Chapter 3
Voyager Telecommunications

Roger Ludwig and Jim Taylor

This chapter 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 and continues in the 2010s [1–3].

The Voyager spacecraft were designed and constructed at the Jet Propulsion Laboratory (JPL) in Pasadena, California. The flight team, very much reduced in size more than 30 years after the launches, is also located at JPL.

3.1 Voyager Interstellar Mission Description

The two Voyager spacecraft are continuing on long-term (1977–2025) exploratory mission. After exploring the outer planets—Jupiter, Saturn, Uranus, and Neptune—the Voyager spacecraft reached the edge of the Solar System and continue heading toward their final destination: interstellar space. They are now traversing regions of space never before encountered, building on the legacy of the National Aeronautics and Space Administration's (NASA's) most successful and productive interplanetary exploration endeavor [1].

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 Fig. 3-1.

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 as defined in NASA's Space

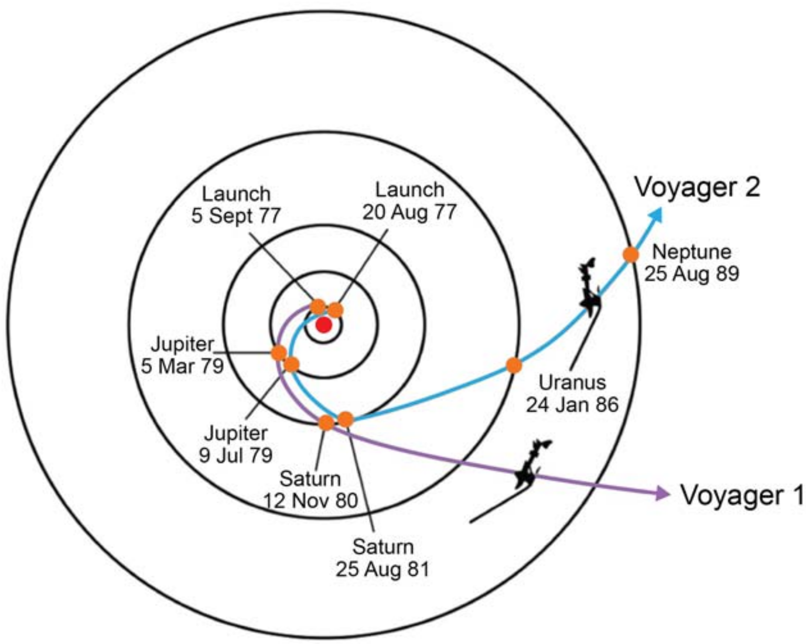

Fig. 3-1. Voyager flight paths.

[1] Earlier mission phases included launch and Earth-Jupiter cruise and the planetary mission (Jupiter, Saturn, Uranus, and Neptune encounters). These phases are archived in a section of Ref. 1, http://voyager.jpl.nasa.gov/news/index.html#

Science Enterprise 2000 Strategic Plan.[2] One objective in the plan that year was to “understand our changing Sun and its effects throughout the Solar System.” A dozen years later, the Voyager mission was the only one continuing to explore the outer heliosphere. The Voyager spacecraft remain on trajectories that 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 defined in 2000 were to “Learn how galaxies, stars, and planets form, interact, and evolve” and to “Use the exotic space environments within our Solar System as natural 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 ones in position to carry out the objective of exploring nearby environments of our Galaxy. 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 IBEX) and Ulysses traveling far south and north of the ecliptic.

The Voyagers and Pioneers 10 and 11, launched 4 and 5 years earlier, are 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 Fig. 3-2, each carry the following instruments:[3]

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[2] The NASA Strategic Plan is available at http://science1.nasa.gov/about-us/science-strategy/. The 2000 Strategic Plan cited in this chapter is no longer accessible to the public. A link to the 2011 Plan is http://www.nasa.gov/pdf/516579main_NASA2011StrategicPlan.pdf

[3] Figure 3-2 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=* in the National Space Science Data Center [4].

- 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 kilo-electron volts (keV) to mega-electron volts (MeV) range
- Cosmic ray system (CRS) measures cosmic ray electron and nuclei energies in the 3 to 30 MeV range

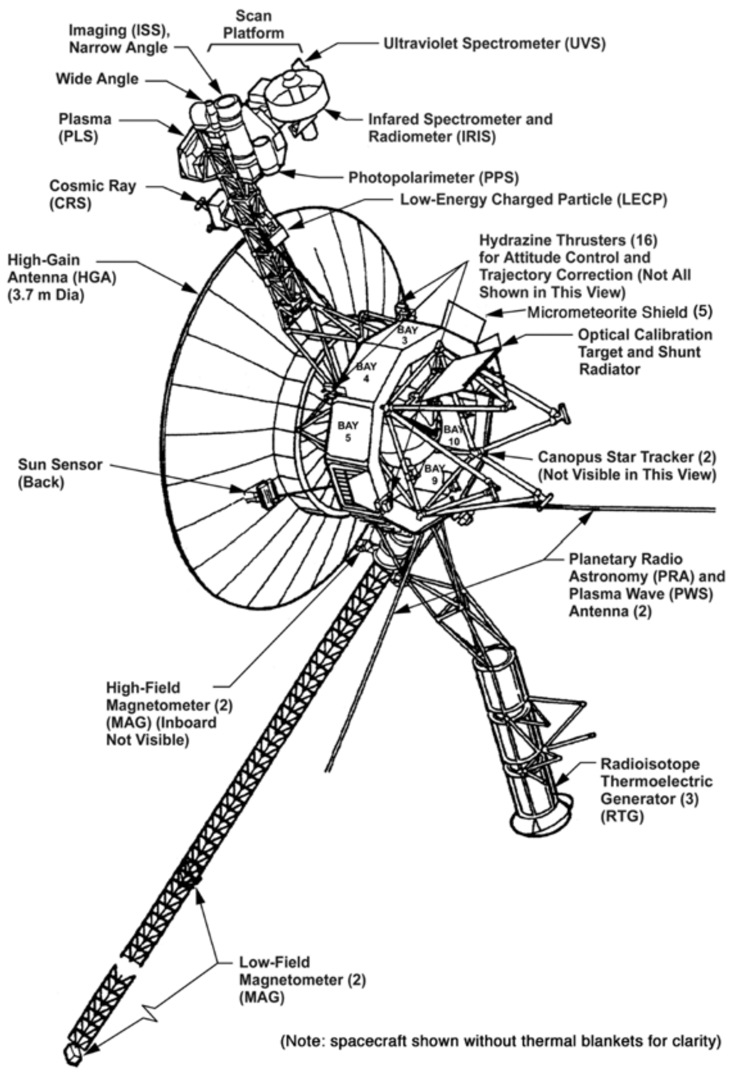

Fig. 3-2. Voyager spacecraft and science instruments.

