97	1.05	15.31
29 21 15	47.81	–127.46	–145.51	–151.75	21.7	39.50	13.05	1.06	15.39
29 21 30	50.61	–127.46	–145.50	–151.76	21.4	39.58	13.12	1.06	15.46
29 21 45	53.42	–127.46	–145.50	–151.75	21.1	39.63	13.18	1.07	15.52
29 22 00	56.25	–127.46	–145.51	–151.76	20.8	39.68	13.22	1.07	15.56
29 22 15	59.09	–127.46	–145.53	–151.77	20.6	39.71	13.26	1.07	15.60
29 22 30	61.93	–127.46	–145.55	–151.80	20.4	39.74	13.29	1.08	15.63
29 22 45	64.77	–127.46	–145.58	–151.82	20.2	39.75	13.30	1.08	15.64
29 23 00	67.61	–127.45	–145.62	–151.86	20.0	39.76	13.31	1.08	15.65
29 23 15	70.43	–127.45	–145.66	–151.90	19.8	39.76	13.31	1.09	15.65
29 23 30	73.22	–127.45	–145.71	–151.95	19.6	39.75	13.30	1.09	15.64
29 23 45	75.97	–127.45	–145.76	–152.00	19.5	39.72	13.27	1.09	15.61
30 00 00	78.62	–127.45	–145.82	–152.06	19.4	39.68	13.22	1.09	15.56
30 00 15	81.09	–127.45	–145.88	–152.12	19.4	39.63	13.17	1.09	15.51
30 00 30	83.17	–127.45	–145.93	–152.17	19.4	39.58	13.12	1.09	15.46

continued

Table 5-5. Voyager 2 telecom predictions, 1996 DOY 030. (cont'd)

DOY/Time	Elev	UL P_t	P_t	D P_t	SNT	P_t/N_0	Marg	TOL	ST/N_0
30 00 45	84.40	–127.45	–145.96	–152.21	19.3	39.55	13.10	1.10	15.44
30 01 00	84.21	–127.45	–145.96	–152.20	19.3	39.55	13.10	1.10	15.44
30 01 15	82.71	–127.45	–145.92	–152.16	19.4	39.59	13.14	1.09	15.48
30 01 30	80.51	–127.45	–145.86	–152.11	19.4	39.64	13.19	1.09	15.53
30 01 45	77.98	–127.45	–145.81	–152.05	19.4	39.69	13.24	1.09	15.58
30 02 00	75.30	–127.45	–145.75	–151.99	19.5	39.74	13.29	1.09	15.63
30 02 15	72.54	–127.45	–145.70	–151.94	19.6	39.75	13.30	1.09	15.64
30 02 30	69.74	–127.45	–145.65	–151.89	19.8	39.76	13.32	1.09	15.66
30 02 45	66.91	–127.46	–145.61	–151.85	20.0	39.76	13.31	1.08	15.65
30 03 00	64.08	–127.46	–145.57	–151.82	20.2	39.75	13.30	1.08	15.64
30 03 15	61.23	–127.46	–145.55	–151.79	20.4	39.73	13.28	1.08	15.62
30 03 30	58.39	–127.46	–145.53	–151.77	20.7	39.70	13.25	1.07	15.59
30 03 45	55.56	–127.46	–145.51	–151.75	20.9	39.67	13.22	1.07	15.56
30 04 00	52.73	–127.46	–145.50	–151.75	21.2	39.62	13.16	1.07	15.50
30 04 15	49.92	–127.46	–145.50	–151.74	21.5	39.56	13.11	1.06	15.45
30 04 30	47.12	–127.46	–145.51	–151.75	21.8	39.49	13.03	1.06	15.37
30 04 45	44.35	–127.47	–145.52	–151.76	22.2	39.41	12.95	1.05	15.29
30 05 00	41.59	–127.47	–145.54	–151.78	22.5	39.31	12.85	1.05	15.19
30 05 15	38.85	–127.47	–145.56	–151.80	22.9	39.21	12.75	1.04	15.09
30 05 30	36.14	–127.48	–145.59	–151.83	23.4	39.09	12.62	1.04	14.96
30 05 45	33.46	–127.48	–145.63	–151.87	23.9	38.97	12.49	1.03	14.83
30 06 00	30.81	–127.49	–145.66	–151.90	24.5	38.83	12.35	1.03	14.69
30 06 15	28.19	–127.49	–145.71	–151.95	25.1	38.67	12.18	1.02	14.52
30 06 30	25.61	–127.50	–145.76	–152.00	25.8	38.49	12.00	1.01	14.34
30 06 45	23.07	–127.51	–145.82	–152.07	26.7	38.29	11.78	1.01	14.12
30 07 00	20.58	–127.52	–145.89	–152.13	27.6	38.08	11.55	1.00	13.89
30 07 15	18.13	–127.53	–145.96	–152.20	28.8	37.83	11.29	0.99	13.63
30 07 30	15.73	–127.55	–146.03	–152.27	30.1	37.56	11.00	0.98	13.34
30 07 45	13.39	–127.57	–146.12	–152.36	31.9	37.22	10.64	0.97	12.98
30 08 00	11.11	–127.60	–146.21	–152.46	34.2	36.82	10.21	0.97	12.55

