Odyssey Telecommunications

Andre Makovsky,
Andrea Barbieri,
and
Ramona Tung

October 2002

JPL DESCANSO
Deep Space Communications and Navigation Systems
Center of Excellence
Design and Performance Summary Series

DESCANSO Design and Performance Summary Series

Article 6
Odyssey Telecommunications

Andre Makovsky
Andrea Barbieri
Ramona Tung

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

National Aeronautics and
Space Administration
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

October 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.

Prologue

2001 Mars Odyssey

The cover image is an artist's concept of 2001 Mars Odyssey in orbit around Mars communicating with the Deep Space Network via its large antenna and ready to communicate with vehicles on Mars' surface beginning in 2004 via its ultra-high-frequency link. The photograph above is of the Odyssey spacecraft in Assembly Test and Launch Operations.

Ever since the time of Mariner 9 in the early 1970s, a large part of the focus of Mars science has been questions related to water: how much was there and where did it go? In 2001, Odyssey began to fill in vital pieces of information to solve the "water puzzle" by mapping the basic elements and minerals that are present in the upper centimeters of the planet's surface.

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

Article 4—"Voyager Telecommunications"
Roger Ludwig and Jim Taylor

Article 5—"Galileo Telecommunications"
Jim Taylor, Kar-Ming Cheung, and Dongae Seo

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 the communications capabilities of the Odyssey spacecraft, both for the direct links with the Deep Space Network and the relay links that will be available for rovers, landers, and other vehicles at the surface of Mars. The article is at a functional level, intended to illuminate the unique mission requirements and constraints that led to the design of the communications system and how it has been operated in flight. This article provides a reasonably complete single source from which to look up specifics of the Odyssey radio communications.

Lockheed Martin Astronautics (LMA) in Denver, Colorado, is the prime contractor for the project and developed and built the orbiter. LMA designed the telecommunications system, specified and procured the system’s components, and assembled and tested the system. Mission operations are conducted jointly from Lockheed Martin and from the Jet Propulsion Laboratory (JPL) in Pasadena, California; JPL also manages the Odyssey mission for the National Aeronautics and Space Administration (NASA).

Acknowledgements

The authors would like to express their appreciation to many individuals in the Interplanetary Network Directorate (IND) and the Telecommunications Science and Engineering Division (33) at JPL for their encouragement and support during the preparation of this article.

While the authors work at JPL, we want to stress that Lockheed-Martin Astronautics (LMA) in Denver was the prime contractor during spacecraft development and continuing into operations after launch. While JPL has provided management and technical support, the brunt of the work was done by LMA. For Odyssey telecommunications system development, we especially want to thank Charles E. Johnson for providing technical support and excellent collaboration from his entire group. At JPL, Stanley Butman was the Telecom PEM (Project Element Manager) and provided leadership and technical guidance in ensuring that the necessary tests and issues were addressed. Odyssey is an excellent example of JPL–LMA cooperation, and the success of the mission is a credit to both teams.

In the writing of this article, the authors are especially grateful to Bill Adams, Scott Toro-Allen, and Marty Schmitzer of Odyssey telecom ops in the LMA Denver flight team for providing diagrams and information and for reviewing the material. We also appreciate the review of this article by Charles Johnson at LMA and Stan Butman at JPL, and the discussion with Anthony Mittskus about the solid-state power amplifier (SSPA) development for Odyssey.

Section 1

Odyssey Mission Description

1.1 Mission and Spacecraft Overview[1]

The Odyssey orbiter carries scientific payloads that will, over a full Martian year, determine the surface mineralogy and morphology, provide global gamma-ray observations, and measure the Mars radiation environment. In addition, it will provide data relay support to future missions operating from the Mars surface.

The orbiter launched in April 2001. After a 7-month cruise, the spacecraft inserted propulsively into an elliptical orbit around Mars, requiring nearly 3 months of aerobraking to achieve the desired 400-km circular orbit. The orbiter mission is planned to take 917 days following the completion of aerobraking, with a goal of an additional 457 days of relay operations. These numbers add up to a total of 2 Martian years.[2]

Table 1-1 presents a summary of the main mission phases with associated planning boundaries. Some events described in this article occur within a larger phase. For example, trajectory correction maneuver (TCM) 4 was on October 12, 2001, and Mars orbit insertion (MOI) had engine burn on October 24, 2001.

Table 1-1. Mission phases and timeline.

Phase	Time Boundaries for Mission Planning
20 day launch period	April 7 through April 27, 2001 (actual launch was April 7, 2001)
Heliocentric cruise to Mars	April 7 through October 28, 2001 (actual Mars orbit insertion (MOI) was October 24, 2001)
Mars arrival and aerobraking	October 20, 2001 through January 31, 2002
Science and relay mission	February 1, 2002 through October 2005
Mapping (science) mission	February 1, 2002 through August 2004
Relay mission (planning goal)	August 2004 through November, 2005

Figure 1-1 gives an overview of the spacecraft configuration.

For communications with the ground at X band,[3] the spacecraft has three antennas:

---

[1] The data in this section were obtained from [1] and [2].

[2] A Martian year is 687 Earth days [Ref. http://seds.lpl.arizona.edu/nineplanets/nineplanets/data.html].

[3] For spacecraft in the deep-space frequency bands, X-band refers to an uplink frequency in the band of about 7150–7190 MHz and a downlink frequency in the band of about 8400–8440 MHz. The DSN channels are defined in [7], module 201, "Frequency and Channel Assignments."

1) A high-gain antenna (HGA), transmitting and receiving, with the boresight along the x-axis;
2) A medium-gain antenna (MGA), transmitting only, mounted in the HGA reflector and with the boresight along the x-axis;
3) A low-gain antenna (LGA), receiving only, with the boresight in the (z,x) plane pointed 45 deg from the x- and z-axes.

An ultra-high-frequency (UHF)[4] antenna, with boresight along the –x-axis, will be used for communications with surface elements[5] on Mars during the relay phase of the mission.

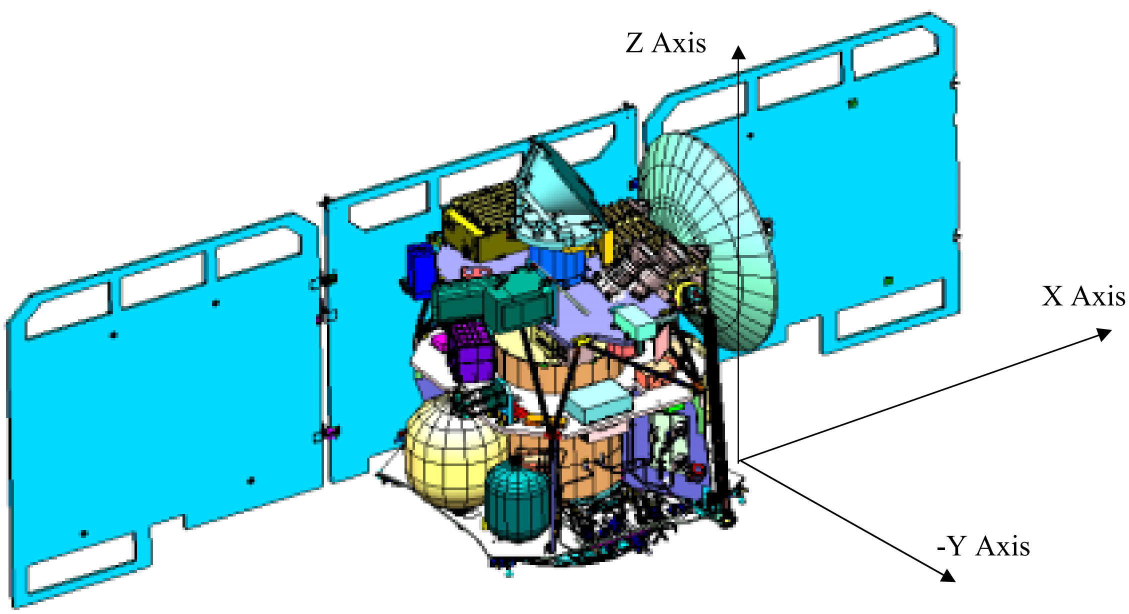


Fig. 1-1. Overview of the orbiter configuration.

1.2 Mission Phases

1.2.1 Launch and Initial Acquisition Phase

The Odyssey orbiter was launched on a Delta II 7925 from the ETR (Eastern Test Range) in April 2001. Once the spacecraft separated from the upper stage, it deployed the solar array and nominally found the Sun within 10 minutes. The telecommunications

[4] UHF is the frequency band between 300 MHz and 3 GHz. Odyssey operates near 401 MHz and 437 MHz.
[5] "Surface element" is used in this article as a general term for a lander, rover, or similar vehicle.

system (telecom) was on, trying to establish communications with the Deep Space Network (DSN). The MGA was used during this phase to transmit telemetry, while the LGA was used to receive commands.

Due to the far southerly declination of the trajectory at separation from the launch vehicle, the DSN stations in the northern hemisphere (Goldstone and Madrid) had no view of the spacecraft during this phase. In order to cover this gap, a 12-m antenna at the University of Chile in Santiago provided telemetry support for the first few days of the mission.

1.2.2 Cruise Phase

The cruise phase was the interplanetary transit from the Earth to Mars and had a duration of slightly more than 7 months. The primary activities during this phase were the monitoring of the health of the orbiter and navigation activities as necessary to correct the flight path to Mars. In addition, instrument calibrations and engineering tests (such as UHF electromagnetic compatibility (EMC) tests and UHF downlink/uplink performance tests) were conducted.

The spacecraft communicated in a two-way coherent mode on a routine basis with the ground to receive commands, to transmit engineering telemetry, and to allow the collection of radio-metric tracking data. The requested coverage consisted of three 8-hour passes per week of 34-m stations until MOI minus 50 days, then continuous 34-m coverage.

The primary attitude during this phase is shown in Fig. 1-2. The +x-axis with the stowed HGA and MGA boresight is pointed to the Earth. The (x,z) plane lies in the plane containing the Sun and the Earth, with the Sun in the (–z,x) quadrant of the frame. The spacecraft slewed away from this attitude briefly to perform the TCM's calibration events for the imager and the UHF uplink/downlink test.

Figure 1-3 shows the orbiter–Earth range during the cruise phase for 3 different launch days.[6] Figure 1-4 illustrates the Sun–probe (orbiter)–Earth (SPE) angle. This angle is an important consideration when the spacecraft is Sun-pointed and communications via an x-axis-oriented antenna (the MGA) are required.

Finally, Fig. 1-5 shows the pass duration per day during Earth–Mars cruise for the three DSN complexes. Because of the southerly declination during early cruise, as Fig. 1-5 indicates, the orbiter had to rely mostly on the Canberra antennas from launch until June–July 2001, when Goldstone and Madrid passes became longer than 4 hours.

---

[6] Figures 1-3 and 1-4 were created before launch for mission planning. Please refer to the "Day 1" curves for values applicable to the actual launch date, April 7, 2001.

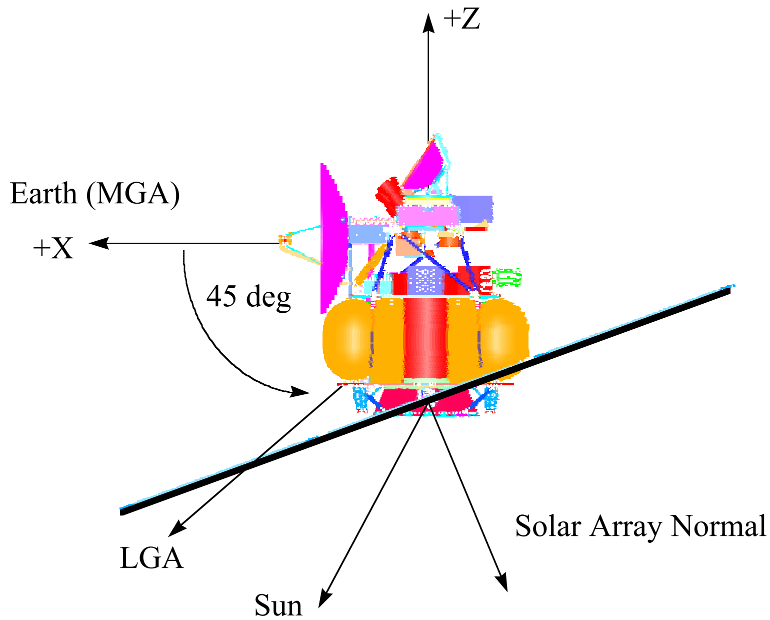


Fig. 1-2. Orbiter cruise attitude.

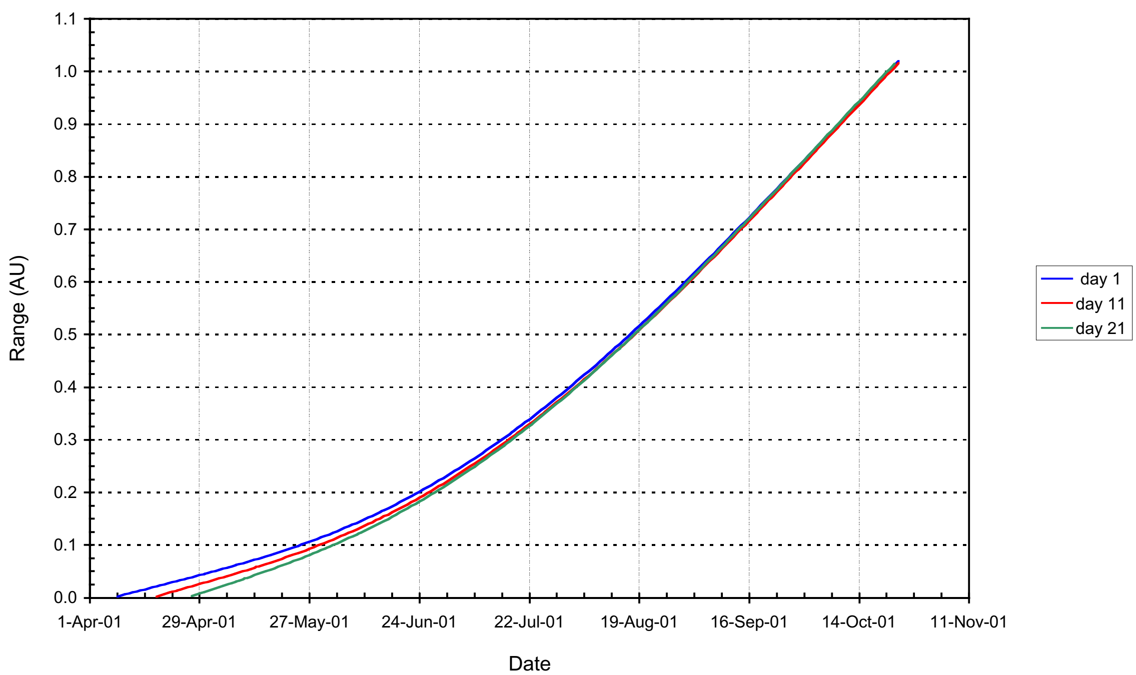


Fig. 1-3. Orbiter–Earth range during cruise.