- 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-nanometers (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 and again in 2013 has made that problem more tractable.

The VIM consists of three distinct phases: termination shock, heliosheath exploration, and interstellar exploration. The two Voyager spacecraft began the VIM operating in an environment controlled by the Sun's magnetic field with the plasma particles being dominated by those contained in the expanding supersonic solar wind. This is the characteristic environment of the termination shock phase. At some distance from the Sun, the supersonic solar wind is held back from further expansion by the interstellar wind. The first feature encountered by a spacecraft as a result of this interstellar wind/solar wind interaction is the termination shock where the solar wind slows from supersonic to subsonic speed and large changes in plasma flow direction and magnetic field orientation occur.

Passage through the termination shock ended the termination shock phase and began the heliosheath exploration phase. Voyager 1 crossed the termination shock at 94 AU in December 2004, and Voyager 2 crossed at 84 AU in August 2007. After passage through the termination shock, each spacecraft was operating in the heliosheath environment, which is still dominated by the Sun's magnetic field and particles contained in the solar wind. The thickness of the heliosheath had been uncertain, estimated to be tens of astronomical units thick, taking several years to traverse.

The heliosheath exploration phase ends with passage through the heliopause which is the outer extent of the Sun's magnetic field and solar wind. Voyager 1 has completed its passage through the heliopause [5], thus starting the interstellar exploration phase with the spacecraft operating in an interstellar wind dominated environment. This interstellar exploration is the ultimate goal of the Voyager Interstellar Mission.

Voyager 1 has been escaping the Solar System at a speed of about 3.6 AU per year, 35 degrees (deg) out of the ecliptic plane to the north, in the general direction of the Solar Apex (the direction of the Sun’s motion relative to nearby stars). Voyager 2 is also escaping the Solar System at a speed of about 3.3 AU per year, 48 deg out of the ecliptic plane to the south.

Both Voyagers were expected to cross the heliopause 10 to 20 years after reaching the termination shock. The crossing has been determined to be 2012 for Voyager 1 and should be within the span of ~2017–2027 for Voyager 2. In late-2013, Voyager 1 was announced as the first human-made object to venture into interstellar space [6]. “We believe this is mankind’s historic leap into interstellar space,” said Ed Stone, Voyager project scientist based at the California Institute of Technology, Pasadena. “The Voyager team needed time to analyze those observations and make sense of them. But we can now answer the question we’ve all been asking – ‘Are we there yet?’ Yes, we are.”

Voyager 1 is just outside the solar bubble, where some effects from our sun are still evident. Figure 3-3 is an artist’s concept of the outer environments or regions that were being explored by the VIM at about the time of the Voyager 1 entry into interstellar space.[4]

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[4] A summary of the “solar bubble” (heliosphere) boundaries and regions defined in Figure 3-3 is in http://www.jpl.nasa.gov/news/news.php?release=2013-209.

In 2004, Voyager 1 passed through the termination shock into the slow-down region, as it first detected the increased pressure of interstellar space on the heliosphere.

In 2010, it then passed into the “stagnation region” where the outward velocity of the solar wind slowed to zero and sporadically reversed direction. In Fig. 2-3, in the slow-down and stagnation regions, the prevalence of low-energy charged particles from the heliosphere jumped dramatically and is indicated by the green dots.

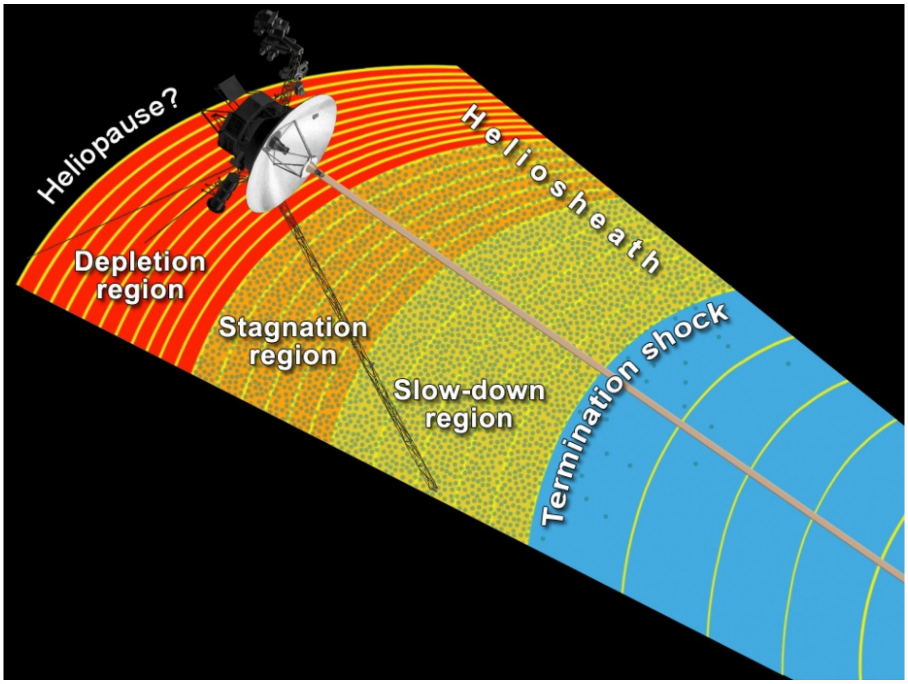

Fig. 3-3. Voyagers 1 and 2 exploration of the outer regions of the solar bubble as of 2013.

The Voyagers have enough electrical power and thruster fuel to operate at least until 2025. By that time, Voyager 1 will be 15.5 billion miles (24.9 billion kilometers [km]) from the Sun and Voyager 2 will be 13.0 billion miles (20.9 billion km) away. Eventually, the Voyagers will pass other stars. In about 40,000 years, Voyager 1 will drift within 1.6 light years (9.3 trillion miles) of AC+79 3888, a star in the constellation of Camelopardalis. In some 296,000 years, Voyager 2 will pass 4.3 light years (25 trillion miles) from Sirius, the brightest star in the sky. The Voyagers are destined—perhaps eternally—to wander the Milky Way.