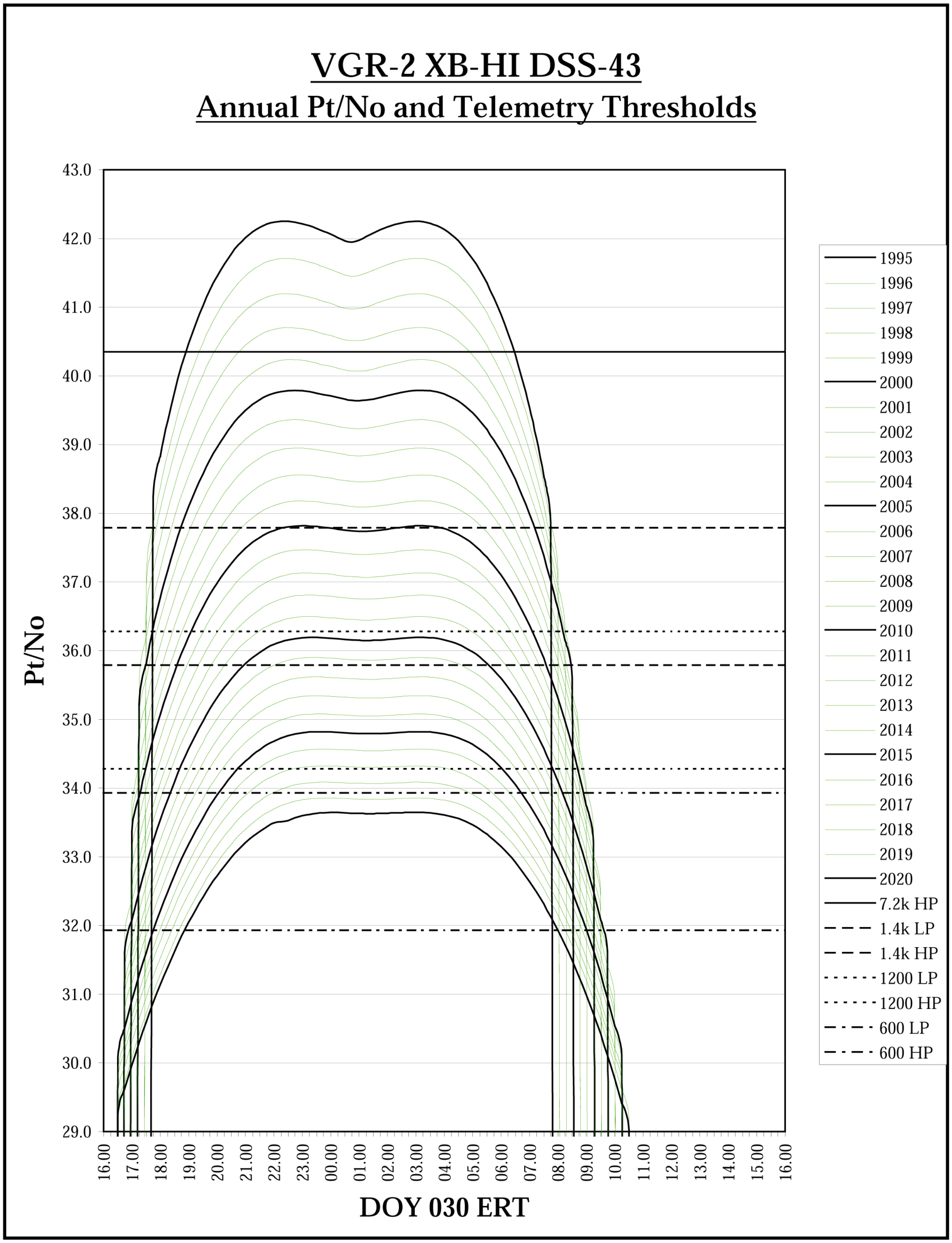


Fig. 5-1. 25 years of Voyager 2 telecom performance predictions.