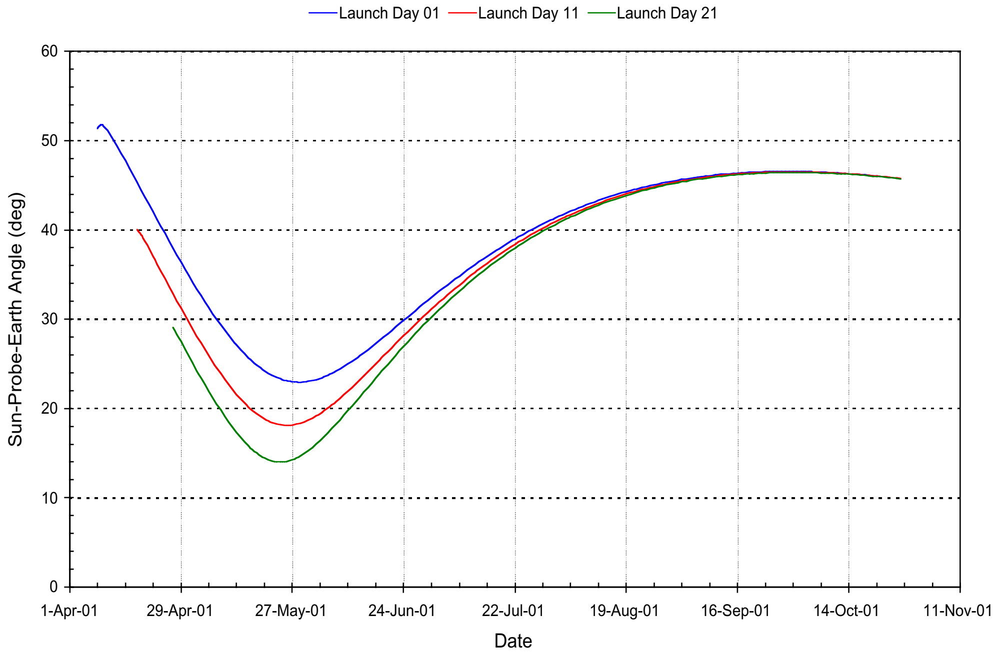


Fig. 1-4. Sun–probe (orbiter)–Earth angle during cruise.

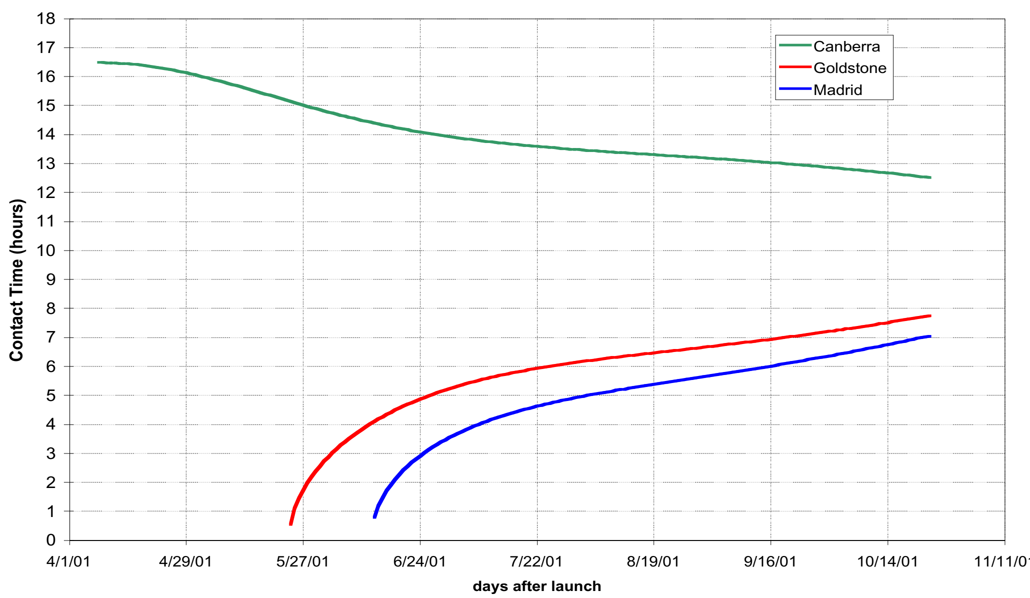


Fig. 1-5. Pass duration during cruise with a 10-deg elevation mask.

1.2.3 Mars Orbit Insertion Phase

Odyssey inserted in Mars orbit with a propulsion maneuver on October 24, 2001. Two MOI burns placed the spacecraft in a stable orbit with an apoapsis of 27,000 km, and the closest approach was targeted over the Northern polar region. See Fig. 1-6 for a timeline of MOI.

During the burns, only two-way carrier communication was possible. Because the MGA cone angle varied between 29 and 34 deg, and the Earth range was approximately 1 AU, the power of the received signal would have been too low for the DSN to receive telemetry. The Doppler signature of the downlink carrier provided immediate evidence that MOI went as planned (see Section 5).

1.2.4 Aerobraking Phase

To lower the apoapsis to 400 km after MOI, the orbiter began aerobraking. This phase lasted for a period of almost 3 months, during which the HGA remained stowed, with the boresight on the x-axis. The spacecraft x-axis was Earth-pointed for communications via the HGA, except for about a half-hour period around the periapsis of each orbit while the spacecraft did an atmospheric drag pass. The final fine tuning of the 400-km orbit was achieved with orbit trim maneuvers on January 28 and 30, 2001.

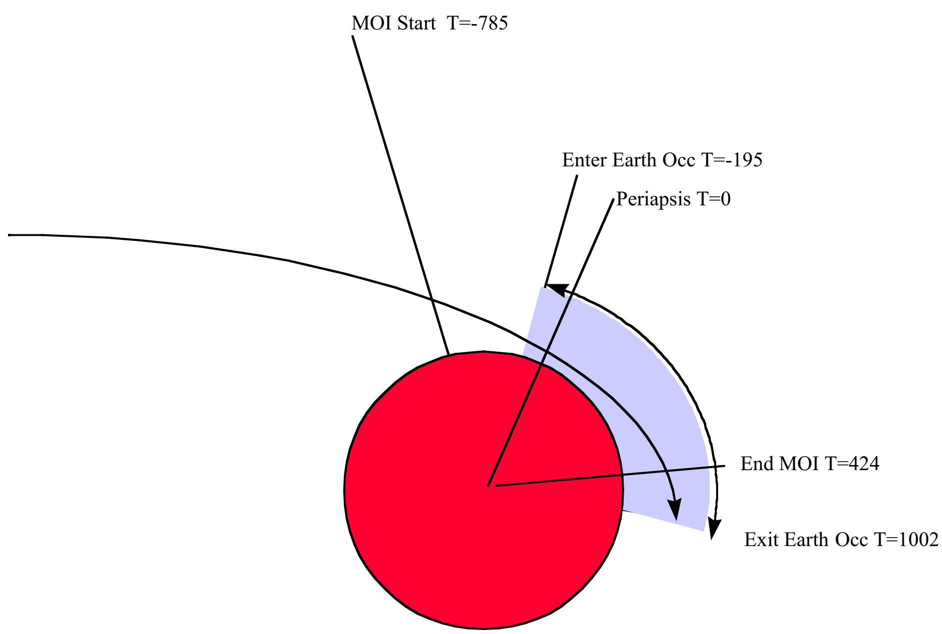


Fig. 1-6. MOI timeline in seconds.

1.2.5 Science and Relay Phase

After the end of the aerobraking phase, the HGA was deployed and began to track the Earth. After an initial instrument check-out, the science phase of the mission (described in Section 5) began with the orbiter in a circular orbit 400 km above the surface. In late 2003, the orbit will be made Sun-synchronous with planned values of orbital parameters as defined in Table 1-2.[7]

Table 1-2. Science and relay—mean orbital elements.

Parameter	Sun-Synchronous Orbit
Epoch	19-Oct-2003 00:00:00 ET
Semi-major axis	3793.4 km
Eccentricity	0.0
Inclination	93.064°
Argument of Periapsis	0.0°
Longitude of Ascending Node	34.98°
Mean Anomaly	0.0°

Figure 1-7 shows the orbiter attitude during the science phase with respect to the velocity and the nadir pointing vectors. To reduce fuel usage, the orbiter is canted 17 deg off the velocity vector (the angle between the y-axis and the velocity vector is 17 deg), so the UHF antenna, along the –x-axis, will be nominally pointed 17 deg off nadir.

If a safe mode occurs, the spacecraft will orient itself with the solar array pointed to the Sun, as illustrated in Fig. 1-8. Depending on the mission phase, the safe mode will offset the z-axis from the Sun to ensure that the Earth is in the LGA beamwidth for commands to be received.

Figure 1-9 shows the Earth–Mars distance, and Fig. 1-10 shows the Sun–probe–Earth (SPE) angle and Sun–Earth–probe (SEP) angle during the science and relay phase.

Communications are not possible when Mars blocks the radio frequency (RF) signal during an orbit. Finally, Fig. 1-11 illustrates the duration of a pass over each DSN complex. These durations vary through the mission as the declination of Mars changes.

---

[7] In a Sun-synchronous orbit, the local mean solar time of the ascending node is fixed.

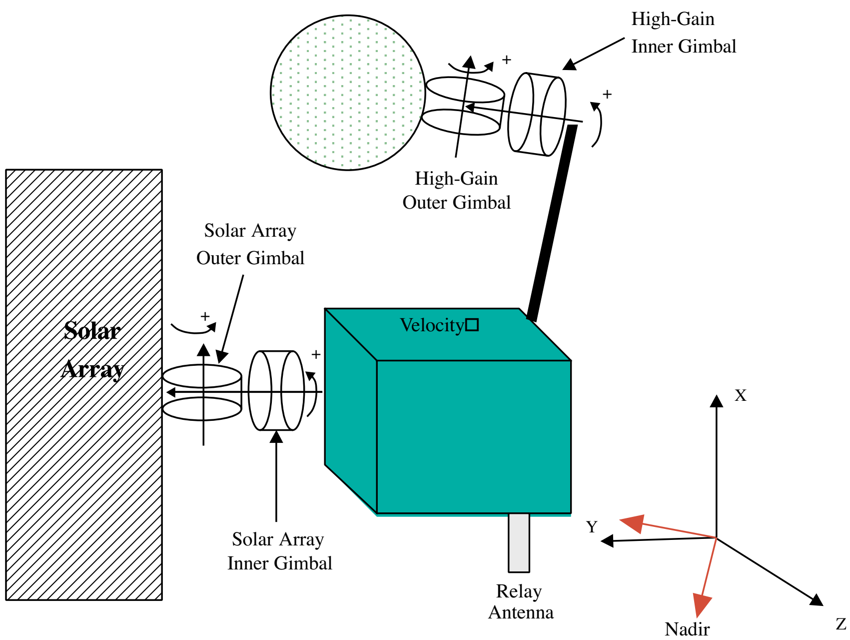


Fig. 1-7. Spacecraft attitude during the science and relay phase.

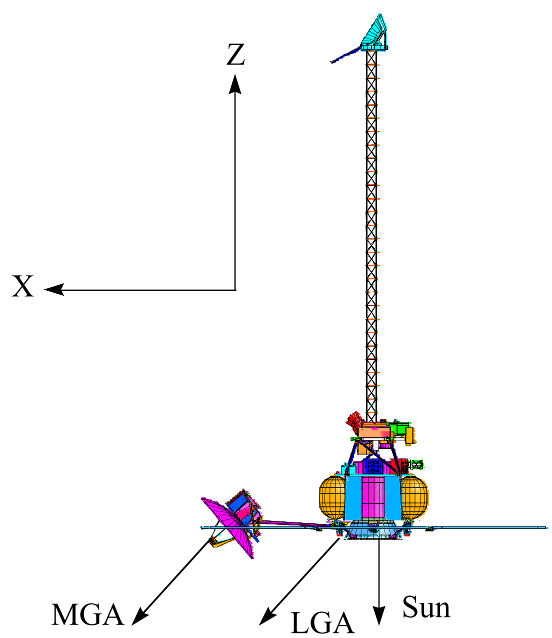


Fig. 1-8. Safe mode attitude during the science and relay phase.

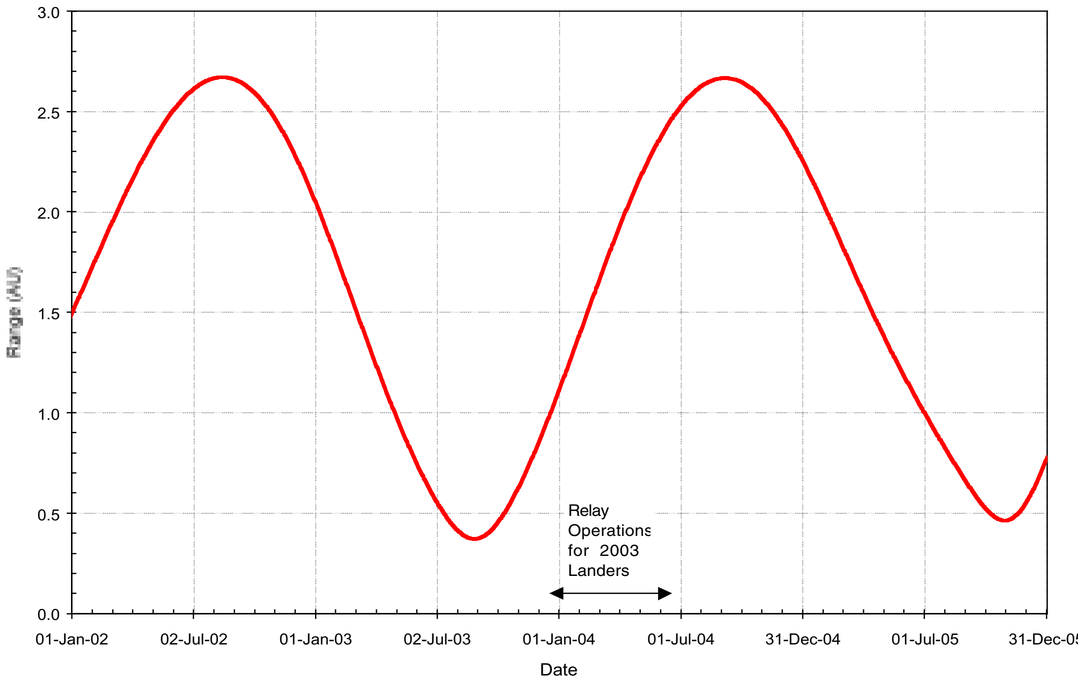


Fig. 1-9. Orbiter–Earth range during the science and relay phase.