The two Voyagers were the first operational spacecraft to reach the heliopause and to return the science observations from that region. The duration of the VIM will be limited primarily by the decreasing spacecraft electrical power from the two radioisotope thermoelectric generators (RTGs) and telemetry link

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On August 25, 2012, Voyager 1 entered the depletion region, where the magnetic field allows energetic ions from inside the heliosphere to escape out, and cosmic rays from interstellar space zoom in. This outer region is also called the magnetic highway for the magnetic field and its effect on the ions and cosmic rays. Additional details are in a section of Ref. 1 that also has references to mid-2013 scientific papers. http://www.jpl.nasa.gov/news/news.php?release=2013-209 capability. Table 3-1 provides life estimates for electrical power, telecommunications, and hydrazine (for attitude control).

Table 3-1. 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
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 (antenna)

Voyager 1 can be tracked by stations at all three sites. With Voyager 2 far south of the ecliptic, it is not visible from the northern hemisphere stations so the telecommunications link is only through Canberra. 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.

The Voyager project continuously 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 percent, from approximately 300 in 1989 to 10 in 2002. Reduced staffing since then has constrained 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 bits per second (bps) or 600 bps, the different data types are interleaved.)

- Playbacks of data recorded at 7200-bps or 1400-bps on the tape recorder
- 160-bps real-time fields, particles, and waves; UVS subset; engineering
- 40-bps real-time engineering data.

3.2 Overview of Telecom Functional Capabilities

This section describes telecom system capabilities that existed at launch. Figure 3-4 shows the functions of the spacecraft and the DSN telecom system. Some functions, such as S-band downlink and the spacecraft low-gain antenna

(LGA), are no longer used. Section 3.7, Operational Scenarios of the Voyager Interstellar Mission, describes the combinations of capabilities being used in the Voyager Interstellar Mission (VIM).

3.2.1 Uplink

3.2.1.1 Uplink Carrier. Each Deep Space Station (DSS) transmits an uplink carrier frequency[5] of 2114.676697 megahertz (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[6] 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.

3.2.1.2 Ranging Modulation. Voyager uses standard DSN turnaround sequential ranging modulation. "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 Module 203, Sequential Ranging, of the *DSN Telecommunications Link Design Handbook* [7].)

The spacecraft transponder has the capability to demodulate the uplink ranging data from the uplink carrier and modulate it on the S-band[7] 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.

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[5] 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 Module 201, Frequency and Channel Assignments, in the *DSN Telecommunications Link Design Handbook* [7].

[6] A transponder includes a receiver and an exciter. An exciter is the part of a radio transmitter that produces the downlink carrier frequency.

[7] 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.

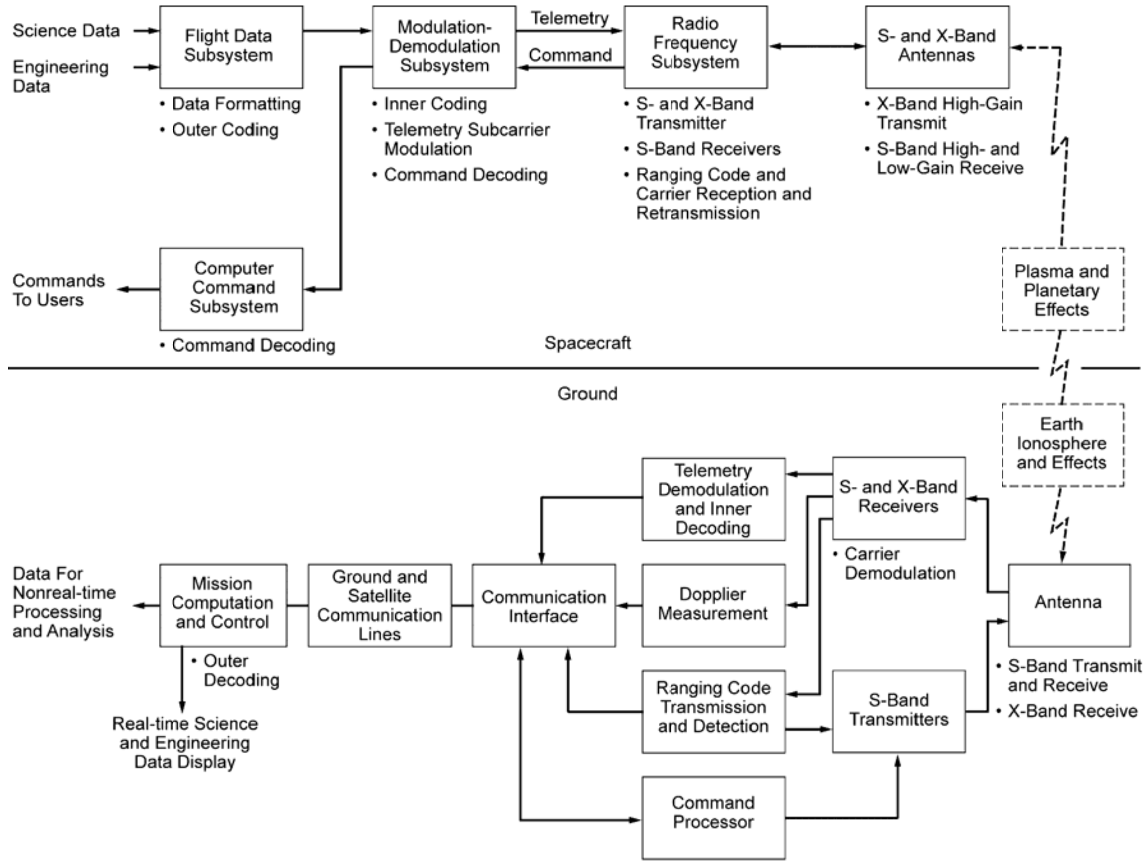

Fig. 3-4. Overview of spacecraft and ground telecommunications functions for Voyager.

3.2.1.3 Command Demodulation. Voyager receives and demodulates the command signal from the uplink carrier. (DSN command modulation is described in the *DSN Telecommunications Link Design Handbook* [7], module 205, 34-m and 70-m Command.) The signal consists of 16-bps, Manchester-encoded commands, biphase modulated onto a squarewave subcarrier frequency of 512 hertz (Hz).

3.2.2 Downlink

3.2.2.1 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.[8] In this mode, or when the receiver is not locked to an uplink carrier, an onboard frequency source generates the downlink carrier frequencies.

3.2.2.2 Transmit Frequencies. Table 3-2 contains the downlink carrier frequencies and associated DSN channel numbers that Voyager 1 and Voyager 2 produce in the coherent and non-coherent modes.