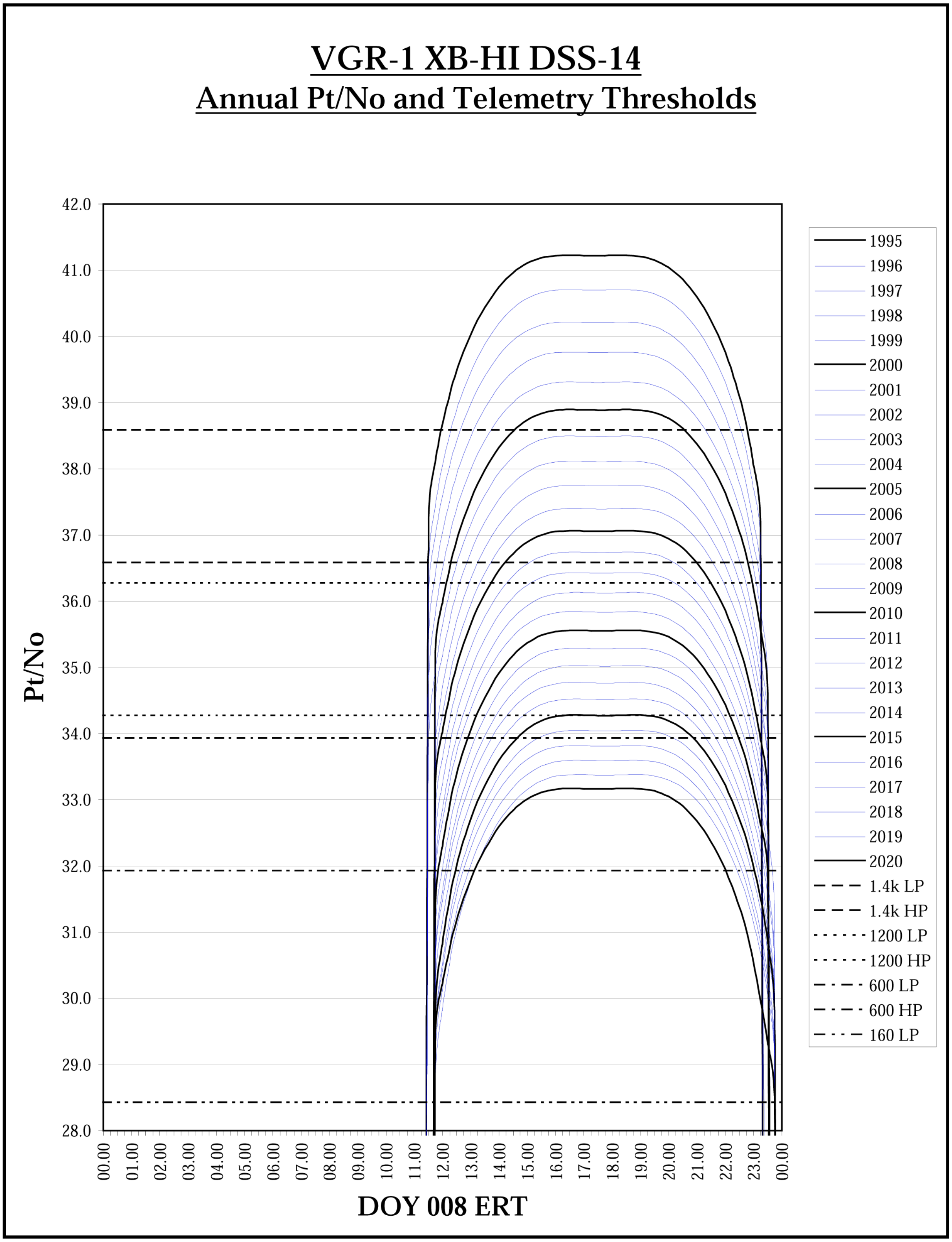


Fig. 5-2. 25 years of Voyager 1 telecom performance predictions.

Section 6

New Spacecraft and Ground Telecom Technology

6.1 Spacecraft and Telecom Link Design Compared with Previous Missions

The Voyager telecom system design was heavily influenced by the telecom system designs for Mariner-Venus-Mercury (1973 launch) and Viking Orbiter (1975 launch). Both of these prior missions flew primary S-band uplink and downlink systems and performed X-band experiments. Key Voyager design improvements consisted of:

1. First-ever use of X-band rather than S-band for primary downlink telemetry
2. Dual-output-power X-band TWTAs*, designed to minimize weight and maximize efficiency while operating over 50,000 hours
3. A 3.66-m diameter antenna, the largest solid reflector flown as of 1977
4. A single-channel telemetry system with concatenated Golay and convolutional coding to provide efficient transmission of data, later upgraded in-flight to concatenated Reed-Solomon and convolutional coding.

Voyager retained the S-band uplink and downlink similar to earlier deep space missions. However, it was the first spacecraft to use X-band as the primary encounter downlink frequency. Both the S-band and X-band power amplifiers were designed to operate at two power levels for flexibility in spacecraft power loading. Simultaneous operation of both at high power was prohibited due to the excessive thermal load that would develop.

6.2 Spacecraft Improvements for Uranus and Neptune Encounters

6.2.1 Image Data Compression

After the Jupiter and Saturn encounters, JPL completed image data compression (IDC) software for Voyager. The project loaded the software into the backup flight data subsystem

*Look up this and other abbreviations and acronyms in the list that begins on page 45.

(FDS) computer that was reconfigured to handle just that task [5, 13].[1] Uncompressed Voyager images contain 800 lines, 800 dots (pixels) per line, and 8 bits per pixel (to express one of 256 gray levels). However, much of the data content in a typical planetary or satellite image is dark space or low-contrast cloud features. By counting only the differences between adjacent pixel gray levels, rather than the full 8-bit values, image data compression reduced the number of bits for the typical image by 60% without unduly compromising the information. This reduced the time needed to transmit each complete image from Uranus and Neptune to Earth.

6.2.2 Error-Correcting Coding

Like other deep space links, the Voyager telemetry link is subject to noise in the communications channel changing the values of bits transmitted over the channel—in other words, causing bit errors. Error-correcting coding reduces the rate of errors in the received information that is output. Such coding increases the redundancy of the signal by increasing the number of bits transmitted relative to the information bit rate.[2] The Golay encoding algorithm used at Jupiter and Saturn required the transmission of one overhead bit for every information bit transmitted (100% overhead). Voyager carried an experimental Reed-Solomon data encoder, expressly for the greater communication range of the Uranus and Neptune phase of the mission. The new Reed-Solomon encoding scheme reduced the overhead to about one bit in five (20% overhead) and reduced the bit-error rate in the output information from 5×10^{-3} to 10^{-6}.

6.3 Ground System Performance Improvements

The capability of the DSN 64-m stations, as it existed during the Voyager Jupiter and Saturn encounters, allowed for maximum downlink rates of 115,200 bps at Jupiter (in 1979) and 44,800 bps at Saturn (in 1981 for Voyager 2). Prior to Voyager 2's Uranus and Neptune encounters (1986 and 1989), several major enhancements described in this section were made to the ground receiving system used for Voyager.

The comparison in Table 6-1 provides an overview of the effectiveness of the upgrade in capabilities. The comparison is between what the maximum downlink rates actually were at each of the four planetary encounters and what they would have been at Uranus and Neptune without the upgrades. The comparison is approximate because of the finite set of Voyager downlink rates available and differences in mission priorities and margin criteria at each encounter.