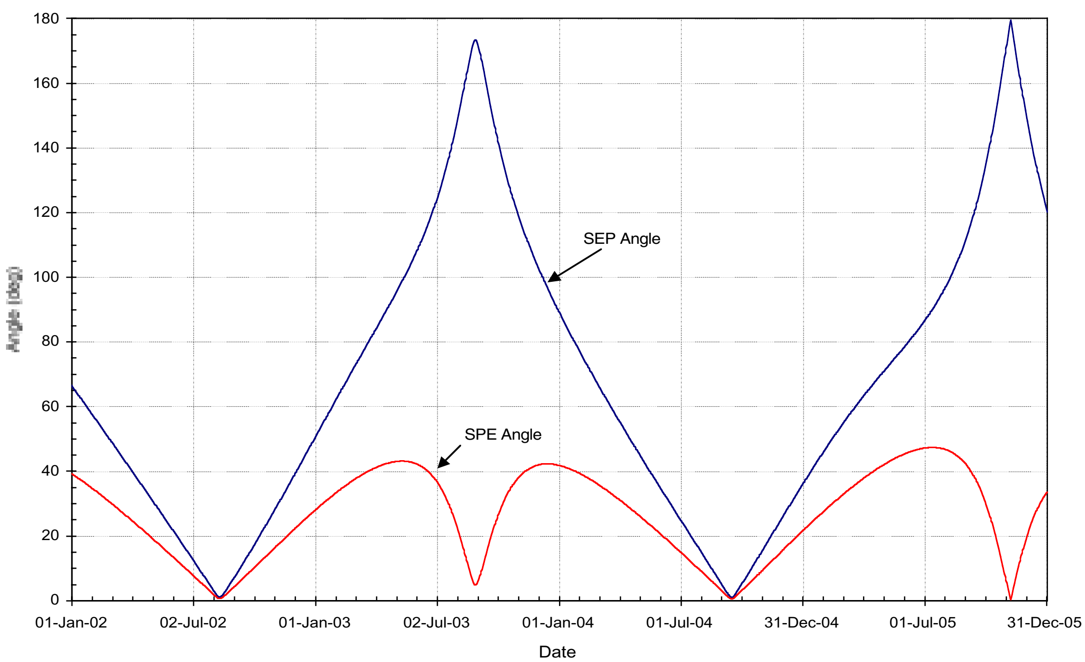


Fig. 1-10. SEP and SPE angles during the science and relay phase.

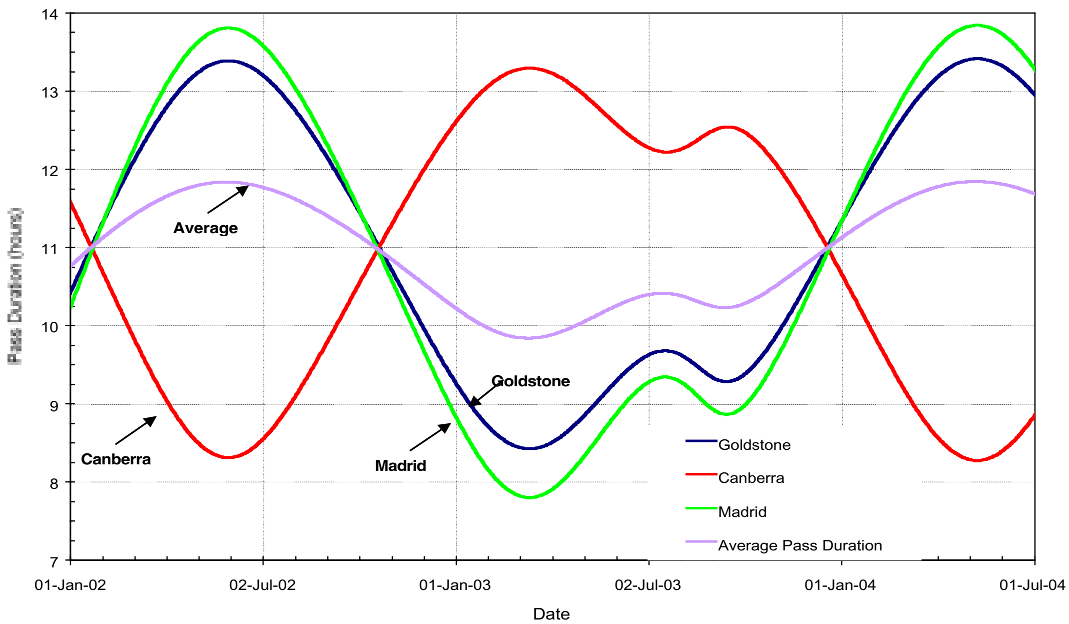


Fig. 1-11. Pass duration during the science and relay phase.

Section 2

Telecommunications System Requirements

This section will provide a useful reference to readers wondering: "Why was the telecom system designed this way?"

This section has the main high-level requirements that apply to the telecom system. There are more requirements placed on individual hardware and software elements, which are not presented here.[8]

2.1 X-Band

The "flight system" refers to the on board hardware and software. The X-band[9] transponder is the small deep-space transponder (SDST). The orbiter is the Odyssey spacecraft.

Command requirements

DSN compatibility	The flight system shall be compatible with the Deep Space Network (DSN) at X-band.
X-band channel allocation	The transponder downlink frequency shall be Channel 8 (8406.851853.0 MHz).
Uplink frequency	The transponder uplink frequency shall be 749/880 times the selected downlink frequency (7155.377316 MHz).
X-band communication	The flight system shall provide X-band communications at maximum spacecraft–Earth range during cruise.
Uplink data rates	As a minimum, the orbiter shall be capable of receiving commands at 7.8125 b/s (emergency) and 125 b/s (operational).

[8] The system-level requirements were taken from [3] and [4]. Consultative Committee for Space Data Systems (CCSDS) standards are given in [5]. The Odyssey environmental requirements are given in [6].

[9] For spacecraft in the deep-space frequency bands, X-band refers to an uplink frequency in the band of about 7150–7190 MHz and a downlink frequency in the band of about 8400–8440 MHz. The DSN channels are defined in [7], module 201, "Frequency and Channel Assignments."

Telemetry requirements

DSN compatibility	The flight system shall be compatible with the DSN at X-band.
X-Band channel allocation	The transponder downlink frequency shall be Channel 8 (8406.851853 MHz).
Cruise downlink data rate	The orbiter shall be capable of a minimum cruise downlink data rate of 40 b/s, which is also the emergency downlink data rate.
X-band communication	The flight system shall provide X-band communications at maximum spacecraft–Earth range during cruise.
Minimum on-orbit downlink rate	The orbiter shall be capable of a minimum on-orbit downlink rate of 3.6 kb/s at maximum Earth range during nominal operations.

Fault protection requirements

Redundancy	Redundancy shall be employed to avoid mission-critical single-point failures.
Redundant transceivers	X-band and UHF systems shall be redundant.
Functionality with single-point failures	No single-point failure in the orbiter shall result in the failure to achieve primary mission success.
X-band uplink path swapping	The orbiter shall be capable of autonomously swapping the X-band uplink path in the event of loss of communication with Earth.
Safe commandable state (safe mode)	The fault protection design shall ensure that the spacecraft (and instruments) can autonomously attain a safe, commandable state on the occurrence of a credible failure[10] and can continue to maintain this state without ground commands for up to 72 hours, except in solar conjunction, when the duration shall be 14 Earth days.
Emergency uplink rate	The orbiter shall be capable of accepting the emergency uplink signal following detection of a fault condition.

[10] For telecom, the antennas are not electronically active elements and are therefore considered exempt (in terms of credible failures) from having to be redundant.

Navigation requirements

Simultaneous commanding and two-way coherent ranging	During nominal operations, the orbiter shall support X-band uplink, with simultaneous commanding (at the operational rate's mod index) and two-way coherent ranging.
Simultaneous telemetry and two-way coherent ranging	During nominal operations, the orbiter shall support X-band downlink, with simultaneous telemetry (at the operational rate) and two-way coherent ranging.
Differential one-way ranging (DOR)	Only on one SDST, SN 107

2.2 UHF

The Odyssey UHF subsystem was designed to act first as a data relay for the Mars'01 Lander mission.[11] The UHF system was also made compatible with the UHF relay systems of future surface missions, including Doppler capability for the location of rovers, landers, or other surface elements on Mars.

The functions of the Odyssey UHF subsystem are:

- Transmission of commands at 8, 32, 128, and 256 kb/s;
- Reception of telemetry data at 8, 32, 128, and 256 kb/s;
- Measurements of Doppler offset of incoming signal;
- Reception of a low-power signal with open-loop recording.

The data protocol (UHF1) implemented for the relay communication was designed under CCSDS patronage in order to enable cross-compatibility between all the missions at Mars.

The driving requirement for the design of the subsystem was to support an average of 50 Mbits per Martian sol in the telemetry return link from the Mars'01 lander, which had a design similar to Odyssey's for its UHF transceiver and UHF antenna. With an elevation mask of 20 deg, the visibility at the Mars equator is a maximum of 11 minutes per pass, resulting in a planned total of 12 minutes of communication per sol from the sum of two or three passes per sol. The return link requirements can be supported with the 128-kb/s data rate. The command forward link to the Mars '01 lander was much less constrained and could be supported with an 8-kb/s data rate.

The Odyssey UHF relay capability will be used by the Mars Exploration Rovers (MERs) and by the Beagle 2 lander. NASA's MERs essentially have the same data volume requirements as the Mars'01 lander would have had even though the antenna

[11] The Mars '01 Lander mission was cancelled in the aftermath of the failures of the Mars'98 missions (Mars Climatological Orbiter and Mars Polar Lander).

design is different. The link capability between the European Space Agency's (ESA's) Beagle 2 lander and Odyssey is less than that of the MER rover, providing an average of approximately 10 Mbits per sol.

The Odyssey relay antenna is not articulated, and the spacecraft will not be pointed during a relay pass; these mean the relay antenna must have a large beam width to reach any vehicle on Mars' surface. The fact that neither the surface-element antenna nor the orbiter antenna is directive explains the choice of a low frequency (UHF, between 400 and 437 MHz) for the relay link. The antenna is not considered to be a likely failure and is not protected by redundancy.

To meet the functionality requirement with a single failure, the UHF subsystem has dual redundant transceivers. The transceivers are block redundant with the command and data handling (C&DH) subsystem. The side A transceiver is linked only to the C&DH side A (and similarly for side B).

Section 3

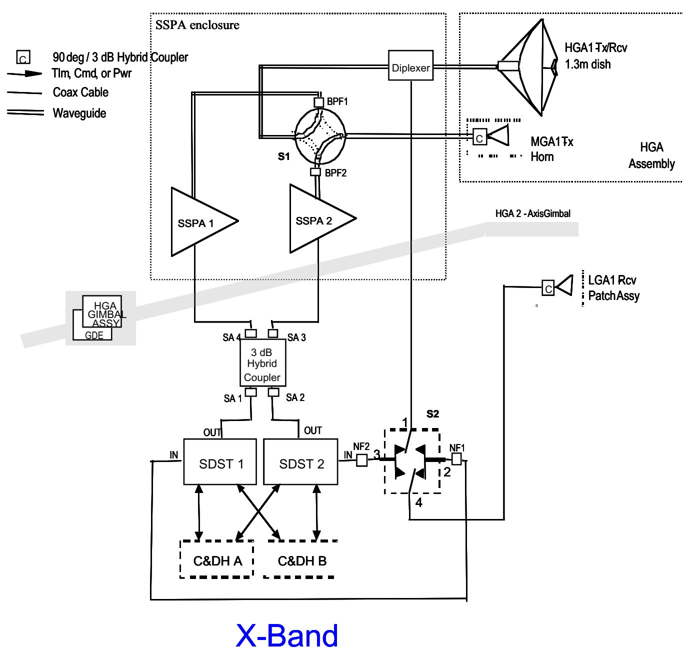
Odyssey Telecommunications System Hardware and Software

3.1 X-Band[12]

Refer to the block diagram in Fig. 3-1 and to the sketches of the layout of the main X-band system components in Figs. 3-2 and 3-3.

The powered X-band components include two small deep-space transponders (SDSTs) and two solid-state power amplifiers (SSPAs). Besides the high-gain antenna (HGA, shown), the system also has a low-gain antenna (LGA) and a medium-gain antenna (MGA).

The X-band system is described according to its transmit and receive functions.



Switch Configuration:

Waveguide transfer switch (S1)	Coaxial transfer switch (S2)
Position 1:	Position 1:
SSPA 1 to HGA and	LGA to SDST 1 and
SSPA 2 to MGA	HGA to SDST 2
Position 2:	Position 2:
SSPA 1 to MGA and	HGA to SDST 1 and
SSPA 2 to HGA	LGA to SDST 2

Fig. 3-1. Odyssey X-band telecommunications system block diagram.

[12] A more extensive description of both the X-band and UHF systems is given in [8].

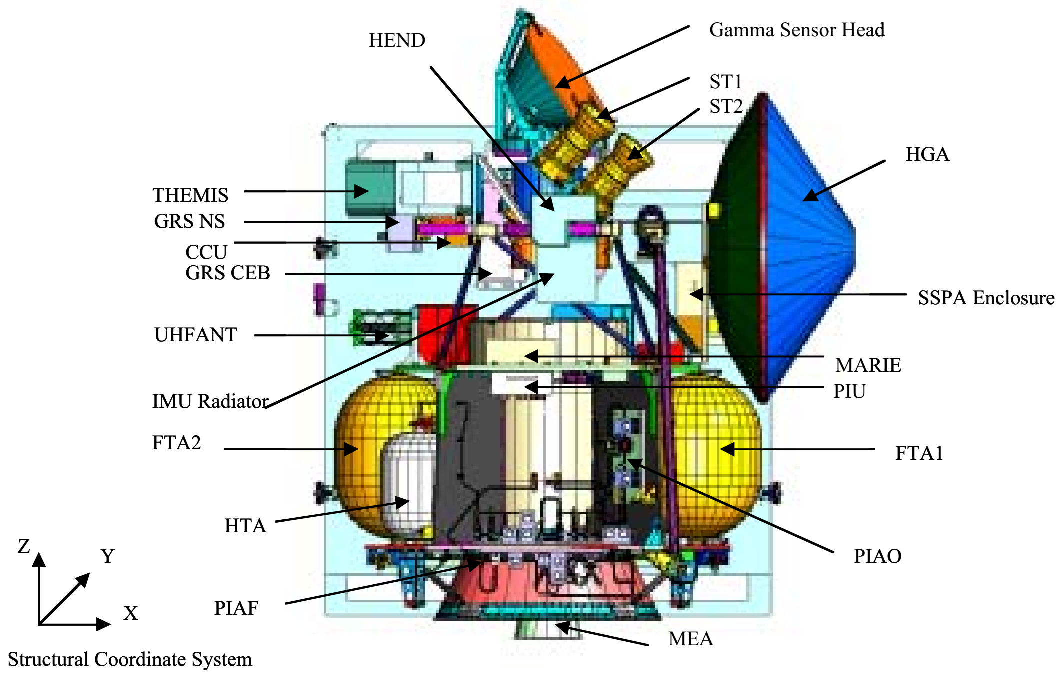


Fig. 3-2. Side view of the orbiter showing the stowed HGA and the SSPA enclosure.