Table 3-2. 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

[8] 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.” (Beginning in the late 1990s, the term “coherency disabled” replaced “TWNC on” and “coherency enabled” replaced “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.

3.2.2.3 Downlink Polarizations. Table 3-3 defines the downlink polarization produced at S-band (from either power amplifier) and X-band (from the selected traveling wave tube amplifier (TWTA).

Table 3-3. 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

3.2.2.4 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 kilobits per second (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 biphase-modulate the telemetry symbols onto either a 22.5-kilohertz (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.[9]

3.3 Spacecraft Telecom System Design

3.3.1 Spacecraft Telecom System Overview

The telecom system consists of three subsystems, as detailed in Table 3-4. The table shows the subsystem acronyms for reference.

[9] DSN telemetry data bit, symbol, and subcarrier waveform requirements are defined in the *DSN Telecommunications Link Design Handbook* [7], Module 207, 34-m and 70-m Telemetry Reception.

Table 3-4. Voyager spacecraft telecom subsystems and their components.

Subsystem/Component Quantity	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)	
S/X-band antenna subsystem (SXA)	
High-gain antenna (HGA)	1
Low-gain antenna (LGA)	1

Note: In Table 3-4, 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.

Figure 3-5 is a functional block diagram of the Voyager telecom system.[10] 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 3-2.

The radio frequency subsystem 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,

[10] 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 3.7, Operational Scenarios.

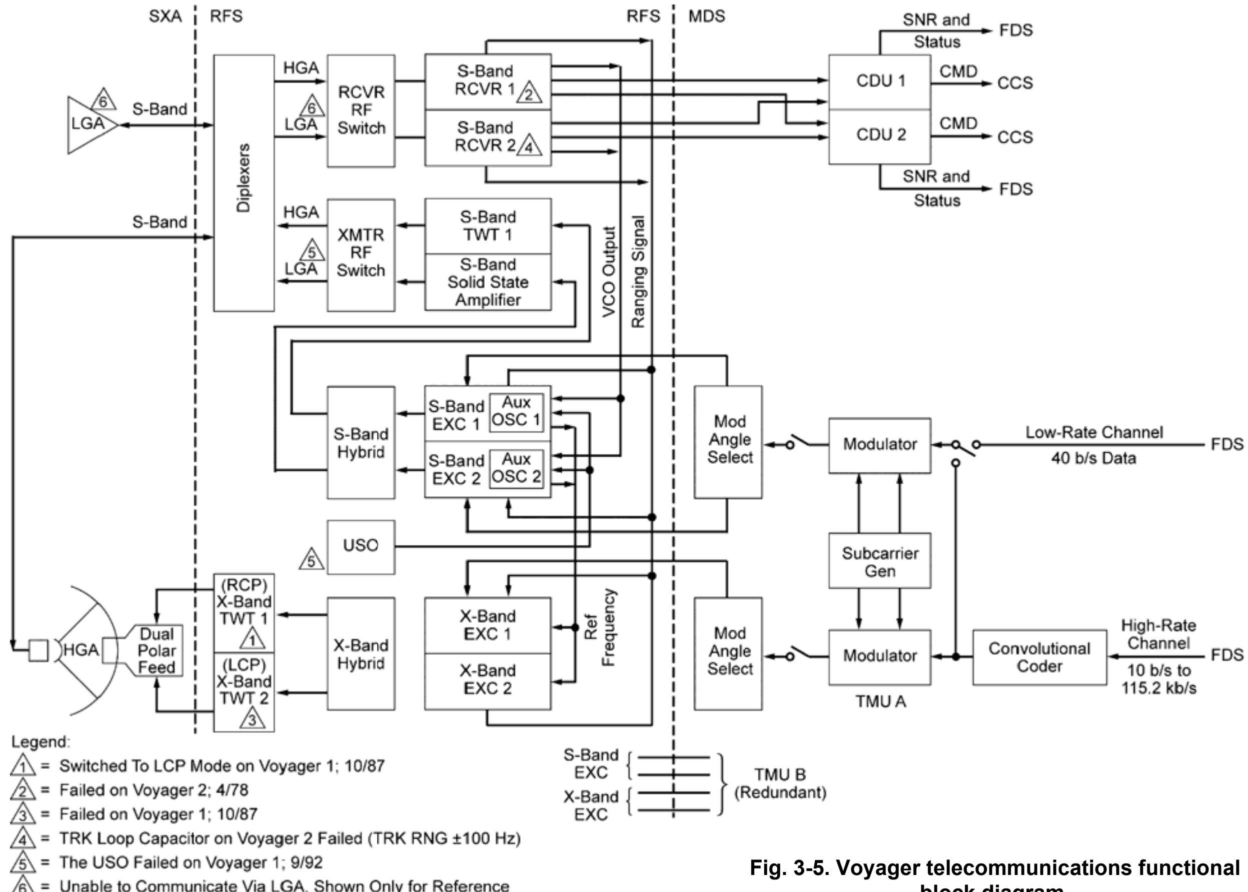

Fig. 3-5. Voyager telecommunications functional block diagram.

working as a redundant pair. Microwave components provide radio frequency (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 an LGA and an HGA. The subsystem receives S-band signals and transmits 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

In Table 3-5, S-band bit rates are convolutionally coded, except for 40 bps which is uncoded. X-band planetary cruise bit rates 10–2560 bps are convolutionally coded, while all VIM rates and planetary playback rates (7.2–115.2 kbps) are coded with a concatenation of convolutional and Golay or convolutional and Reed-Solomon coding.

Table 3-5 displays typical configurations used by Voyager for each mission phase.

Mission Phase	Transmitter Power		Antenna	Ranging		Subcarrier Freq (kHz)		Link Data Rates and Coding (bps)		RFS Tracking Configuration
	S	X		S	X	S	X	S	X	
Launch	Lo	Off	LGA	Off	Off	22.5	22.5	1200[a]	Off	1-way
1st 80 days	Hi	Off	LGA	Off	Off	22.5	Off	10–2560[a]	Off	2-way coherent
Planetary cruise	Off	Low	HGA	Off	On	Off	22.5	Off	10–2560[a]	2-way coherent
Planetary playback	Lo	Hi	HGA	On	On	22.5	360	40[c]	7.2 k–115.2 k[b]	2-way coherent
VIM cruise	Off	Lo	HGA	Off	Off	Off	22.5	Off	160[b]	1-way
VIM playback	Off	Hi	HGA	Off	Off	Off	22.5	Off	1.4 k–7.2 k[b]	1-way

[a]Convolutionally coded; [b]convolutionally coded with Golay or Reed-Solomon; [c]uncoded

3.3.2 Modulation Demodulation Subsystem

3.3.2.1 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.