With other factors constant, communications capability is inversely proportional to the square of the distance from the spacecraft to the Earth. At the encounters, Jupiter-Earth distance averaged 5.2 AU, Saturn-Earth averaged 10 AU, Uranus-Earth was 19 AU, and Neptune-Earth

[1] *The Voyager Neptune Travel Guide* [5] describes the specific IDC algorithm implemented on Voyager. In *Channel Coding and Data Compression System Considerations* [13], Rice discusses Voyager image data compression in context with other aspects for error-correcting coding for the deep space channel. These include convolutional (Viterbi) and Reed-Solomon codes, interleaving, and frame synchronization.

[2] The total channel data rate can be considered apportioned between the original information rate and the redundancy bits as an "overhead". The bits of coded data transmitted over the channel are often referred to as symbols. Because of overhead, the symbol rate is higher than the information bit rate. The power of an error correcting code is that the reduced effect of noise on the signal allows a higher information rate, a lower bit error rate, or a lower transmitter power, or a desirable combination of these.

Table 6-1. Voyager 2 ground system performance improvements.

Encounter	(DSN with 1979–1981 capability) Inverse Square	Expected Rate (bps)	Achieved Maximum Rate (bps)	Factor of Improvement
Jupiter	1/1	115,200 (ref.)	115,200	—
Saturn	1/4	~29,000	44,800	×1.5
Uranus	1/13	~9,000	29,900	×3.3
Neptune	1/36	~3,200	21,600	×6.8

was 30 AU. With no ground upgrade the communications capability at Saturn, Uranus, and Neptune would have been 1/4, 1/13, and 1/36 that at Jupiter, respectively.

6.3.1 DSN 64-m to 70-m Upgrade

The most significant DSN upgrade benefiting Voyager was the upgrade of the 64-m antennas to 70 m. The 70-m upgrade was accomplished by removing the old metallic surface plates and structural outrigger beams, then installing a totally new outer support structure along with precision surface plates that could be adjusted to sub-millimeter accuracy. Holographic alignment techniques were introduced that permitted sharp focusing of the X-band radio signals. Together, the larger surface area and alignment and calibration techniques yielded an improvement in signal strength of 1.4 dB for each 70-m antenna.

6.3.2 Arraying with DSN Antennas

The second-most significant DSN upgrade benefiting Voyager was the installation of baseband combiner technology for arraying multiple antennas. Baseband combining added another 0.8 dB to 70-m performance by arraying the 70-m antenna with a 34-m high-efficiency (HEF) antenna and 1.2 dB by arraying it with two 34-m antennas.

6.3.3 Arraying with Non-DSN Antennas for Neptune Encounter

The Voyager Project called upon ground resources beyond the NASA/JPL-operated DSN for data acquisition at the Neptune encounter. As had been done for the Uranus encounter, the DSN again teamed up with the Australian government’s Parkes 64-m radio astronomy antenna operated by the Commonwealth Scientific and Industrial Research Organization (CSIRO). The 70-m antenna and a 34-m antenna of the DSN facility in Canberra were arrayed with the Parkes antenna, connected by a 320-km (200 mi) microwave link.[3]

[3] Voyager 2’s closest approach with Neptune was on August 25, 1989. Arrays with the Parkes antenna were used as early as March. Parkes was used more days than not during June, July, and August. Closer in time to encounter, Voyager 2 received nearly continuous downlink using arrays at all three sites on most days. At Canberra, the array for a particular pass included up to three stations scheduled from among: DSS-43, DSS-45, DSS-42 and DSS-49 (the numerical designator for Parkes). At Madrid, the array consisted of DSS-63 and DSS-65. At Goldstone, it usually consisted of DSS-14 and DSS-15, with occasional inclusion of DSS-19 (the numerical designator for the VLA).

By simultaneously tracking Voyager from these three antennas during the Neptune encounter period, the DSN and Parkes radio observatory achieved an increase in the combined signal strength roughly proportional to the combined surface areas of the arrayed antennas. Other factors being the same, the DSN-Parkes array provided double the bit-rate capability of a single 70-m antenna.

By far the greatest signal strength improvement for Neptune resulted from arraying the twenty-seven 25-m dishes of the National Radio Astronomy Observatory's (NRAO) Very Large Array (VLA) near Socorro, New Mexico with the 70-m DSN antenna at Goldstone, California. The received signal power (or data rate capability) with the VLA arrayed with the 70-m DSN antenna was nearly triple that of the 70-m antenna by itself. An array of a 70-m antenna, two 34-m antennas, and the VLA increased the downlink capability by 5.6 dB relative to the 70-m antenna alone, almost a factor of four in bit rate.

Last, a cooperative venture with the Japanese space agency permitted use of its 64-m Usuda antenna on encounter day for non-real-time combining of radio science data.

6.3.4 The Block V Receiver

During the early 1990s the DSN developed a software receiver, the BVR. Among other benefits, the BVR offered Voyager the capability to operate in the suppressed carrier mode. By changing the spacecraft exciter's phase modulation index to 90 deg, there is no separate carrier and all of the power goes into the modulated telemetry subcarrier. With the BVR in suppressed carrier mode, the 7200-bps tape recorder playback capability was extended for Voyager 2 by approximately two years beyond the capability using traditional residual carrier mode.[4]

6.3.5 Improvements in System-Noise Temperature

During 2000 to 2001 the DSN replaced the high-maintenance maser preamplifiers with HEMT technology and decreased the preamplifier system noise temperature at the 70-m stations.[5] The two upgrades produced approximately 0.5-dB performance increase for downlink telemetry. From Figure 5-1 or Figure 5-2, the spacecraft recedes from the Earth by the equivalent of 0.5 dB per year in the late 1990s, falling to 0.2 dB per year nearer 2020. Thus, the two upgrades have the effect of prolonging the bit-rate capability (as compared to that with no upgrade) at any time by another year or two.