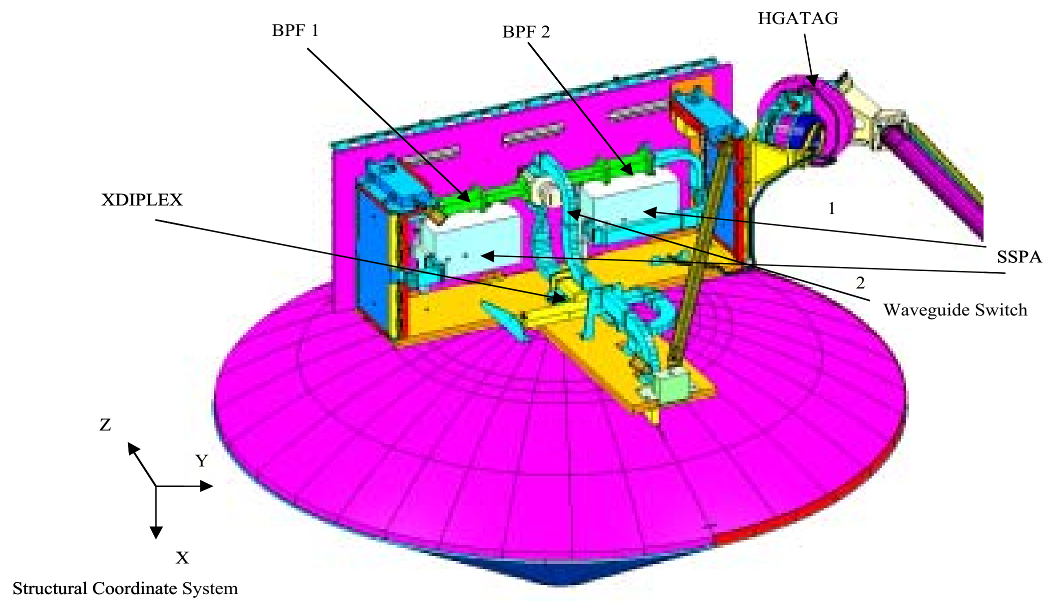


Fig. 3-3. Layout of the orbiter X-band telecom components in the SSPA enclosure.

3.1.1 X-Band Transmit

For the transmit path, there are

- Two redundant SDSTs, with one active at a time;
- A 3-dB hybrid coupler, to allow either SDST to drive either SSPA without requiring active switching;
- Two redundant SSPAs (RF output power 15.0 W)[13], one active at a time;
- A bandpass filter (BPF) on each of the 2 transmit paths. The BPF filters the SSPA output for increased isolation at Odyssey's receive frequencies;
- Two transmit antennas (HGA and MGA). The MGA is transmit only;
- A waveguide transfer switch (labeled S1 on the block diagram of Fig. 3-1) for transmit path switching. Depending on the S1 position, one SSPA is connected to one transmit antenna, while the other SSPA is connected to the other.

3.1.2 X-Band Receive

For the receive path, there are

- Two receive antennas (HGA and LGA). The LGA is receive only;
- A coaxial transfer switch (labeled S2 in the block diagram). S2 connects one antenna to one SDST, and the other antenna to the other SDST;
- A notch filter (NF) on each of the two receive paths. The NF passes signals only at the Odyssey receive frequency band;
- Two SDSTs, with one active at a time to avoid interference.

3.1.3 SDST Functions and Description[14]

A transponder such as the SDST has a receiver and an exciter that together provide for the downlink carrier to be phase coherent with (that is, a fixed multiple of) the uplink carrier transmitted by the ground. Coherency enables the downlink carrier to be transmitted with the same stability that the received uplink carrier has. A very stable oscillator (a maser) can drive the ground transmitter. Though the maser is more stable in frequency than a crystal oscillator (about 1 order of magnitude at a 1000-s integration time), a maser is also much heavier (about 200–500 kg for a maser versus 1 kg for an ultra-stable oscillator [USO]). This is why the maser remains on the ground. Frequency stability translates into better navigation accuracy (estimating the spacecraft's position and velocity).

As a receiver, the SDST can

---

[13] This article uses 15.0 W in the text as a nominal X-band RF output. The output is a function of the telecom system operating temperature. The initial acquisition downlink design control table (Table 5-3) shows an RF output of 41.4 dBm (13.8 W) in line 1; this is the minimum at higher operating temperatures.

[14] The functional specification for the MER SDST is given in [9].

- Lock onto an uplink carrier, and track Doppler shifts affecting it;
- Track and demodulate the command subcarrier and provide the detected command bits to the hardware command decoder (HCD) in the command and data subsystem (CDS), also called the avionics. The receiver does not do bit-error checking on the detected bits; that is left to the HCD;
- Demodulate the ranging code that was modulated on the uplink (and re-modulate it onto the downlink carrier);
- Provide a frequency reference to the exciter that is phase coherent with the uplink.

As a transmitter, the SDST can

- Generate (in its exciter) a downlink carrier signal that is either non-coherent with the uplink (if it's produced by a local crystal oscillator, called an auxiliary oscillator) or phase coherent with the uplink. If there is no uplink, the downlink is automatically derived from the auxiliary oscillator;
- Re-modulate the ranging code (that was demodulated by the receiver) onto the downlink carrier, at one of four ranging modulation indices;
- Convolutionally encode with either a (7,1/2) or (15,1/6) code the telemetry signal received from the CDS, or leave the telemetry uncoded;
- Binary phase-shift keying (BPSK) modulate the coded or uncoded telemetry data onto a square-wave telemetry subcarrier;[15]
- Phase modulate the composite telemetry signal onto the downlink carrier, using one of 64 possible modulation index values.

3.1.4 The Odyssey SDST Compared with Earlier Transponders

The SDST, manufactured by Motorola,[16] is the first deep-space transponder with significant digital implementation and was first used on the Deep Space 1 (DS1) spacecraft. Some of the differences between the SDST and the entirely analog transponders carried by spacecraft before DS1 are

- The SDST implements the functions of carrier tracking, command subcarrier demodulation, command detection, ranging demodulation (from the uplink) and re-modulation (on the downlink), and telemetry modulation in one assembly, rather than four, as the Galileo system did, or three, as Cassini did. This is a savings in mass and power. See the mass and power summary in Section 3.3;
- Significant parts of the carrier-tracking phase-locked loop are implemented in the digital domain with an application-specific integrated circuit (ASIC). The

---

15 The subcarrier frequency is produced by a digitally controlled, numerically controlled oscillator (NCO) that can generate frequencies up to 12 MHz. For operational simplicity, Odyssey is sequenced to use only two of the subcarrier frequencies, either 25 kHz (with low data rates) or 375 kHz (with high data rates).

16 In late 2001, this part of Motorola became part of General Dynamics.

digital design leads to repeatability: we've done testing on nine SDSTs destined for five projects and found they had very similar characteristics;

- The SDST design is more flexible (provides more choices in modes of operation). For example, we are no longer limited to only two telemetry subcarrier frequencies fixed at launch. It's true that on Odyssey we have chosen to use only two, but projects such as MER use more subcarrier frequencies in a specialized communication scheme. The Odyssey SDST has a design similar to the DS1 SDST. The most significant differences from DS1 are
  - Odyssey has no Ka-band[17] exciter (nor a Ka-band power amplifier);
  - DS1 had DOR. On Odyssey, only the primary SDST, S/N 107, has it;
  - For telemetry, the DS1 single-stage phase modulator has been replaced by a dual-stage modulator. The two stages are in series with each other, each operating over half the phase deviation of the single-stage modulator.[18]

3.1.5 Solid-State Power Amplifier

The SSPA (Fig. 3-4) was manufactured by Electromagnetic Sciences (EMS). It is used in the telecommunications subsystem to take the modulated spectrum from the exciter output of the small deep-space transponder (SDST) and provide a 15-watt RF output. The RF input power required for the 15-watt RF output is 0 dBm (1 watt). This input power operates the SSPA at 3-dB compression. The DC power required on the power bus is 60 watts for a 15-watt RF output for an efficiency of 25 percent. The power bus can operate over the voltage range of +22 V to +36 V. The SSPA input RF interface from the SDST is coaxial, and the SSPA RF output interface to the antenna is waveguide. Both the input and output ports contain RF isolators. Its mass is 1.8 kg, including the electronic power converter.

[17] The most recent deep-space mission with a Ka-band downlink for telemetry was DS1, which operated at about 32 GHz.

[18] This change makes the Odyssey phase modulator substantially linear, whereas the DS1 modulator was significantly non-linear. Because less energy is wasted on intermodulation products, Odyssey's telemetry thresholds occur at lower threshold P_t/N_o values. For example, DS1 required 39.1 dB-Hz to support 2100 b/s and simultaneous high-index ranging, whereas Odyssey requires only 38.3 dB-Hz. Another benefit of the linear modulator is that the telemetry modulation index (mod) can be the same whether ranging is off, low index, or high index. For example, at 2100 b/s, the DS1 mod index was 76 deg without ranging, 66 deg with "low mod index" ranging, and 55 deg with "high mod index" ranging. MER uses 72 deg, independent of ranging. This simplifies telecom operations as compared with DS1.

Fig. 3-4. Odyssey SSPAs.

3.1.6 X-Band Antennas

There are three antennas: the high-gain antenna (HGA), the medium-gain antenna (MGA), and the low-gain antenna (LGA).

3.1.6.1 High-Gain Antenna (HGA). The HGA includes a parabolic reflector that is mounted on a long arm. The arm is attached to the spacecraft via azimuth and elevation (az/el) gimbals. The gimbals allow the HGA to stay Earth-pointed while Odyssey orbits Mars.

Figure 3-5 is a drawing of the HGA and its associated components. System-level parameters and characteristics of the HGA are in Table 3-1.

Figure 3-6 shows the HGA pattern (expressed relative to 0 dB gain at boresight) at the transmit frequency. Figure 3-7 shows the HGA pattern at the receive frequency. This pattern is normalized to 0 dB at the boresight. The two curves in each figure, intended to illustrate the amount of symmetry in the HGA pattern, come from different "cuts" in roll (clock) angle.[19]

---

[19] The Odyssey antenna patterns are defined in a polar coordinate system. The angle from boresight, theta, is often called the "cone" angle in antenna discussions. The angle orthogonal to that (phi) is often called "clock." See Fig. 5-6 for a diagram and definitions of theta and phi.

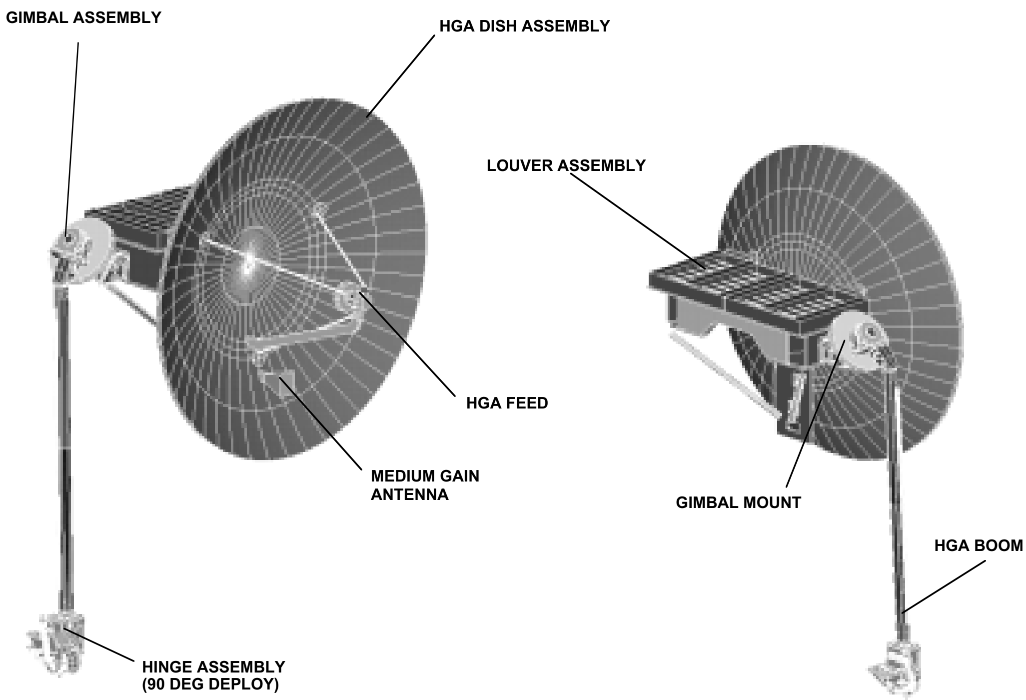


Fig. 3-5. Odyssey HGA, feed with MGA, and mount with gimbal.

Table 3-1. HGA parameters and characteristics.

Parameter	Value
Diameter	1.3 m
Mass (includes the MGA horn)	3.15 kg
Frequency, transmit	8406.851853 MHz
Frequency, receive	7155.377316 MHz
Gain, transmit	38.3 dBi
Gain, receive	36.6 dBi
Polarization	RCP
Axial Ratio, transmit	1.35 dB
Axial Ratio, receive	1.24 dB
Beamwidth,[20] transmit	1.9 deg.
Beamwidth, receive	2.3 deg.
Heritage	Mars Climate Orbiter (MCO)

[20] Beamwidth is defined as the two-sided width between the points on the antenna pattern where the gain is 3 dB lower than the peak gain.

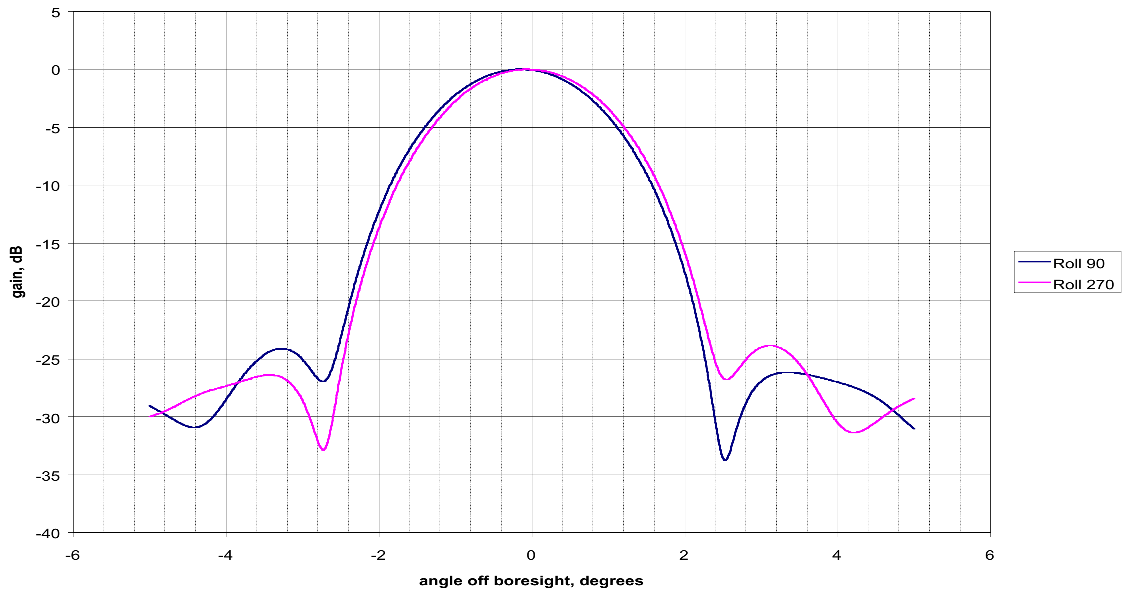


Fig. 3-6. HGA gain pattern, transmit.