3.3.2.2 Telemetry Modulation Units. The TMU can receive both high-rate and low-rate, non-return-to-zero (NRZ), serial digital data from the FDS. By using control input from the CCS, shown as switches in the TMU-A section of Figure 3-5, the TMU selects for a set of modes to process telemetry data through the TMU. CCS control inputs determine low-rate/high-rate data routing for S-band, 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.

3.3.3 Radio Frequency Subsystem

3.3.3.1 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.

3.3.3.2 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 auxiliary oscillator (aux osc) that can generate the downlink (D/L) in the TWNC-on mode or when there is no uplink (U/L). Although the USO (Section 3.3.3.6) is preferred as the D/L source in these cases, the aux osc can take over if the USO fails[11] or is switched off.

3.3.3.3 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

[11] The Voyager 1 USO failed in September 1992, as flagged by legend item 5 in Figure 3-5. 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.

no S-band downlink is required. Both power amplifiers have two RF output power levels available.[12] 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.

3.3.3.4 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.

3.3.3.5 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 by CCS control input. (The low-power and high-power RF levels to the HGA for the X-TWTA are 12 W and 18 W.)

In October 1987, the Voyager 1 X-TWTA-2 failed, as annotated in Figure 3-5, 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.[13] For both spacecraft, legend item 1 in the figure flags the changes from X-TWTA-2's right-hand circular polarized (RHCP) downlink to X-TWTA-1's left-hand circular polarized (LHCP) downlink. (The relationship between X-TWTA selection and the resultant polarization of the X-band downlink is described in the SXA Section 3.3.4 that follows.)

3.3.3.6 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.

3.3.4 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

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[12] The low-power and high-power RF levels to the HGA for the S-band TWTA are 6.5 W and 19 W. For the S-SSA, they are 6 W and 15 W [8].

[13] The switch to the backup X-TWTA is in the status report section of the Voyager mission status web page, http://voyager.jpl.nasa.gov/news/voyager_status.html [1].

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 3-6 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 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.

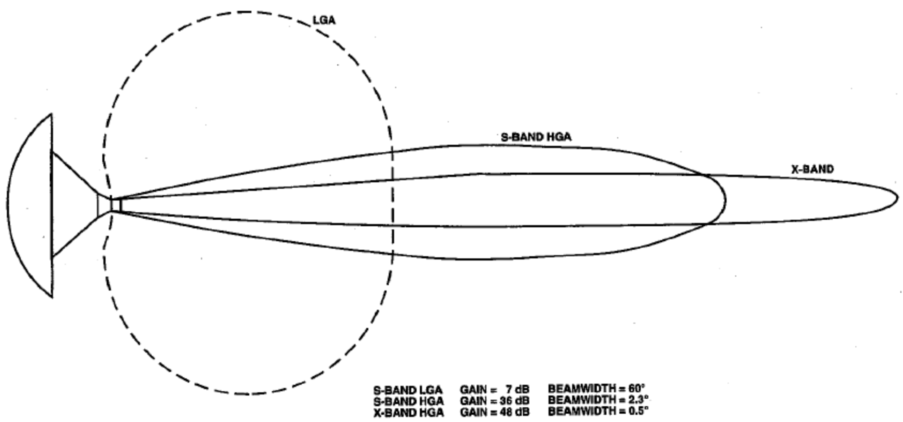

Fig. 3-6. Voyager SXA patterns and beamwidths.

3.3.4.1 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.

3.3.4.2 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.

3.3.5 Telecom System Input Power and Mass

Table 3-6 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.

3.4 Telecom Ground System Description

The DSN is an international network of ground stations (antennas, transmitters, receivers, and associated systems) that operated intensively only at S-band and X-band during the first decades of the Voyager mission, with a Ka-band capability being developed in the 1990s.[14] 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).

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[14] A link to the home page of the DSN is http://deepspace.jpl.nasa.gov/ which has an "About the DSN" section with brief descriptions of the functions and history of the Network, as well as information about the tracking station complexes in Australia, Spain, and California.

Table 3-6. 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			
TMU	2	5.7	2.2
CDU	2	5.4	2.0
SXA			53.0
SXA, SXA coax, SXA waveguide			2.1
SXA structure, including main reflectors			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 kilograms (kg).

[c] Antenna control and interface system.

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* [7] includes functional capability descriptions of each antenna type for the purpose of modeling link capability between a spacecraft and station.[15]

3.4.1 Uplink and Downlink Carrier Operation

Voyager uses an S-band uplink, X-band primary downlink, and S-band secondary downlink.[16] 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 3-7 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 the *DSN Telecommunications Link Design Handbook* [7] for corresponding figures and descriptions of the other types of DSN stations.

3.4.1.1 Uplink. The uplink signal produced by the 20-kilowatt (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.

3.4.1.2 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 3-7) to the S-band feed and passes the X-band through to the X-band feed with very low loss.

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[15] 810-005 (Rev. E) [7], was initially released January 2001 as a paper document. Modules in Rev E are updated as needed and are now maintained online at the link http://deepspace.jpl.nasa.gov/dsndocs/810-005/. Though the Voyager spacecraft was originally designed to work with ground systems defined in previous versions of the Handbook, the Rev E systems continue to support the Voyagers. Also, 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.

[16] For Neptune encounter and later, 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 would be selected by system fault protection if the X-band link were to fail.