---

[4] Voyager 1 exhausted its 7200 bps capability before the BVR became available.

[5] The overall efficiency of a receiving system is sometimes expressed as G/T, where G is antenna gain and T is the system noise temperature. The 70-m upgrades included the X-band transmit receive (XTR) cone shown in Figure 4-1. Besides providing X-band transmit capability, use of the XTR cone results in an X-band system noise temperature that is lower by the equivalent to 0.5 dB at higher elevation angles for Voyager. See [10], module 101, *70-m Subnet Telecommunications Interfaces*. The XTR cone's feed design includes a diplexing junction to inject the transmitted signal directly into the feed. This eliminates the need for a waveguide diplexer and a common path for the received and transmitted signals. As a result, much of the received path can be cryogenically cooled with a significant reduction in operating system temperature.

6.3.6 Future Planned Improvements

Later this decade, the DSN plans to upgrade the array capability at all three communication complexes from baseband to full-spectrum combining[6] and install more 34-m stations. Full spectrum combining should allow Voyager to extend the use of science playbacks beyond termination shock, heliosheath, and heliopause into the vast unknowns of interstellar space. Additional 34-m stations should reduce competition among projects for scarce DSN resources, thereby improving the likelihood that Voyager will meet daily DSN tracking requirements through 2020 end of mission.

6.4 Ground Display and Operability Improvements

Prior to VIM, the flight team viewed real-time spacecraft telemetry produced by the Voyager implementation of the Test and Telemetry System (TTS) [14]. The TTS was a 1960s-era system of Univac 1530 and 1219 and Modcomp II computers that ran a Viking operating system and Voyager-specific applications. Flight team inputs to operate the TTS were submitted on punch cards. Fixed format output was viewed either on small black and white monitors called DTV (for digital television) or “green-bar” fan-fold printer paper.

At the start of VIM in 1990, Voyager was the second project (after Magellan) to adopt the JPL Advanced Multimission Operations System (AMMOS) [15]. Use of AMMOS leapfrogged Voyager to networked Unix workstations, including such improvements over TTS as color graphical user interfaces, real-time “on-the-fly” charting, laser printers, and much greater file storage capacity. AMMOS technology contributed significantly to flight team efficiency gains.

[6] See http://deepspace.jpl.nasa.gov/dsn/new_34mbwg.html for a brief discussion of the newest 34-m antenna, under construction near Madrid, and scheduled for completion in late 2003.
See http://www.nasatech.com/Briefs/Aug01/NPO20874.html and http://descansymposium.jpl.nasa.gov/cfm/abstract_detail.cfm?requestid=107&from=search for a description of the DSN’s 34-m array project that includes full spectrum combining.

Section 7

Operational Scenarios of the Voyager Interstellar Mission

When planning VIM* in the late 1980s, it was recognized from the outset that planning thirty-year missions (1990 to 2020) for spacecraft that had already flown for 12 years (1977 to 1989) might appear unreasonably optimistic. The fundamental goal for this long-term mission is to return significant science data from environments not yet well understood. The approach was to establish a basic operational framework with the inherent flexibility to respond to new situations or reformulated goals, as necessary. Conservative spacecraft operation practices were generally planned to maximize lifetime for the various subsystems [16].

7.1 Tracking Coverage

7.1.1 Termination Shock, Heliosheath, Heliopause

The need for increased tracking coverage depends somewhat on the abruptness of the termination shock and heliopause. If the transition regions are spread out so that conditions change over a period of many weeks or months, most of the structure can be determined even with the current level of tracking.[1]

Unfortunately, not much is known about the time scales and sharpness of the boundaries. Some models predict that passage of the spacecraft through the termination shock will take only a few hours. To be conservative, tracking should be planned so that the most abrupt transitions can be characterized. The probability of seeing a very thin shock is proportional to the percentage of tracking coverage. Most of the Voyager investigators feel that continuous or nearly con-

[1] The VIM tracking requirement is for 16 hours per day per spacecraft. The actual coverage in 2000–2001 has been closer to 12 hours per day in consideration of the many new missions that compete for DSN resources today.

*Look up this and other abbreviations and acronyms in the list that begins on page 45.

tinuous (95% to 100%) coverage should be employed in order to cover the possibility of such transitions.

7.1.2 Uplink

Because of the large spacecraft-Earth distance, 70-m stations are used to transmit uplinks to each Voyager to meet the following periodic requirements:

- Weekly: transmission of a Command Loss timer reset command[2]
- Every 4 months: loading a command sequence
- Annually: transmission of a computer command subsystem (CCS) clock calibration, timing test, and memory refresh.

7.1.3 Downlink

The Voyager primary cruise data rate is 160 bps. Either a 34-m beam waveguide (BWG) or 34-m HEF station provides sufficient capability for cruise data.