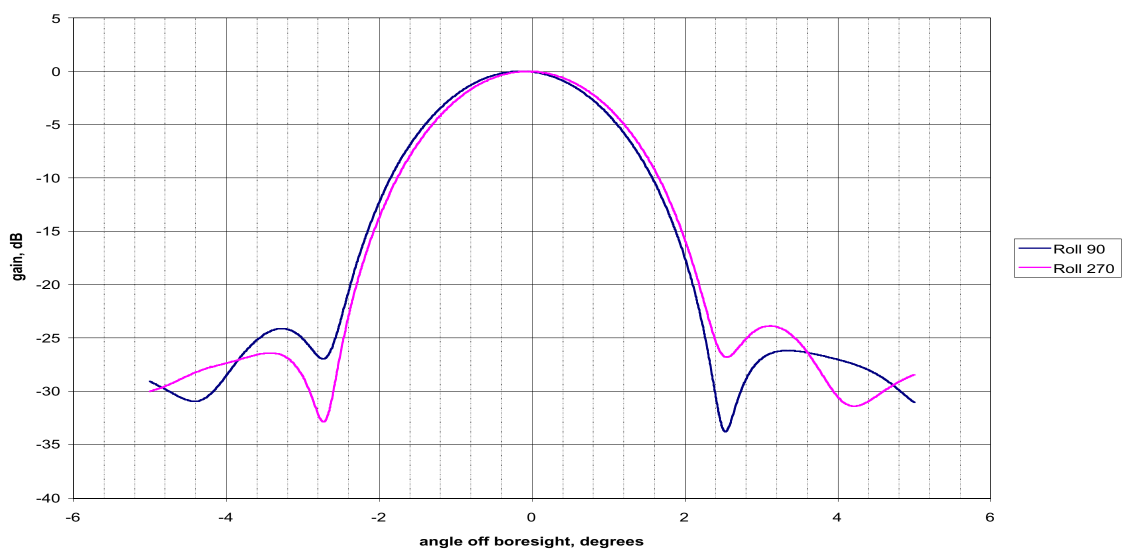


Fig. 3-7. HGA receive gain pattern.

3.1.6.2 Medium-Gain Antenna (MGA). The MGA (see Table 3-2) is mounted on the HGA reflector (see Fig. 3-5), so that the HGA and MGA boresights are parallel. The MGA is a transmit-only antenna.

Figure 3-8 shows the pattern of the MGA (transmit frequency only). Unlike Figs. 3-6 and 3-7 for the HGA, Fig. 3-8 expresses absolute gain values in dB above isotropic (dBi). The dotted, smoother curve is the mean gain as a function of angle from boresight. The solid, more variable curve is the mean minus 2-sigma gain, with the sigma calculated from tolerances that also vary with angle from boresight.

Beyond 30 deg from the boresight, the MGA pattern becomes significantly non-roll-symmetric, as the large variations in the mean minus 2-sigma curve of Fig. 3-8 suggest. As a consequence, for mission-critical events such as Mars orbit insertion, the spacecraft orientation had to be very narrowly controlled in both cone angle and clock angle as defined in Fig. 5-6. This careful control of spacecraft orientation relative to Earth avoided regions of the MGA pattern with deep nulls.

Table 3-2. MGA parameters and characteristics.

Parameter	Value
Type	Horn
Mass	Included in mass of HGA
Frequency, transmit only	8406.851853 MHz
Gain, boresight	16.5 dBi
Polarization	RCP
Beamwidth	28 deg.
Heritage	Mars Climate Orbiter (MCO)

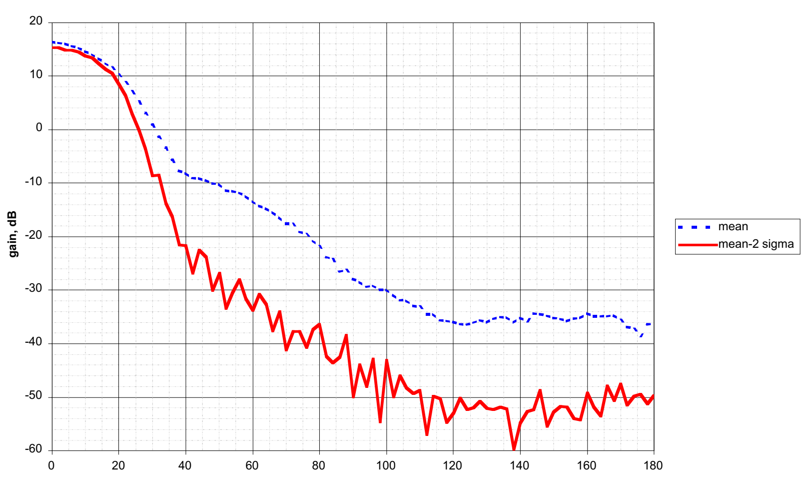


Fig. 3-8. MGA transmit gain pattern.

3.1.6.3 Low-Gain Antenna (LGA). The LGA (see Table 3-3), a receive-only antenna, has a very broad beamwidth that is roll-symmetric out to 60 deg from the boresight. The boresight of the LGA is pointed along the spacecraft x-axis (Fig. 3-9). The LGA was used for initial acquisition after launch and to keep the SDST phase locked to an uplink throughout the trajectory correction maneuvers (TCMs) during cruise. In all mission phases, the LGA is also used for emergency-mode commanding. During an emergency in which the spacecraft has lost its stellar orientation, the spacecraft x-axis will go into a Sun-coning mode.

Figure 3-9 is the LGA antenna's receive gain pattern (receive only). As is the case for the MGA, Fig. 3-9 is an absolute pattern, with gain values in dBi.

Table 3-3. LGA parameters and characteristics.

Parameter	Value
Type	Patch
Mass	40 g
Frequency, receive only	7155.377316 MHz
Gain, boresight	7 +/- 0.4 dBi
Polarization	RCP
Axial ratio, on boresight	3 dB
Axial ratio, 85 deg. off boresight	8 dB
Beamwidth	82 deg.
Heritage	Mars Climate Orbiter (MCO)

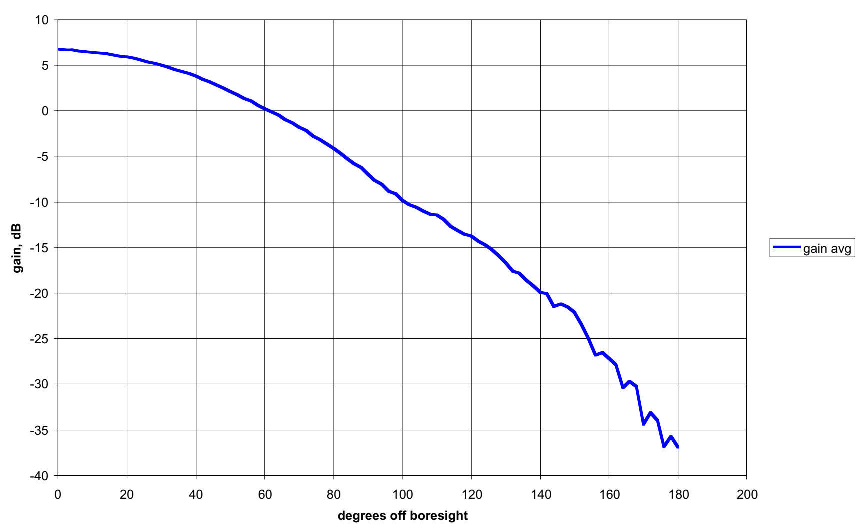


Fig. 3-9. LGA receive gain pattern.

3.1.7 Switches

Odyssey has two types of RF switches

- A coaxial transfer switch (CTS) to connect the HGA and LGA to either SDST, and
- A waveguide transfer switch (WTS) to connect either SSPA to the HGA and the MGA.

The WTS has the lower insertion loss, so it is used on the most power-limited path, which is the transmit path.[21]

To prevent arcing or damage to the WTS, the exciter power is required to be turned off briefly before switching antennas, and then re-established.

3.1.8 Power-On Reset (POR) State

Whenever the power is discontinued to the SDST, the flight software brings it back up in a well-defined state, known as the POR state. The DSN and the flight team can recognize an unplanned POR state and can begin taking corrective action quickly.

3.2 UHF

Odyssey transmits to surface elements (rovers, landers, etc.) via what's called the forward link and receives from the surface elements via the return link.

The Odyssey UHF subsystem consists of the following components (Fig. 3-10):

- A transceiver that performs transmission and reception of UHF communications, and that also interfaces with the C&DH subsystem;
- A single UHF antenna;
- Two diplexers and a coaxial switch to connect the active transceiver to the single antenna;
- Two band-pass filters (BPFs) to enhance the rejection of the diplexer at the transmitting frequency, so that receiver sensitivity is not degraded during receive–transmit (duplex) communications;
- Two sufficiently stable oscillators (SSOs) to enhance stability for Doppler measurements and open-loop recording.

[21] The insertion-loss advantage of a WTS is only available if waveguides are used as the transmission lines. A WTS is also heavier than a CTS, about 400 g versus 80 g.

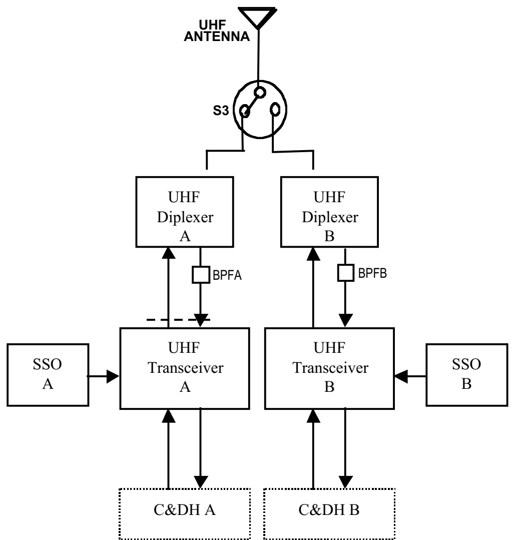


Fig. 3-10. UHF communications system.

3.2.1 UHF Antenna

The UHF relay antenna (Fig. 3-11) is a four-arm quadrifilar helix manufactured by Litton. The height of the antenna is 26.7 cm, and the diameter is 16.5 cm.

The antenna is designed to provide a broad beamwidth to reach surface elements anywhere in Odyssey's view. With the antenna nadir-pointed and a circular 400-km orbit, the required beam to include the limb of Mars is 63 deg off boresight. Given that the Odyssey spacecraft is tilted 17 deg from Nadir during the mapping orbit, the required beamwidth is 80 deg off boresight.

Fig. 3-11. Odyssey UHF antenna.

The patterns at 401 and 437 MHz are depicted in Fig. 3-12, with a peak gain of approximately 5 dB. The patterns are shown as contour plots, to show how unsymmetrical they are. The regions in red have the highest gain (> 4 dB), those in blue the lowest (< –8 dB). A symmetrical pattern would have concentric circles, evenly distributed regions of equal gain. The consequence is that which region of the pattern is traversed during an orbital pass will make a significant difference in the antenna gain (this is discussed in Section 5.2.1).

The antenna has right circular polarization (RCP). The gain measurements were taken with the flight antenna mounted on a mock-up of the spacecraft for both RCP and left circular polarization (LCP). The solar array was not modeled by the mock-up.

The voltage standing wave ratio (VSWR) of the antenna was measured to be below 2:1 (the specification value), except at 437.1 MHz (the transmitting frequency), where at +125 deg C and –115 deg C the VSWR was close to 3:1.

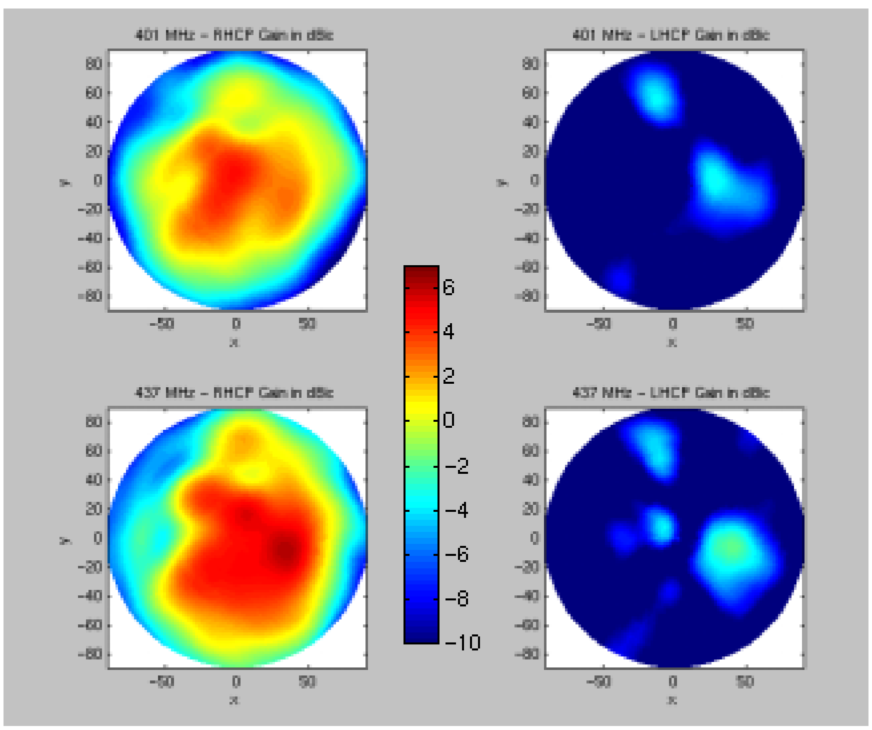


Fig. 3-12. UHF antenna pattern as measured on the spacecraft.

3.2.2 UHF Transceiver

The UHF transceiver, shown in Fig. 3-13, is the core of the UHF subsystem.[22] It was manufactured by Cincinnati Electronics.[23]

Fig. 3-13. Odyssey UHF transceiver.

The receiver can be described at two levels, the physical layer and the data frame layer. At the physical layer, the following are its main characteristics:

- Power
  - Spacecraft input power is typically less than 6 W in the receive-only mode and less than 50 W receiving and transmitting;
  - RF output power is typically 12 W;
- Carrier frequencies
  - Forward frequency at 437.1 MHz;
  - Unmodulated carrier forward frequencies at 437.1, 440.7425, 444.38, and 448.0275 MHz;
  - Return frequency at 401.585625 MHz;
- Modulation
  - Pulse code modulation (PCM)/bi-Phase-L/phase modulation, with a modulation index of 1.05 radians (60 deg);
  - Frequency shift keying (FSK) non-return to zero (NRZ);
- Data rates
  - Forward link: 8, 32, 128, 256 kb/s;
  - Return link: 8, 32, 128, 256 kb/s;
- Convolutional coding and decoding
  - Convolutional encoding with rate 1/2 (G2 vector not inverted) and constraint length 7;
  - Convolutional decoding with 3-bit soft quantization;

[22] The reference for how the UHF transceiver is implemented is given in [10].

[23] Cincinnati Electronics, through corporate mergers and transfers, is part of Canadian Marconi Company (CMC) [Ref. http://www.cinele.com/about.htm].