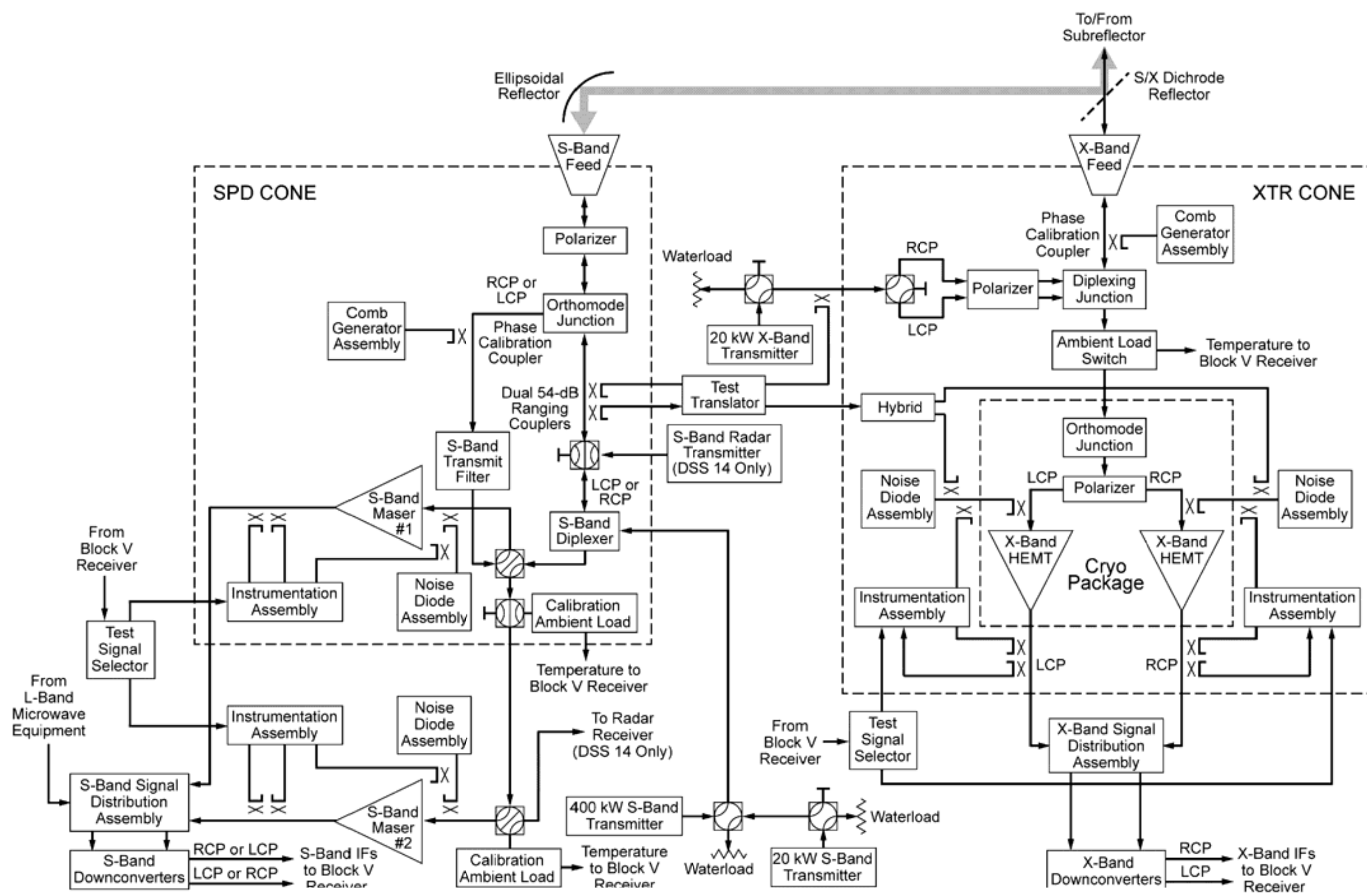

Fig. 3-7. DSS-14 and DSS-43 microwave and transmitter block diagram.

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.

3.4.2 Command Processing

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

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.

3.4.3 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).[17]

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)[18] to process the (7,1/2) convolutional code. The MCD outputs decoded telemetry bits to the frame synchronizer subsystem (FSS).

An MCD/FSS pair makes 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.

3.5 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 the *DSN Network Operations Plan for VIM* [9] and the *DSN Telecommunications Link Design Handbook* [7].

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 the *Voyager Telecommunications Design Control Document* [10] for planned telecom configurations and predicted uplink and downlink performance during Voyager's prime mission. (This section is limited to a summary of the telemetry performance during VIM.)

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

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[17] 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 3.6, New Telecom Technology.

[18] See Module 208, Telemetry Data Decoding, in the *DSN Telecommunications Link Design Handbook* [7] 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 since 1997.

The four VGR telecom functions are carrier tracking (Doppler), command, telemetry, and ranging. The performance of each function is expressed as a signal-to-noise ratio (SNR), as shown in Table 3-7.

Table 3-7. 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

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), 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.

3.5.1 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 two conditions of Command at mean minus 3-sigma and Telemetry at mean minus 2-sigma. Sigma refers to the standard deviation of the command E_b/N_0 and telemetry E_s/N_0.

A DCT includes numerous link parameters and their tolerances, but it applies to only one point in time. For planning and analyzing performance during flight, the project may prefer tabulations or plots of key quantities versus time.

The original JPL Deep Space Communications and Navigation Systems (DESCANSO) article from which this chapter is based [3] contains DCTs for the S-band uplink (carrier and command channel) and the X-band downlink (carrier and telemetry channel).

3.5.2 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 3-8 summarizes predictions of downlink P_t/N_0 [19] at one station (DSS-43) and one day of the year

[19] 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.

(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). All of the Fig. 3-8 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 and Earth increases steadily from year to year. Telemetry thresholds are displayed as horizontal lines per the legend on the 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. The project will continue to plan data rate usage and scheduled station support. In the same manner, Fig. 3-9 displays 25 years of Voyager 1 day-of-year (DOY) 008 performance predictions and bit-rate thresholds at DSS-14.

3.6 New Spacecraft and Ground Telecom Technology

3.6.1 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

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Performance of bit rates that extend over orders of magnitude (600 bps to 7.2 kbps in Fig. 3-8 and 160 bps to 1.4 kbps in Fig. 3-9) 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. 3-8) and Voyager 1 (Fig. 3-9) represents the additional 0.8 dB gain achieved by using suppressed carrier for that rate on Voyager 2 only. See Section 3.4.3 Telemetry Processing and Section 3.6.3 Ground System Performance Improvements for additional information regarding the suppressed carrier downlink.