Two 6.6-hour digital tape recorder (DTR) playbacks are received per year per spacecraft, plus occasional special playbacks requested by scientists. These playbacks require a 70-m downlink station. Near the start of VIM, playbacks were downlinked at 7200 bps. As the 7200-bps link margin approached exhaustion at the 70-m stations, 70-m/34-m HEF arrays were employed to gain a 0.8 dB performance improvement for approximately two more years of capability. When array link margin was exhausted, Voyager reduced the playback data rate to 1400 bps and returned to the use of 70-m stations standing alone. The mission will require arrays again if it is to capture 1400 bps playbacks downlinked from Voyager 1 beginning in 2007 and from Voyager 2 in 2011.

Four 7-hour and two 0.5-hour attitude control calibration maneuvers are performed per spacecraft every year, each requiring 70-m station downlink coverage to ensure uninterrupted downlink telemetry.

Once per year, a 70-m downlink is required to capture a 1200-bps CCS Timing Test from each spacecraft.

A 70-m station is required to capture 600-bps ultraviolet science downlink telemetry, when requested by scientists.

7.2 RFS Strategies

7.2.1 X-Band TWTA High-/Low-Power-Level Drivers

Selection of a power level is a function of such considerations as amount of ultraviolet and cruise science data coverage, periodic general science and engineering (GS&E) telemetry and DTR playbacks, and TWTA lifetime relative to heliopause attainment. Both spacecraft are operated in X-band low power, except when high power is needed to receive the selected data rate at the required level of confidence and at the required bit error rate with the available tracking sup-

[2] Please see Section 7.3.2 for an explanation of the Command Loss timer.

port. Power-level choices derive from 1) the fact that the high-power-based science data are generally of significant value, 2) the risk that the spacecraft may fail first from other causes, and 3) the knowledge that low- versus high-power operation can affect lifetime by at most 25%.

7.2.2 X-Band TWTA Power-Level Switching Cycles Minimized

The X-TWTA power level is switched from high to low power whenever high power is not needed for more than two weeks. Fewer TWTA power switches will maximize TWTA lifetime.

7.2.3 X-Band TWTA On/Off Switching Not Planned

There are no TWTA on/off switches planned, unless there is a spacecraft anomaly. On/off switching is thought to degrade the TWTAs faster than low-/high-power mode switching.

7.2.4 S-Band Downlink Not Required

For both spacecraft, the S-band system will not be turned on again unless there is a spacecraft anomaly because VIM has no requirement for S-band, and the electrical power load is considerably higher than for X-band. If the last X-band TWTA failed or a spacecraft attitude anomaly degraded the pointing accuracy required for X-band, a decision could be made to turn on the S-band system.

7.2.5 Two-Way Coherent Tracking Not Required

Voyager has no plan to deviate from trajectories established prior to the start of VIM. Planetary encounter navigational exactitude is not necessary for VIM. Requirements for two-way coherent Doppler and ranging were eliminated from VIM to reduce cost.

7.2.6 Voyager 2 Procedures to Compensate for Voyager 2 Receiver Problem

On April 6, 1978, a fault-protection algorithm onboard Voyager 2 automatically switched from the prime to backup receiver. However, the backup receiver's tracking-loop capacitor[3] was found to have failed sometime previously. Soon after returning to the prime receiver by ground command, that receiver failed, leaving the spacecraft uncommandable. Seven days later, the algorithm switched back to the crippled backup receiver, forever thereafter requiring special detailed uplink procedures in order to command Voyager 2.

For a command pass, the DSN offsets the Voyager 2 uplink frequency to compensate for the predicted Doppler. The failed tracking loop necessitates that the uplink signal be received within 100 Hz of the best-lock frequency (BLF)[4] to maintain lock. The BLF changes by approximately 100 Hz with each 0.25-deg receiver temperature change. Major temperature changes are caused by spacecraft configuration changes. However, even with a constant configuration,

[3] The tracking-loop capacitor is in the receiver phase-lock loop circuitry to facilitate uplink acquisitions and track Doppler induced frequency shifts resulting from changes in relative velocity between the spacecraft and the DSN antenna. For Voyager, these velocity changes are due primarily to the Earth's rotation, so occur on every pass.

[4] The term "best-lock frequency" in a phase-locked loop refers to the frequency the loop would naturally oscillate at with no input. When the receiver loop is receiving an uplink carrier exactly at BLF (the center of its bandwidth), the loop would indicate a zero static phase error telemetry measurement. The bandwidth of a healthy Voyager receiver is about 100 kHz, as compared with 100 Hz for the receiver with the failed tracking loop.

seemingly random temperature variations affect the BLF significantly. Two special procedures (BLF test and command moratorium), described in the next two paragraphs, are required to reliably command Voyager 2 in the presence of the spacecraft thermal conditions.

Standardized BLF tests, performed about twice per week, tune the uplink signal through the last-known range of the BLF. By observing the resulting spacecraft-receiver signal-level peak time in downlink telemetry and subtracting the round-trip light time, flight-operations staff determine the DSN uplink frequency that produced the peak. The frequency that is determined becomes the latest BLF and is used for commanding and centering the next BLF test.

The flight team plans a Voyager 2 “command moratorium” (a period with no command uplinking permitted) for up to 3 days following any configuration changes that affect the spacecraft thermal profile. The command moratorium is to provide a period of stabilization of the thermal profile before the next BLF test in preparation for commanding.

7.3 Spacecraft Fault Protection

The CCS has five fault-protection algorithms (FPAs) stored in memory, as summarized in Table 7-1. The two algorithms most directly related to the telecommunications system are named RF Loss and Command Loss [17].

Table 7-1. Voyager fault-protection algorithms.