  - Option of by-passing independently the convolutional coding and decoding;
- Carrier acquisition at ±8 kHz off center frequency
- Thresholds, phase shift keying (PSK) mode, coded
  - 8 kb/s, –122.9 dBm;
  - 32 kb/s, –116.8 dBm;
  - 128 kb/s, –110.5 dBm;
  - 256 kb/s, –106.5 dBm;
- Reception of low-power signal with open loop recording;
- Measurement of Doppler offset of received signal (PSK only).

At the data frame layer, Odyssey implements the CCSDS Proximity-1 Protocol [UHF1], the standard that will be used for relay communications by all the missions at Mars beginning in the 2003 timeframe. The data layer of this protocol provides the structure (frame sequence number and forward error correction (FEC) coding) that allows the establishment of a compatible link and the exchange of error-free information between the orbiter and the surface element. It also allows verification that the orbiter is communicating with the intended surface element.

The link is always initiated by the Odyssey at 8 kb/s sending a Proximity-1 transfer frame (17-bytes long) with “Set Transmit” and “Set Receive” directives in order to configure the transceivers at both ends in a compatible mode. Information about the intended communications mode, data rates, coding, and modulation are all contained in this data frame.

The normal mode of communications with a surface element is the sequence-controlled service defined in the Proximity-1 protocol. This mode ensures the error-free transmission of the input bit stream to the receiving end. The serial data from the transceiver transmit buffer is formatted in the data field of Proximity-1 transfer frames. Odyssey can receive and send Proximity-1 frames up to 1024 bytes long. The following are the most important fields of this transfer frame:

- Attached synchronization marker for identification of the start of the frame;
- Spacecraft identification number (ID) of the surface element;
- Frame sequence number for the receiving end to verify that data are being received in the proper order;
- 32-bit cyclic redundancy code (CRC) appended after the frame for the receiver at the opposite end of the link to check if any bit of the packet suffered an error during transmission.

If no errors are detected, a 14-byte acknowledgement frame (called an ACK) will be returned on the opposite link, indicating the next expected sequence number incremented by one. Otherwise, the sequence number will stay the same.

In the sequence controlled mode, Odyssey implements a Go-Back-2 ARQ (Automatic Repeat Request) protocol, which causes the transmission of the next sequenced frame while receiving the ACK for the one previously sent. In this way, the throughput is increased relative to a Stop and Wait protocol. In the case where an ACK is not received before the end of the transmission of the second frame, the orbiter will keep sending the two transfer frames still to be acknowledged.

The sequence-controlled service needs both forward and return links to be active to transfer data. If an anomaly (such as the failure of the transmitter) occurs in either of the two links, data can still be sent on the link that is still functional by operating that link in the so-called unreliable bit-stream mode. In this mode, the Proximity-1 protocol is by-passed, and data delivery is not guaranteed to be error free or in order.

Another Odyssey UHF mode is the open-loop recording that has been envisioned to receive a low-power signal like the one from the planned Mars Sample Return canister. In this mode, the transceiver samples the incoming baseband signal at 83.6 kHz and does a 1-bit analog-to-digital (A/D) conversion. The phase-locked loop (PLL) used for tracking the carrier is also by-passed. The data at the outputs are formatted into fixed length packets by the C&DH.

The transceiver can measure the Doppler frequency offset of the incoming signal with an accuracy of better than 10 mHz. These measurements will be used by the MER project for high-accuracy locating of the rovers on the surface of Mars.

3.2.3 Sufficiently Stable Oscillator

The sufficiently stable oscillator (SSO), manufactured by Vectron, has higher stability than that of the transceiver’s internal oscillator. The SSO is used for both open-loop recording and Doppler measurements. This oscillator has an Allen deviation better than 10^{-11} for an integration time between 1 and 1000 seconds.

3.3 Odyssey Telecom System Mass and Input Power Summary

Assembly	Input Power, W	Mass, kg	Quantity	Mass total, kg	Dimensions, cm
X-band					
SDST, each		2.7	2	5.4	
Receiver only	11.1				
Exciter, 2-way (coherent)	13.4				
Exciter, 1-way (using aux osc)	13.9				
SSPA	60	1.687	2	3.374	12.95 x 20.98 x 6.48
Hybrid	0	0.0182	1	0.0182	2.59 x 1.30
WTS	0	0.398	1	0.398	
CTS	0	0.0728	1	0.073	
Coax	0			2.789	
Waveguides	0			0.824	
BPF	0	0.265	2	0.530	
NF	0	0.097	2	0.194	
Diplexer	0	0.342	1	0.342	
Attenuators	0	0.0070	6	0.042	
Terminations	0	0.004	6	0.024	
HGA (w/o MGA)	0	2.527	1	2.527	130 dia.
MGA	0	0.680	1	0.680	l. 18.75 dia. 16.19 at horn aperture
LGA	0	0.042	1	0.042	4.53 x 4.53 x 4.53
Terminations, dummy loads, etc.	0	0.0040	6	0.024	
X-band totals	73.9 max			17.2812	
UHF					
UHF transceiver	6/50[24]	1.852	2	3.704	
BPF	0	0.680	2	0.136	
SSO	5/2[25]	0.160	2	0.320	
Diplexer	0	0.2585	2	0.517	
SPDT	0	0.0728	1	0.073	
UHF antenna	0	1.0900	1	1.0900	26.7 x 16.5
Coax	0			0.425	
UHF totals	55 max			6.265	
Telecom subsystem	X-band and UHF not on simultaneously			23.5462	

[24] Power input for receive-only and receive/transmit modes.
[25] Power input for turn-on and steady-state modes.

Section 4

Ground System

4.1 Background

The Deep Space Network (DSN) consists of tracking stations located in Goldstone (California), Canberra (Australia), and Madrid (Spain). These locations make possible, when needed, round-the-clock communications with deep space spacecraft, even as the Earth's rotation changes the geographical site in view of the spacecraft.[26]

Deep space generally refers to missions that are farther from the Earth than the Moon (384,000 km). In order to provide communications at large distances, the DSN has needed to build very large antennas. (The two sizes used for tracking Odyssey are the 34-m-diameter high-efficiency (HEF) and beam-waveguide (BWG) antennas and the 70-m-diameter antenna.) It also had to equip its stations with powerful transmitters (typically 4 to 20 kW), ultra-low-noise amplifiers (with noise temperatures of only a few kelvin) and very sensitive receivers (the so-called Block V Receiver (BVR), which has a variable-loop noise bandwidth down to 0.75 Hz). The downlink capabilities result in carrier detection thresholds as low as –175 dBm.

The remainder of this section concentrates on DSN X-band uplink and X-band downlink capability, as is required for Odyssey. For S-band[27] capabilities of the DSN, refer to Article 5 in this series (Galileo), and for Ka-band, refer to Article 2 (DS1).

This article describes the existing station configuration that supports Odyssey in 2002 prior to the changeover to the Network Simplification Project (NSP) configuration planned for completion in 2003. For an outline of the NSP configuration, refer to Section 4 of Article 3 in this series (Cassini).

4.2 34-m HEF and BWG Stations

The DSN 34-m antenna subnets contain three 34-m-diameter high-efficiency (HEF) antennas and five 34-m beam-waveguide (BWG) antennas.

Each HEF antenna has an elevation over azimuth (az-el) axis configuration, a single dual-frequency feedhorn, a dual-shaped reflector design, and a 20-kW X-band transmitter. DSS 15 is at Goldstone, DSS 45 is at Canberra, and DSS 65 is at Madrid.

The BWG stations are the newest generation of antennas in the DSN. These antennas differ from the 34-m HEF antennas in the fact that a small series of mirrors

[26] The DSN sites provide "continuous" coverage only when the declination of the spacecraft is not too far north or south. As described in Section 5, Odyssey's initial southerly declination required use of an auxiliary tracking site, Santiago, Chile, for nearly a month after launch.

[27] S-band refers to a carrier frequency of about 2.1 GHz (uplink) and 2.3 GHz (downlink).

(about 2.5 m in diameter) direct microwave energy from the region above the main reflector to a location at the base of the antenna, typically in the pedestal room. As described in 810-005 [7], this configuration enables the use of ultra-low-noise amplifier and feed systems. The BWG stations currently have 4-kW X-band transmitters[28] and downlink performance similar to the HEF stations. The 34-m BWG stations that currently support Odyssey are DSS 25 at Goldstone, DSS 34 at Canberra, and DSS 54 at Madrid. Others are at various stages of development at Goldstone and Madrid.

4.3 70-m Stations

The 70-m subnet has three stations, one at each longitude. Each station has a 20-kW uplink transmitter and, as of 2002, a new X-band transmit–receive (XTR) feedcone. The feed design includes a diplexing junction to inject the uplink signal directly into the feed. This eliminates the need for a waveguide diplexer and a common path for uplink and downlink signals. The result is that much of the downlink path can be cryogenically cooled with a significant (4-K) reduction in operating system temperature. DSS 14 is at Goldstone, DSS 43 is at Canberra, and DSS 63 is at Madrid.

4.4 Carrier Tracking

Carrier tracking is done by the Block V Receiver carrier-tracking loop. Tracking the carrier allows us to do four things:

1) Track the carrier despite any Doppler shifts;[29]
2) Demodulate from the RF carrier the telemetry modulation that contains science data and spacecraft and instrument engineering (health and status) measurements;
3) Demodulate from the RF carrier the ranging modulation (which is another measure for NAV to determine the spacecraft's range from the Earth);
4) Demodulate from the RF carrier any DOR modulation (described later; it is another data type used by NAV to determine the plane-in-the sky motion of the spacecraft relative to quasars).

One more note on Doppler and carrier tracking: in order to have accurate Doppler data, it is necessary to have a transmitter with a highly stable frequency source. As described in Section 3.1.3, the necessary end-to-end stability is achieved by generating the uplink in a maser at the station, and producing a downlink carrier from the spacecraft that is coherent with the stable uplink.

---

[28] The BWG stations are scheduled to be equipped with 20-kW X-band transmitters by mid-2003 for support of the MER project.

[29] Doppler is the shift or change in frequency that occurs while the distance between the transmitter and the receiver is changing. As the distance decreases, the frequency at the receiver increases; as the distance increases, the frequency at the receiver decreases. Besides compensating for the Doppler offset, rate, and rate of change, the Block V Receiver provides Doppler estimates that are used by the navigation (NAV) team to estimate the spacecraft trajectory.

4.5 Command

The command format currently used for deep-space missions, including Odyssey, is defined in the CCSDS standard CCSDS 201.0-B-1 [5]. Commands are converted into digital bits using a PCM, NRZ-level (NRZ-L) data waveform. The digital sequence of bits has a specific structure, which will be used by the spacecraft to help command detection: first there are 176 alternating 0–1 bits, then a command start word (the pattern is EB90 in hex), and then the command itself (according to the CCSDS standard). The command waveform is BPSK-modulated onto a 16-kHz sinewave command subcarrier.

The subcarrier-plus-command-data composite is then phase modulated (PM) onto the RF carrier. The command bit rate for Odyssey can be between 1000 b/s and 7.8125 b/s (decreasing in factors of 2). The bit rate chosen depends on the available signal-to noise margin.

The DSN command system can produce a command modulation index in the span from 0 to 1.5 rad. The Odyssey project determined that it would use an index value from 0.94 rad for the lowest bit rate (7.8125 b/s) to 1.5 rad for the higher command rates. These values are similar to those used by other missions, such as DS1, Voyager, and Cassini.

At the spacecraft end of the link, the spacecraft receiver demodulates the composite command signal, then demodulates the 16-kHz command subcarrier, and provides the detected command stream to the HCD in the C&DH. The HCD detects a valid command start word and passes to the C&DH the subsequent command bits. The C&DH does the command error detection and validation.

4.6 Telemetry

Odyssey generates telemetry according to the CCSDS standard CCSDS 101.0-B-3 [5], modulates it onto a square-wave subcarrier, and phase modulates the composite signal for transmission to Earth. Because of the low signal-to-noise-ratios (SNRs), the telemetry signal has been encoded with two codes, a Reed–Solomon (RS) outer code (in the C&DH) and a convolutional code, either a (7,1/2) or a (15,1/6) code by the SDST.

On the Earth, the station receives the weak downlink signal, which must therefore be amplified while keeping a very low noise temperature. Depending on elevation angle and Earth weather in the signal path, the X-band system noise temperature typically varies between 15 and 35 K.

The downlink signal first has to be demodulated from the RF carrier by the BVR carrier loop, already described. Next the telemetry subcarrier is demodulated by the BVR subcarrier loop; the remaining symbol detection and synchronization is done by the BVR symbol-synchronization loop.

The output of the BVR is a stream of soft-quantized symbols that must be convolutionally decoded. Decoding is done either with an MCD2 (maximum likelihood convolutional decoder 2) for a (7,1/2) code, or an MCD3, a decoder capable of decoding several convolutional codes, up to the (15,1/6) code.

The output of the convolutional decoder is sent to a frame synchronizer (FSS), where the telemetry frames' synchronization markers attempt to synchronize to a specific 32-bit pattern (in hex, 1ACFFC1D).

When the telemetry frames are synchronized, they are delivered to JPL's Advanced Multi-Mission Operations System (AMMOS). There, they are Reed–Solomon decoded, and the data are sorted according to their channel.

4.7 Ranging

Ranging allows NAV to determine a spacecraft's range relative to Earth. The station starts the process by modulating a series of square waves (called a ranging code) on the uplink RF carrier.

At the other end, the spacecraft receiver demodulates the ranging signal from the uplink carrier and phase modulates it onto the downlink carrier.

Back on the ground, the demodulated signal is sent to the sequential ranging assembly (SRA), where it is correlated with a replica of the transmitted ranging signal.

If only one ranging frequency were used (say, 1 MHz), this correlation process would provide an ambiguous output because points located every one-half wavelength apart at 1 MHz give the same correlation result. Thus, with only one ranging frequency, NAV would get an infinite number of possible ranging solutions.

The way around this is to use a series of square waves (called ranging components), all related to one frequency (called the clock) by factors of 2 (for example, 1 MHz, 500 kHz, 250 kHz, and so on).

Every time we correlate with the next-lower frequency, half of all possible ranging solutions are eliminated.

This allows NAV to get one ranging solution, instead of infinitely many.

The highest frequency (the clock) has the smallest wavelength, so the clock provides the best precision.

The lowest-frequency component available (typically around 1 Hz) provides ambiguity resolution to one-half wavelength at 1 Hz, or about 150,000 km.

4.8 Differential One-Way Ranging (DOR)

Turnaround ranging is good for evaluating spacecraft range relative to Earth. However, if a spacecraft is approaching a planet (for example Mars) prior to orbit insertion, the Earth–spacecraft range barely changes from one day to the other. What does vary is the plane-of-the sky motion of the spacecraft, which is best measured with another data type, DOR.

In DOR, the spacecraft phase modulates high-frequency tones (typically 19 MHz and sometimes a sub-multiple of 19 MHz) onto the downlink carrier. In the DOR mode, the one-way downlink carrier comes from the SDST's crystal oscillator, called the auxiliary oscillator.

At the ground, the DSN alternately points the antennas assigned to the DOR pass to a quasar (a star that produces significant radio frequency energy and whose sky position is well known) and to the spacecraft.