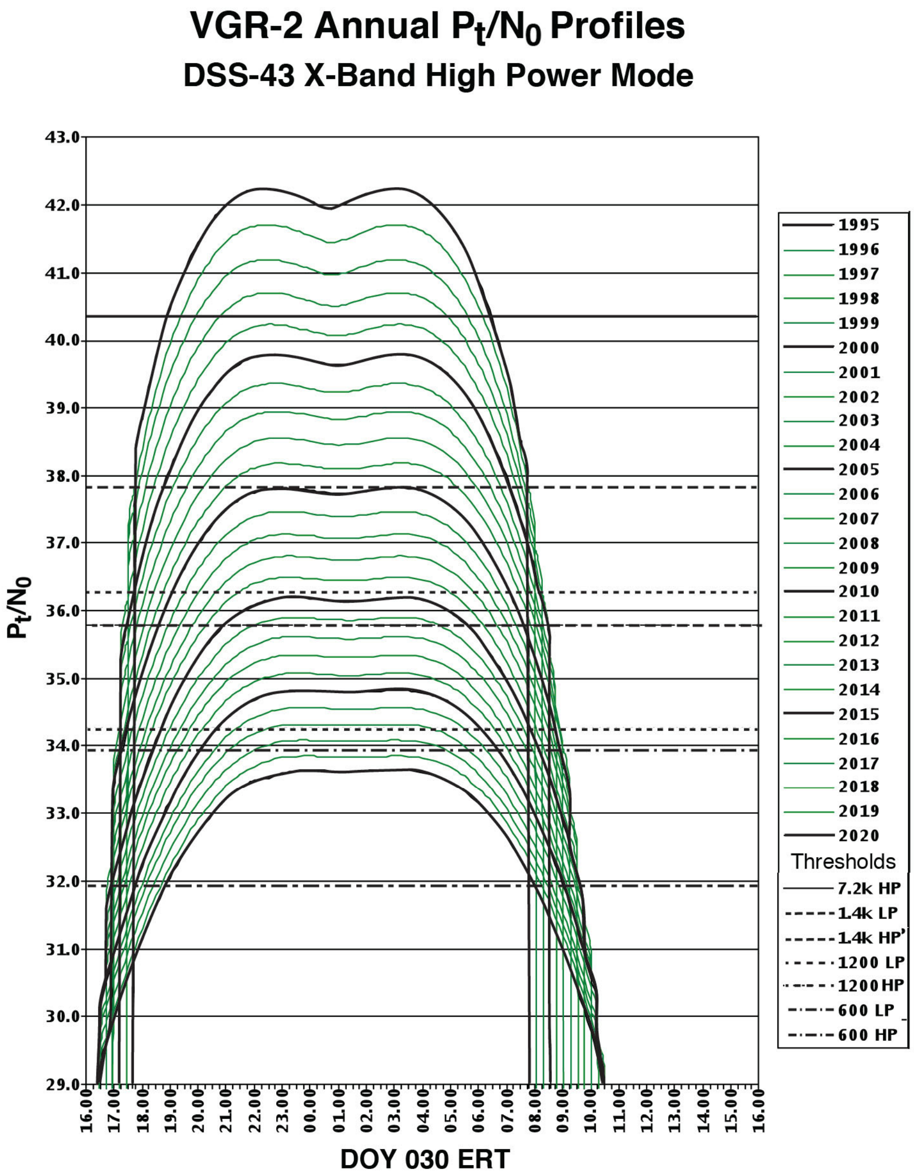

Fig. 3-8. 25 Years of Voyager 2 telecom performance predictions for DSS-43.

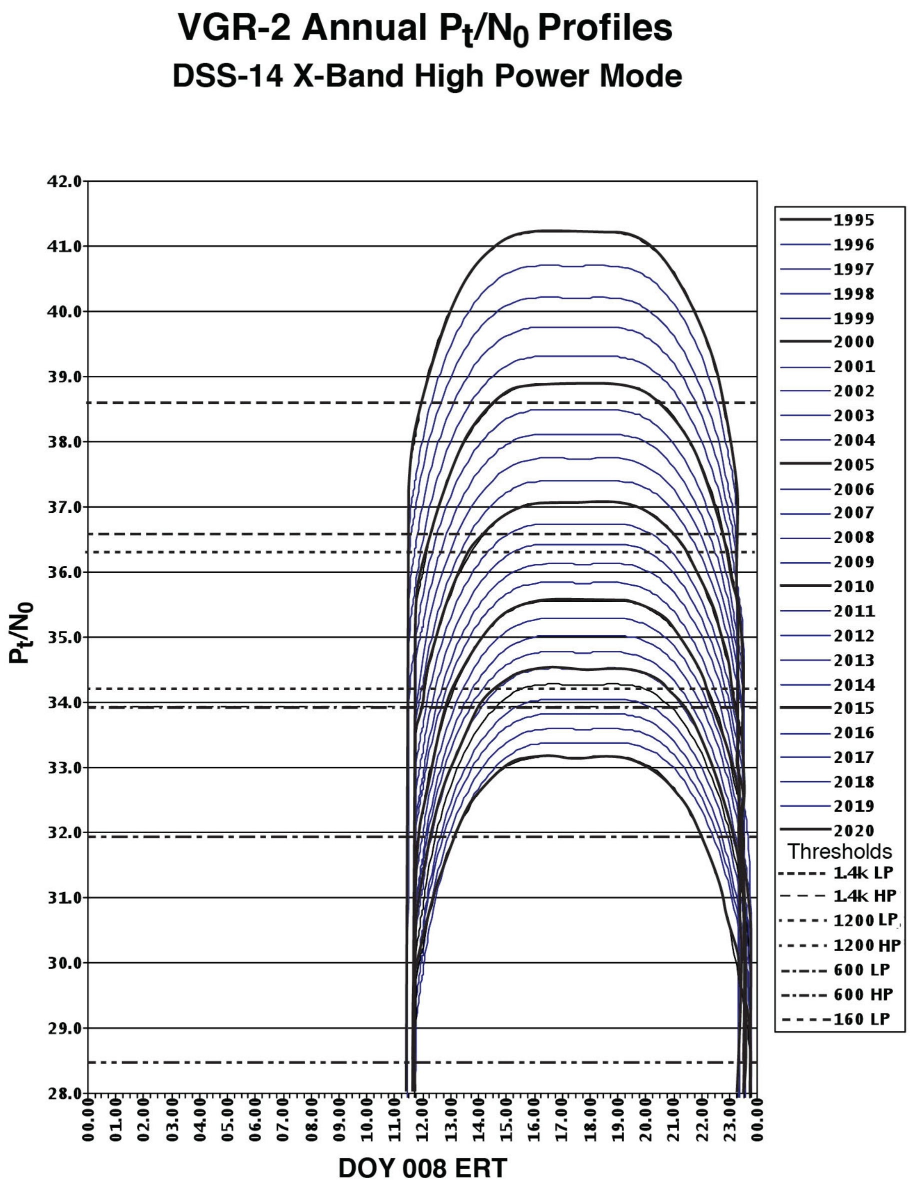

Fig. 3-9. 25 years of Voyager 1 telecom performance predictions for DSS-14.