FPA Name	Description
RF Loss	Monitors S- and X-band exciter and transmitter hardware and switches to redundant units if a failure is detected
Command Loss	Switches to redundant command reception hardware units in an effort to re-establish command reception capability if a command had not been received within a specified interval
AACS[a] Power Code Processing	Monitors AACS status information and issues preprogrammed recovery responses in the event of AACS anomalies
CCS Error	Responds to critical anomalous CCS hardware and software conditions. The response typically stops any on-going sequence activities, places the CCS in a known quiescent state and waits for ground action
Power Check	Responds to CCS tolerance detector trip or spacecraft under-voltage power condition by switching to redundant hardware in an attempt to isolate an electrical fault and then eliminating power loads in a predetermined manner if required

[a] Attitude and articulation control subsystem.

7.3.1 RF Loss

RF Loss provides a means for the spacecraft to automatically recover from an S- or X-band exciter or power amplifier degradation or failure affecting the unit's RF output. The CCS monitors the output RF power at four points in the RFS: the S-band exciter and S-band power amplifier and the X-band exciter and X-TWTA. If the output RF power from one or more powered-on units drops below a threshold level, the algorithm will attempt to correct the problem by switching to the redundant unit.

7.3.2 Command Loss

Command Loss provides a means for the spacecraft to automatically respond to an on-board failure resulting in the inability to receive or recognize ground commands. If a period of time set in the flight software goes by without the spacecraft recognizing a valid uplinked command, the Command Loss timer expires. The algorithm responds to the presumed spacecraft failure[5] and attempts to correct that failure by systematically switching to redundant hardware elements until a valid command is received. Command Loss will be executed four consecutive times if command reception is not successful. After four unsuccessful executions, the CCS will disable Command Loss and activate a set of sequences of commands named the backup mission load (BML) and described below.

7.3.3 Backup Mission Load

In the event of permanent loss of command reception capability, a BML command sequence stored onboard each spacecraft is programmed to continue controlling the spacecraft and achieving fundamental VIM objectives. The BML will begin execution two weeks after the first execution of Command Loss and continue until the spacecraft stops operating. It will transmit cruise science and engineering telemetry, store science observations on the tape recorder, and downlink playbacks regularly.

The BML will configure the downlink to X-band high-power, with S-band remaining off. The basic cruise data rate is 160 bps, with playbacks at 1400 bps. The BML was designed for 34-m station supports, except during playbacks when 70-m or 70-m/34-m HEF array support is assumed.

At the beginning of VIM, HGA pointing information was uplinked to an on-board table that will provide accurate attitude control through the planned end of mission in 2020.

[5] A ground system procedural error or station problem that results in failure to transmit the Command Loss timer reset command can also result in the algorithm tripping. A Command Loss timer reset command is usually transmitted to each spacecraft weekly. If a period of time set in the flight software goes by without the spacecraft recognizing a valid uplinked command, the Command Loss timer expires.

References

[1] JPL internal document 618-257, *Voyager Telecommunications Design Control Document*, January 15, 1988.

[2] JPL internal document 618-822, *Voyager Telecommunications System Functional Description,* Charles R. Paul, June 1980.

[3] JPL internal document Des. Req. MJS77-2003-1, *Design Requirement – Mariner Jupiter/ Saturn 1977 Flight Equipment Modulation Demodulation Subsystem*, April 9, 1974.

[4] JPL internal document 618-804, *Voyager Operational Handbook,* August 1989.

[5] JPL document 89-24, *The Voyager Neptune Travel Guide*, Charles Kohlhase, June 1, 1989.

[6] Voyager Project website, http://vraptor.jpl.nasa.gov, Enrique Medina Webmaster.

[7] The Voyager Interstellar Mission Proposal for the 2001 Senior Review of NASA Sun-Earth Connection Mission Operations and Data Analysis (MO&DA) Programs, Edward C. Stone and Ed B. Massey, May 20, 2001.

[8] Simulation of the plasma and neutral environments being explored by the Voyager Interstellar Mission, G. W. Zank, May 2001.

[9] JPL internal document 618-700, *Deep Space Network Operations Plan, Voyager Interstellar Mission (VIM) Project*, E. Batka, April 1995.

[10] JPL document 810-005, Rev. E, *DSMS Telecommunications Link Design Handbook,* http://eis.jpl.nasa.gov/deepspace/dsndocs/810-005/

[11] *Deep Space Telecommunications Systems Engineering*, ed. Joseph H Yuen, Plenum Press, 1983.

[12] JPL internal document VGR-SCT-048, *Voyager Telecom Planning Predicts,* R. Ludwig, November 27, 1996.

[13] JPL Technical Memorandum 33-695 (Rev. 1), *Channel Coding and Data Compression System Considerations for Efficient Communication of Planetary Imaging Data*, Robert F. Rice, September 1, 1974.

[14] JPL internal document 618-686, *Voyager Telemetry System User's Guide*, *Volume I, Introduction And Overview,* March 1977.

[15] JPL internal document D-6057, *Vol. I, MGDS User Guide*, *Introduction To The Workstation*, May 1995.

[16] JPL internal document 618-123, *Vol. V, Voyager Mission Design Guidelines And Constraints*, Interstellar Mission, March 29, 1991.

[17] JPL internal document 618-235, *Vol. I, Voyager Computer Command Subsystem Flight Software Design Description*, C. E. Presley, August 1, 1999.