The DSN uses two geographically separated antennas. These will receive the quasar signal at slightly different times, the difference expressed as a delay (say, delta t1). Then the two antennas point to the spacecraft and receive its DOR tones. These arrive at the two antennas with another delay (say, delta t2).

It is then possible for NAV to relate the difference [delta t2-delta t1] to the angular separation (as seen from Earth) between the spacecraft and the quasar.

So DOR allows us to measure the spacecraft motion relative to known locations (quasars, which, because they are very distant, can be considered motionless as seen from Earth).

Section 5

Telecommunications Link Performance

5.1 X-Band

5.1.1 Launch and Initial Acquisition

The Mars Odyssey spacecraft was launched on a Delta II 7925 from the Eastern Test Range on April 7, 2001, at approximately 15:02:22 UTC. Operations proceeded nominally. After the spacecraft separated from the upper stage, the solar array was deployed, the star camera attained attitude knowledge, and the spacecraft turned to its nominal initial acquisition attitude.

Due to the highly negative (southerly) declination of the launch trajectory, DSN sites in the northern hemisphere (i.e., Goldstone and Madrid) did not have visibility of the spacecraft during initial acquisition. Since Odyssey launched during the first opportunity, Goldstone had no visibility of the spacecraft until 32 days after launch, and Madrid had no visibility of the spacecraft until 52 days after launch. Because of the gaps in coverage, a 12-m station at the University of Chile in Santiago was used to provide telemetry-only support for the first 26 days after launch.[30] Figure 5-1 shows the overlap of coverage between Canberra and Santiago during the first 3 days. Santiago's X-band performance[31] was well characterized prior to launch. This was accomplished by having the 12-m station track the Stardust spacecraft during an Earth flyby.

Initial acquisition, which occurred when the ground first received communications from the spacecraft after launch, was a critical event for telecom. There were a large number of possible launch and initial acquisition scenarios considered. These depended upon several variables, such as spacecraft trajectory, whether the solar array deployed properly or remained "stuck in the hook,"[32] and whether the star camera was able to attain attitude knowledge. During the pre-launch planning phase, available launch opportunities for a multi-day launch window were identified, and target trajectories for each opportunity were provided to telecom analysts in the form of binary spacecraft kernel (SPK) files.[33] Assuming the star camera attained attitude knowledge,

---

[30] See [14], the user's guide, for more detailed information about the Santiago satellite tracking station.

[31] A primary antenna performance characteristic is the ratio of antenna gain to system noise temperature (G/T). As measured with RF from both the Sun and the Taurus spacecraft, the Santiago 12-m antenna G/T at X-band averaged 35.7 dB/K above 30-deg elevation angle, falling to 35.0 dB/K at 10-deg elevation. In contrast, the G/T at 30-deg elevation averages 52–53 dB/K at 34-m stations and 59–60 dB/K at 70 m.

[32] The solar array has a physical restraint called the hook that was used when the array was stowed against the spacecraft. There was a concern that if the gimbal motors (for example) had a problem, the array might not be able to release from the hook and would remain restrained (thus, "stuck in the hook").

[33] The SPK file is a standard format used to provide ephemeris (trajectory) information. The SPK format was developed by JPL's NAIF (Navigation and Ancillary Information Facility) Group as part of the NAIF SPICE standard.

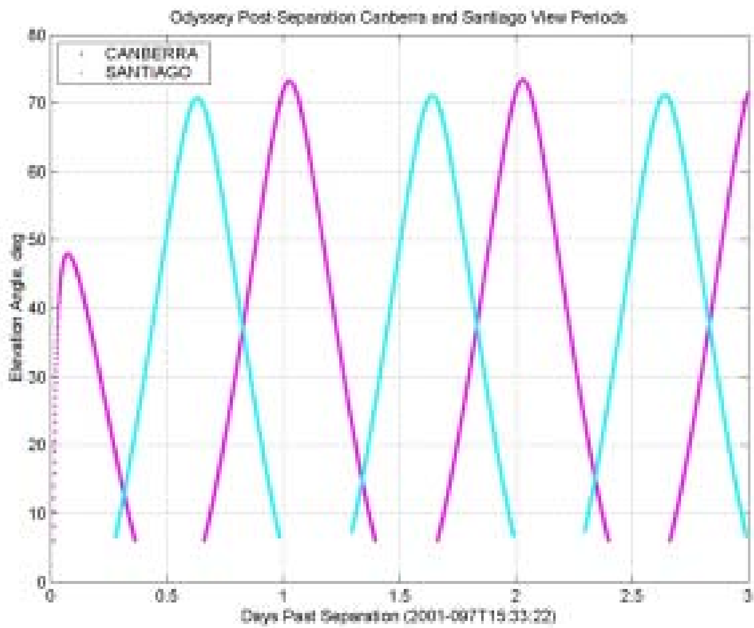


Fig. 5-1. Overlap of Canberra and Santiago coverage post-separation.

the spacecraft would orient itself in a known fixed attitude. These fixed attitudes (specified by quaternions[34]) were modeled using binary camera kernel (CK) files.[35]

A failure to attain attitude knowledge would have caused the spacecraft to initiate Sun coning. Sun coning involves pointing a particular spacecraft body-vector (called the Sun-cone vector) at the Sun, and rotating about that vector. Sun-coning scenarios were modeled using the Telecom Forecaster Predictor (TFP) custom attitude graphical user interface (GUI).[36]

For a given launch date, the fixed-attitude quaternion and Sun-cone vector for the case where the solar array deployed nominally were different from those for the case where the solar array was stuck in the hook. Planned attitude data obtained from Brian Sutter (Mars Odyssey attitude control subsystem [ACS]) are reprinted in the following tables. For the first three of the 21 possible launch dates, Table 5-1 lists nominal fixed-attitude quaternions relative to the EME2000 frame, and Table 5-2 lists Sun-cone vectors relative to the body frame, assuming the solar array is unrestrained (i.e., deployed nominally).

---

[34] A quaternion is a 4-element vector commonly used to represent the orientation of an orthonormal basis with respect to a reference frame. In this case, the orthonormal basis is the spacecraft frame, and the reference frame is EME2000 (J2000). There is a straightforward algorithm for converting a quaternion into its equivalent rotation matrix (and vice versa).

[35] The CK file (or C-kernel) is a standard format used to provide frame orientation (attitude) information. The CK format was developed by JPL's NAIF Group as part of the NAIF SPICE standard.

[36] Telecom performance estimates in this section were made with the TFP, Telecom Forecaster and Predictor. The user's manual for the TFP is given in [11].

Table 5-1. Solar array normal unrestrained attitude quaternions.

Launch Day	Q1	Q2	Q3	Q4
Day 1	0.70613611	0.46444414	0.01882742	0.53414320
Day 2	0.62973860	0.52976420	0.07400150	0.56329652
Day 3	0.65076020	0.52624348	0.08010221	0.54144492
etc.				

Table 5-2. Solar array normal unrestrained Sun-coning rotation vectors.

Launch Day	Body X	Body Y	Body Z
Day 1	0.78349	0.55388	-0.28170
Day 2	0.66679	0.68720	-0.28836
Day 3	0.68478	0.68580	-0.24649
etc.			

For each launch opportunity (two per launch date), there were four possible scenarios to consider:

- Fixed attitude with solar array unrestrained;
- Sun coning with solar array unrestrained;
- Fixed attitude with solar array stuck in the hook;
- Sun coning with solar array stuck in the hook.

Predicts of the carrier power, P_c (also known as downlink automatic gain control [AGC]), for the initial acquisition pass for these four situations were generated using the TFP. Plots for the first 8 hours after spacecraft separation for the first launch opportunity are shown in Fig. 5-2. The downlink AGC (P_{carrier}) threshold for this link was approximately –145 dBm.

The Sun-coning plot, Fig. 5-3, demonstrates the sinusoidal signal variation expected during spacecraft rotation. The phase of the rotation could not be predicted ahead of time, but if Sun coning had occurred, it could have been estimated as follows. When the signal drops below threshold, loss of signal (LOS) occurs. When the signal rises back above threshold, acquisition of signal (AOS) occurs. After noting LOS and AOS times, the phase of the rotation is inferred, and the timing of future peaks is predicted. After adjusting for one-way light time (OWLT), command radiation times are selected such that commands will be received when the geometry is most favorable for communications (i.e., the uplink margin is largest).

Since spacecraft operations proceeded nominally after launch, the downlink AGC signature was very close to that of the fixed-attitude/solar-array unrestrained case shown in Fig. 5-2. A typical initial acquisition downlink design control table (DCT) for this configuration is given in Table 5-3.

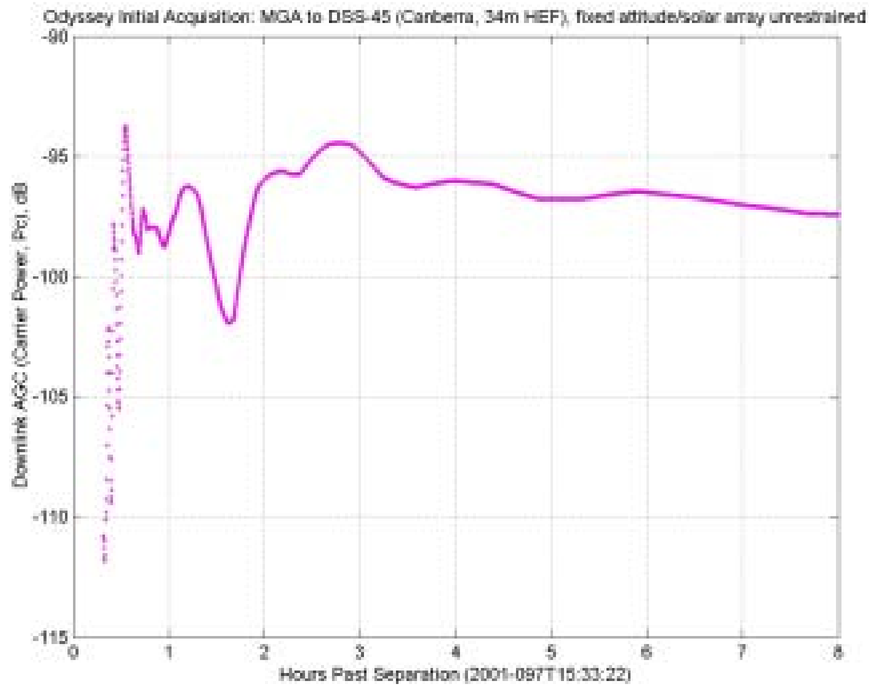


Fig. 5-2. Downlink $P_{carrier}$, initial acquisition, fixed attitude with solar array unrestrained.

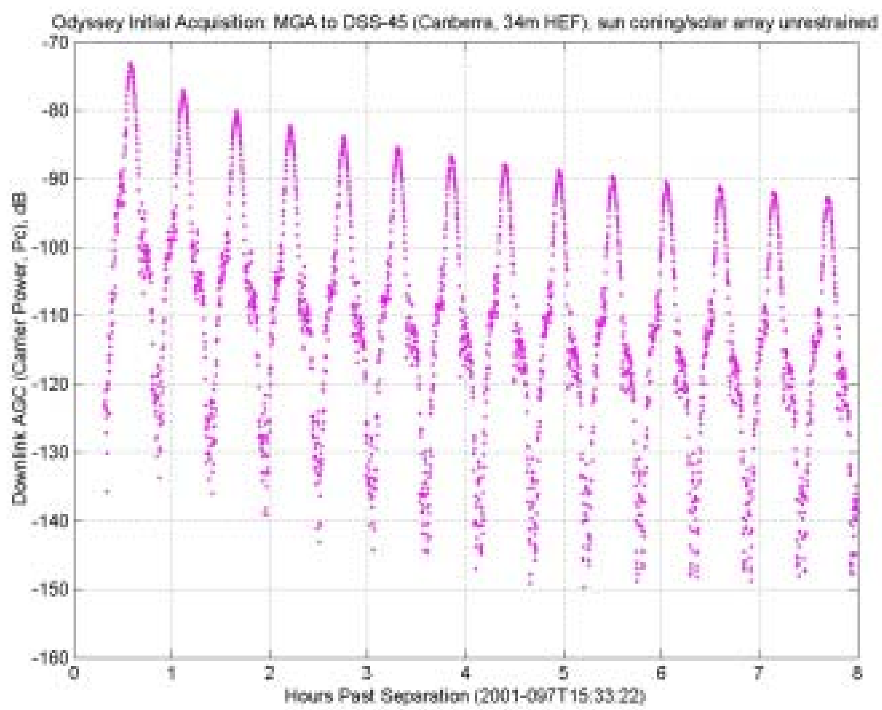


Fig. 5-3. Downlink $P_{carrier}$, initial acquisition, Sun coning/solar array unrestrained.

Table 5-3. Typical initial acquisition downlink design control table.[37]

Predict	2001-097T15:53:00000 UTC	
Up/Down-Link	Downlink	
RF Band	X	
Diplex Mode	Diplex	
LNA Selection	LNA-1	
Telecom Link	Med Gain, DSS 45	
TELEMETRY DOWNLINK PARAMETER INPUTS		
Encoding	Reed–Solomon (255,223) concatenated with C.E. (7,1/2)	
Carrier Tracking	Residual	
Oscillator	Voltage-controlled oscillator (VCO)	
Subcarrier Mode	Square Wave	
PLL Bandwidth	3.00 Hz	
Tlm Usage	Inner Cruise (TMI Set A)	
Tlm Data Rate/Mod Index	2100 b/s/44.37 Degrees	
Tlm Rng/DOR Mod Index	0.31 Rads/Off Radians	
Operations Mode	Nominal	
Mission Phase	Inner Cruise	
DSN Site	Canberra	
DSN Elevation	In View	
Weather/CD	90	
Attitude Pointing	C-Kernels	
EXTERNAL DATA		
Range	(km)	1.1024e+004
Range	(AU)	7.3688e-005
One-Way Light Time	(hh:mm:ss)	00:00:00
Station Elevation(s)	(deg)	[7.47]
MGA Pattern Used:		MgaDnAntPatt3D60.dat
Theta: HGA,MGA	(deg)	87.29 87.29
Phi: HGA,MGA	(deg)	–70.46 –70.46
Added S/C Ant Pnt Offset	(deg)	0
DSN Site Considered:	DSS 45	
At Time:	2001-097T15:53:00000 UTC	

[37] The standard format for a link budget (or Design Control Table) is found in Chapter 1 of [12].

Table 5-3. Typical initial acquisition downlink design control table (cont'd).