2) Dual-output-power X-band TWTAs, designed to minimize mass and maximize efficiency while operating more than 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.

3.6.2 Spacecraft Improvements for Uranus and Neptune Encounters

3.6.2.1 Image Data Compression (IDC). After the Jupiter and Saturn encounters, JPL completed IDC software for Voyager. The project loaded the software into the backup flight data subsystem (FDS) computer that was reconfigured to handle just that task [12, 13].[20] 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 percent without unduly compromising the information. This reduced the time needed to transmit each complete image from Uranus and Neptune to Earth by the same 60%.

3.6.2.2 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

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[20] The *Voyager Neptune Travel Guide* [12] 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 of error-correcting coding for the deep space channel. These include convolutional (Viterbi) and Reed-Solomon codes, interleaving, and frame synchronization.

that is output. Such coding increases the redundancy of the signal by increasing the number of bits transmitted relative to the information bit rate.[21] The Golay encoding algorithm used at Jupiter and Saturn required the transmission of one overhead bit for every information bit transmitted (100 percent 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-percent overhead) and reduced the bit-error rate in the output information from 5×10^{-3} to 10^{-6}.

3.6.3 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 3-8 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 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.

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[21] 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 3-8. Voyager 2 ground system performance improvements (DSN with 1979–1981 capability).

Encounter	Inverse Square	Expected Rate (bps) from Inverse Square	Achieved Maximum Rate (bps)	Factor of Improvement
Jupiter	1/1	115,200 (baseline for inverse square bit rates)	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

3.6.3.1 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 [14]. Together, the larger surface area and alignment and calibration techniques yielded an improvement in signal strength averaging 1.4 dB for each 70-m antenna.

3.6.3.2 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 the 70-m performance by arraying the 70-m antenna with a 34-m high-efficiency (HEF) antenna, and it added 1.2 dB by arraying the 70-m antenna with two 34-m antennas.

3.6.3.3 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 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.[22]

[22] 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

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.

3.6.3.4 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. (Voyager 1 exhausted its 7200 bps capability before the BVR became available.)

3.6.3.5 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.[23] The two upgrades produced approximately 0.5-dB performance

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array for a particular pass included as many as 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).

[23] 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 Fig. 3-7. 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

increase for downlink telemetry. From Fig. 3-8 or 2-9, 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.

3.6.3.6 Additional 34-m Stations and Full-Spectrum Combining for Array. The DSN has upgraded the array capability at all three communication complexes from baseband to full-spectrum combining[24] and has installed more 34-m stations. Full spectrum combining allows Voyager to extend the use of science playbacks beyond termination shock, heliosheath, and heliopause into the interstellar space beyond. The availability of more 34-m stations reduces competition among any given number of projects for scarce DSN resources. In 2013, Voyager routinely arrays a pair of 34-m antennas for daily 160 bps cruise telemetry.

3.6.4 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) [15]. The TTS was a 1960s-era system of Univac 1530, and Univac 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) [16]. 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

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Voyager. See *DSN Telecommunications Link Design Handbook,* Module 101, 70-m Subnet Telecommunications Interfaces [7]. 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.

[24] See http://www.jpl.nasa.gov/news/news.php?feature=553 for a brief discussion of the additional 34-m antenna near Madrid that was completed in late 2003. See http://www.techbriefs.com/component/content/article/1264-ntb/tech-briefs/electronics-and-computers/7394 for a description of the DSN’s 34-m array project that includes full spectrum combining.

capacity. AMMOS technology contributed significantly to flight team efficiency gains.

3.7 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 [17].

3.7.1 Tracking Coverage

The planned VIM tracking requirement was set at 16 hours per day for each Voyager spacecraft. Due to competing needs from other spacecraft, the actual coverage in 2000 and 2001 was roughly 12 hours per day. By late 2012, the coverage had been reduced to 2 to 6 hours per day for each Voyager due to contentions with another project in the same part of the sky in that year as well as simultaneous downtimes of several months at two stations. The coverage for each Voyager returned to the norm by the end of the downtimes.

3.7.1.1 Termination Shock, Heliosheath, and Heliopause. The requirements on spacing and duration of DSN tracking passes depend somewhat on the abruptness of the termination shock and heliopause. The 2013 plan was for one or more passes per day, with as long as 10 hours total per day.[25]

3.7.1.2 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 (see Section 3.7.3.2 for an explanation of the Command Loss timer)
- Every 4 months: loading a command sequence

[25] The information from Voyager 1 as it left the heliosphere was unique. To ensure scientists would catch the change – its timing and duration unknown in advance – when it happened, the project requested as much tracking coverage as possible [18].

- Annually: transmission of a computer command subsystem (CCS) clock calibration, timing test, and memory refresh.

3.7.1.3 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 has needed arrays again 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.

3.7.2 RFS Strategies

3.7.2.1 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 support. 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-power versus high-power operation can affect lifetime by at most 25 percent.

3.7.2.2 X-Band TWTA Power-Level Switching Cycles Minimized. The X-band 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.

3.7.2.3 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.

3.7.2.4 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.

3.7.2.5 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.

3.7.2.6 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[26] 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)[27]

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[26] 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 they occur on every pass.

[27] The term "best-lock frequency" in a phase-locked loop refers to the natural oscillation frequency of the loop with no input. When the receiver loop is receiving an uplink carrier exactly at BLF (the center of its bandwidth), the loop indicates 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.

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, 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, the flight-operations staff determines 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 as long as 3 days following 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.

3.7.3 Spacecraft Fault Protection

The CCS has five fault-protection algorithms (FPAs) stored in memory, as summarized in Table 3-9. The two algorithms most directly related to the telecommunications system are named RF Loss and Command Loss [19].

3.7.3.1 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.

Table 3-9. Voyager fault-protection algorithms.

FPA Name	Description
RF Loss	Monitors S- and X-band exciter and transmitter hardware and switches to redundant unit 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 has 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.

3.7.3.2 Command Loss. Command Loss provides a means for the spacecraft to automatically respond to an onboard 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[28] 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.

3.7.3.3 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.

[28] 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.

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 2025.

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Much of the telecom design information in this chapter comes from original Voyager prime mission design documentation. These include the design control document for the telecommunications links [11], the functional description of the telecommunications system [8], and the hardware design requirement for the modulation demodulation subsystem (MDS) [20]. Much of the mission and operational information was obtained from the Voyager Operational Handbook [21], the Voyager Neptune Travel Guide [12], and the Voyager project public website [1].

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