Additional Resources

[1] "Voyager to reach distant milestone sooner than you think", Heather Sparks, space.com, July 6, 2001
http://www.space.com/missionlaunches/missions/heliosphere_shock_010706.html

[2] "A glowing discovery at the forefront of our plunge through space", Roy Britt, space.com, March 15, 2000
http://www.space.com/scienceastronomy/solarsystem/heliosphere_shock_000315.html

[3] "Plucky Imp Completes 28-Year Observing Marathon", *NASA News*, H01-213,
http://www.gsfc.nasa.gov/news-release/releases/2001/h01-213.htm

[4] WIND spacecraft site, http://www-spof.gsfc.nasa.gov/istp/wind/

[5] ACE spacecraft site, http://www.srl.caltech.edu/ACE/

[6] SAMPEX spacecraft site, http://sunland.gsfc.nasa.gov/smex/sampex/

[7] Univac history, http://www.cc.gatech.edu/services/unisys-folklore/

[8] Modcomp computers, http://www.modcomp.com/

[9] Voyager experiment and instruction descriptions,
http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1977-084A&ex=*

[10] Voyager experiment and instrument descriptions,
http://lepvgr.gsfc.nasa.gov/www/voyager/experiments.html

[11] NASA spacecraft missions, http://spacescience.nasa.gov/missions/

[12] NASA history, http://history.nasa.gov/

[13] DSMS Abbreviations and Acronyms report,
http://csocjplonline.jpl.nasa.gov/ecmweb/82062.htm

[14] Basics of Space Flight, JPL, http://www.jpl.nasa.gov/basics/

[15] "Enhancing Telemetry and Navigation Performance with Full Spectrum Arraying", Timothy T. Pham, Andre P. Jongeling, and David H. Rogstad, presented at the 2000 IEEE Aerospace Conference held in Big Sky, Montana, March 2000

[16] "Space Science Enterprise 2000 Strategic Plan", /s/ Edward J. Weiler,
http://spacescience.nasa.gov/admin/pubs/strategy/2000/index.html

Abbreviations and Acronyms

AACS	attitude and articulation control subsystem
ACE	Advanced Composition Explorer
ACE	call sign (not an acronym) of real time mission controller
ACIS	antenna control and interface subsystem
AGC	automatic gain control
AMMOS	Advanced Multi Mission Operations System
AU	astronomical unit (~1.496 × 10^8 km)
aux osc	auxilliary oscillator
BLF	best-lock frequency
2BLO	loop bandwidth (reference at threshold)
BML	backup mission load
bps	bits per second
BVR	block 5 receiver
BW	bandwidth
BWG	beam waveguide
CCS	computer command subsystem
CDU	command detector unit
CMA	command modulator assembly
CMD	command
CPA	command processor assembly
CRS	cosmic ray system
CSIRO	Commonwealth Scientific and Industrial Research Organization (Australia)
DCT	design control table
deg	degree
DESCANSO	Deep Space Communications and Navigation Systems
dB	decibel
dBi	decibel with respect to isotropic gain
DOY	day of year
DSN	Deep Space Network
DSS	Deep Space Station
DTR	digital tape recorder
DTV	digital television
E_b/N_0	bit energy to noise spectral density ratio

ERT	Earth received time
E_s/N_0	symbol energy to noise spectral density ratio
eV	electron volt
EXC	exciter
FDS	flight data subsystem
FPA	fault protection algorithm
FSS	frame synchronizer subsystem
FSS	frequency selective surface
GS&E	general science and engineering
H	hydrogen
HEF	high efficiency
HEMT	high-electron-mobility transistor
HGA	high-gain antenna
Hz	hertz
IDC	image data compression
IMP	interplanetary monitoring platform
IRIS	infrared interferometer spectrometer
ISS	imaging science subsystem
JPL	Jet Propulsion Laboratory
JSX	Jupiter Saturn Explorer (previous name for Voyager 2 spacecraft)
LECP	low-energy charged particle
LGA	low-gain antenna
LP	low power
MAG	magnetometer
MCD	maximum likelihood convolutional decoder
MDS	modulation demodulation subsystem
MOD	modulation
NASA	National Aeronautics and Space Administration
NRAO	National Radio Astronomy Observatory
NRZ	non-return to zero
ODB	operational database
P_c/N_0	carrier power to noise spectral density ratio
PLS	plasma science
PPS	photopolarimeter system
P_r/N_0	ranging power to noise spectral density ratio
PRA	planetary radio astronomy
P_t/N_0	total power to noise spectral density ratio
PWS	plasma wave system

RCVR	receiver
RF	radio frequency
RFS	radio frequency subsystem
RTG	radioisotope thermoelectric generator
S-EXC	S-band exciter
S-RCVR	S-band receiver
S-TWTA	S-band traveling-wave tube amplifier
SAIC	Science Applications International Corporation
SAMPEX	Solar Anomalous and Magnetospheric Particle EXplorer
SSA	solid state amplifier
ST/N_0	ratio to product of power in data sidebands (S) and bit duration (T) to noise spectral density; equivalent to E_b/N_0
SXA	S- and X-band antenna
sync	synchronization
TCA	telemetry channel assembly
TMU	telemetry modulation unit
TTS	test and telemetry system
TWNC	two-way non-coherent
TWTA	traveling wave tube amplifier
USO	ultrastable oscillator
UVS	ultraviolet spectrometer
VCO	voltage-controlled oscillator
VGR	Voyager
VIM	Voyager Interstellar Mission
VLA	Very Large Array (Socorro, NM)
WIND	full name (not an acronym) of a spacecraft studying near-Earth solar wind
X-EXC	X-band exciter
X-TWTA	X-band traveling-wave tube amplifier
XTR	X-band transmit receive