Link Parameter	Unit	Design Value	Fav Tol	Adv Tol	Mean Value	Var
TRANSMITTER PARAMETERS						
1. S/C Transmitter Power	dBm	41.40	0.10	-0.10	41.40	0.0017
2. S/C Xmit Circuit Loss	dB	-0.32	0.10	-0.10	-0.32	0.0033
3. S/C Antenna Gain	dBi	17.46	0.00	0.00	17.46	0.0000
4. Degrees-off-boresight (DOFF) Loss	dB	-42.45	0.50	-0.50	-42.45	0.0833
5. S/C Transmit Pointing Loss	dB	0.00	0.00	-0.25	-0.13	0.0052
6. EIRP (1+2+3+4+5)	dBm	15.96	0.92	-0.92	15.96	0.0935
PATH PARAMETERS						
7. Space Loss	dB	-191.79	0.00	0.00	-191.79	0.0000
8. Atmospheric Attenuation	dB	-0.45	0.00	0.00	-0.45	0.0000
RECEIVER PARAMETERS						
9. DSN Antenna Gain	dBi	68.02	0.20	-0.20	68.02	0.0067
10. DSN Antenna Pnt Loss	dB	-0.10	0.10	-0.10	-0.10	0.0033
11. Polarization Loss	dB	-0.07	0.10	-0.10	-0.07	0.0033
TOTAL POWER SUMMARY						
12. Tot Rcvd Pwr (6+7+8+9+10+11)	dBm	-108.43	-0.98	0.98	-108.43	0.1069
13. SNT at Zenith	K	26.65	-2.00	2.00	26.65	0.6667
14. SNT due to Elevation	K	1.67	0.00	0.00	1.67	0.0000
15. SNT due to Atmosphere	K	27.52	0.00	0.00	27.52	0.0000
16. SNT due to the Sun	K	0.00	0.00	0.00	0.00	0.0000
17. SNT due to other Hot Bodies	K	0.00	0.00	0.00	0.00	0.0000
18. SNT (13+14+15+16+17)	K	55.84	-2.00	2.00	55.84	0.4444
19. Noise Spectral Density	dBm/Hz	-181.13	-0.16	0.15	-181.13	0.0027
20. Received P_t / N_o (12-19)	dB-Hz	72.71	0.99	-0.99	72.71	0.1096
21. Required P_t / N_o	dB-Hz	39.46	-0.48	0.48	39.46	0.0258
22. P_t / N_o Margin (20-21)	dB	33.25	1.10	-1.10	33.25	0.1354
23. P_t / N_o Marg Sigma	dB	0.00	0.00	0.00	0.37	0.0000
24. P_t / N_o Margin-2Sigma (22-2*23)	dB	0.00	0.00	0.00	32.51	0.0000
CARRIER PERFORMANCE						
25. Recovered P_t / N_o (20+[AGC+BPF])	dB-Hz	72.71	0.99	-0.99	72.71	0.1096
26. Telemetry Carrier Suppression	dB	-2.92	0.36	-0.39	-2.93	0.0230
27. Ranging Carrier Suppression	dB	-0.51	0.06	-0.07	-0.51	0.0007
28. DOR Carrier Suppression	dB	0.00	-0.00	-0.01	-0.00	0.0000
29. Carrier Power (AGC) (12+26+27+28)	dBm	-111.86	-1.08	1.08	-111.86	0.1306
30. Received P_c / N_o (25+26+27+28)	dB-Hz	69.27	1.10	-1.10	69.27	0.1332

Table 5-3. Typical initial acquisition downlink design control table (cont'd).

31. Carrier Loop Noise BW	dB-Hz	4.77	0.00	0.00	4.77	0.0000
32. Carrier Loop SNR (CNR) (30-31)	dB	64.50	1.10	-1.10	64.50	0.1332
33. Recommended CNR	dB	10.00	0.00	0.00	10.00	0.0000
34. Carrier Loop SNR Margin (32-33)	dB	54.50	1.10	-1.10	54.50	0.1332
TELEMETRY PERFORMANCE						
35. Telemetry Data Suppression	dB	-3.11	0.37	-0.40	-3.12	0.0251
36. Ranging Data Suppression	dB	-0.51	0.06	-0.07	-0.51	0.0007
37. DOR Data Suppression	dB	0.00	-0.00	-0.01	-0.00	0.0000
38. Received P_d / N_o (25+35+36+37)	dB-Hz	69.08	1.10	-1.10	69.08	0.1354
39. 2-Sigma P_d / N_o (38-2*sqrt(38var))	dB-Hz	68.34	0.00	0.00	68.34	0.0000
40. Data Rate	dB-Hz	33.22	0.00	0.00	33.22	0.0000
41. Available E_b / N_o (38-40)	dB	35.85	1.10	-1.10	35.85	0.1354
42. Subcarrier Demod Loss	dB	0.00	0.00	0.00	0.00	0.0000
43. Symbol Sync Loss	dB	0.00	0.00	0.00	0.00	0.0000
44. Radio Loss	dB	0.30	0.00	0.00	0.30	0.0000
45. Output E_b / N_o (41-42-43-44)	dB	35.55	1.10	-1.10	35.55	0.1354
46. Required E_b / N_o	dB	2.31	0.00	0.00	2.31	0.0000
47. E_b / N_o Margin (45-46)	dB	33.24	1.10	-1.10	33.24	0.1354
48. E_b / N_o Marg Sigma	dB	0.00	0.00	0.00	0.37	0.0000
49. E_b / N_o Margin-2Sigma (47-2*48)	dB	0.00	0.00	0.00	32.51	0.0000
50. BER of Conv Decoder (from 45)	none	0				

5.1.2 Nominal Cruise Attitude

The nominal attitude of the spacecraft during cruise is shown in Fig. 1-2. The +x-axis, parallel to which were the MGA and stowed HGA boresights, was pointed at the Earth, and the –z-axis was oriented as close to the Sun as possible. Communication was normally via the HGA at 28,440 b/s (downlink) and 125 b/s (uplink), with support provided by 34-m stations. During maneuvers that involved turning the +x-axis away from the earth, uplink was via the LGA at 125 b/s, and downlink was via the MGA at 100 b/s.

5.1.3 Maneuvers (TCMs, Star Camera Calibration, MOI Checkout)

During cruise, Odyssey performed a number of maneuvers that involved changing the attitude, and sometimes the trajectory, of the spacecraft. These maneuvers included four trajectory correction maneuvers (TCMs), a Star Camera calibration maneuver, and a "checkout" maneuver that simulated the expected attitude during Mars orbital insertion (MOI). Like several other recent and future missions, Odyssey was expected to communicate during most maneuvers. Therefore, telecom is involved in maneuver planning to ensure (or validate) that attitudes are "telecom-friendly." For instance, before planning a maneuver, navigation or attitude control might ask telecom how far off boresight the Earth can be, or where in the spacecraft frame the Earth vector can lie, and still support downlink communications.

During maneuvers, more attention is paid to the downlink than the uplink. The uplink usually is the more "forgiving" link for two reasons. The receive-only LGA has a broader, more roll-symmetric gain pattern than the transmit-only MGA. Also, the DSN 34-m HEF and 70-m antennas have 20-kW transmitters, whereas the spacecraft has a (nominal) 15-W transmitter. Downlink communications is often limited to carrier only, since navigation just needs the carrier to get Doppler data. However, for Odyssey, there was a desire to provide telemetry during maneuvers when practical.

Maneuvers are simulated in LMA's Spacecraft Test Laboratory (STL) in Denver, Colorado. After an STL run, telecom analysts obtain time-stamped quaternions describing the spacecraft attitude by query. The quaternions are used to construct a predict CK file that describes the spacecraft attitude. Performance during maneuvers is predicted using the TFP, which reads the CK files.

For example, TCM 4 was conducted on October 12, 2001 (2001-285). During the maneuver, the spacecraft was two-way coherent with carrier-only uplink via the LGA, and telemetry was via the MGA at 100 b/s. TCM 4 began at approximately 03:22 UTC, but due to the one-way light-time delay, the downlink was received at approximately 03:30 UTC.

For all maneuvers performed, there has been good agreement between predicted and observed signal levels. Comparisons of actual versus predicted AGC for the downlink and uplink at DSS 43 are displayed in Fig. 5-4 and Fig. 5-5, respectively. The TFP predicted curves are relatively smooth curves marked by circles, and the actual curves are jagged and marked by squares.[38]

[38] The approximate 3-dB discrepancy (average offset) in the uplink is largely due to the fact that the uplink AGC calibration curves were developed during pre-launch testing. The noise temperature for an antenna on Earth is about 3 dB higher than it is looking toward cold space. So the "actuals" are in fact about 3 dB too high.

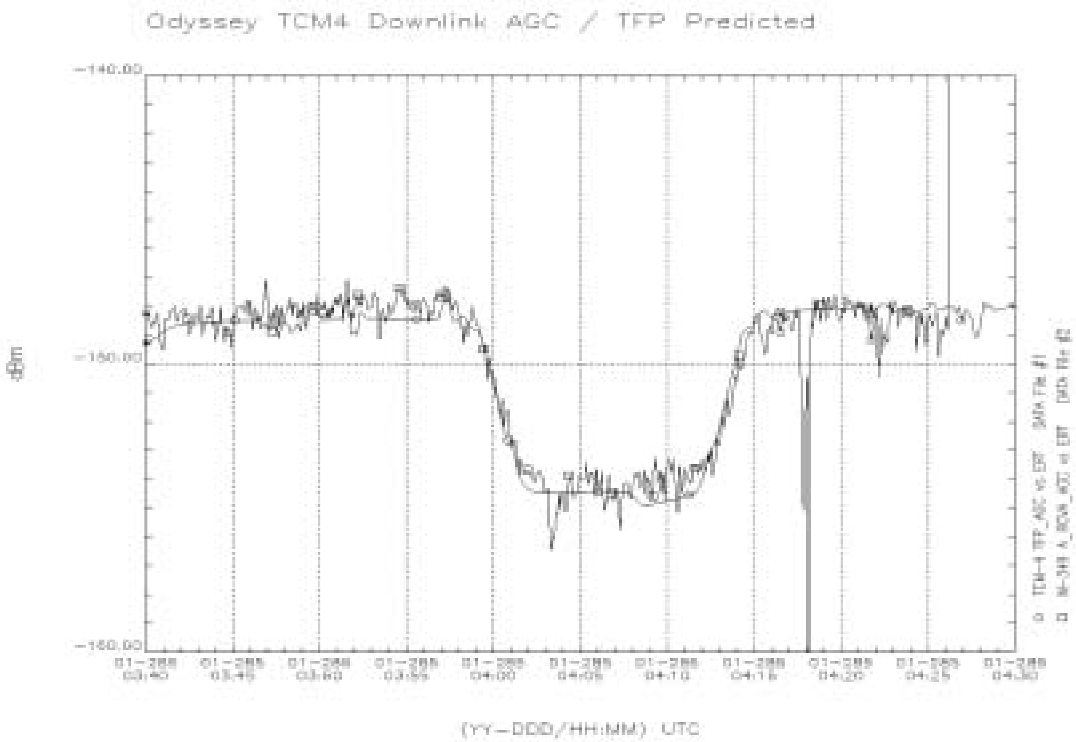


Fig. 5-4. Odyssey TCM4—downlink $P_{carrier}$ (AGC): predict versus actual.

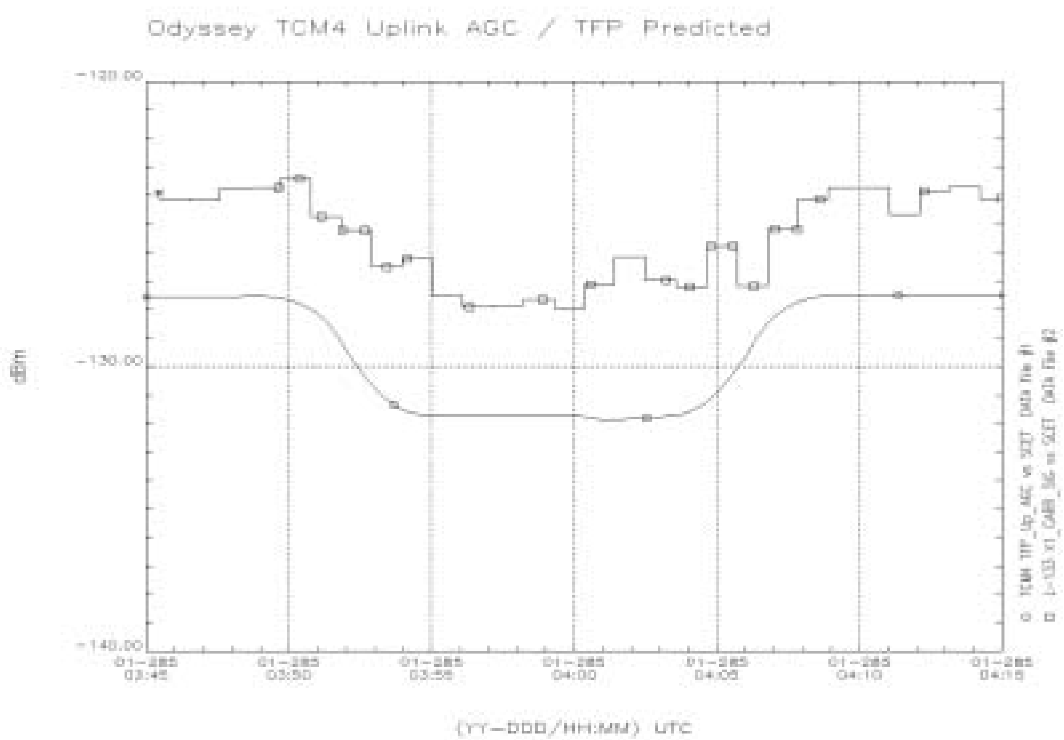


Fig. 5-5. Odyssey TCM4—uplink $P_{carrier}$ (AGC): predict versus actual.

5.1.4 MOI

Mars orbital insertion (MOI) was another mission-critical event for Odyssey. The MOI burn, which lasted about 20 minutes on October 24, 2001, placed Odyssey into a highly elliptical 20-hour capture orbit around Mars that enabled the next mission phase, aerobraking, to begin. The required MOI geometry was such that shortly after the start of the MOI burn, Odyssey went into occultation behind Mars, and there was an approximately 20-minute communications blackout period until the spacecraft emerged from the other side of the planet.

Due to the large MGA off-boresight angles and large Earth–spacecraft (S/C) range (~1 AU) during MOI, there was not enough downlink capability for telemetry. Therefore, only the unmodulated carrier was transmitted.

During MOI, the main engine (oriented toward the –z-axis) was pointed along the velocity vector to produce thrust in the opposite direction. As part of the maneuver planning, telecom provided input on which roll angle around the thrust vector (+z-axis) was the most favorable for MGA communications. For each roll angle, the path of the Earth in terms of angles relative to the MGA boresight (+x-axis) was needed. Theta is defined as the cone (or degrees-off-boresight) angle, which is the angle of the Earth vector from the MGA boresight (+x-axis). Phi is defined as the clock angle, which is the angle around the boresight (in the right-handed sense) of the projection of the Earth vector into the Y–Z plane measured from the +y-axis. A diagram showing the definitions of theta and phi with respect to the spacecraft body frame is shown in Fig. 5-6. Since the MGA boresight and the thrust vector were not co-aligned, STL simulations were conducted to produce time-stamped quaternions of the spacecraft attitude. Predict C-kernels built from the quaternions served as inputs to the TFP, which computed the desired angles.

Plots showing the path of the Earth through the MGA pattern for all roll angles considered appear in Fig. 5-7. Theta is plotted along the X-direction, and phi is plotted along the Y-direction. In that plot, paths are labeled 60 to 130, which correspond to the roll angles considered. The most favorable roll angle, which corresponded to the path labeled 75, was selected for MOI. The choice of 75 provided margin for error in the actual roll angle. The traces labeled 70 and 80 show the path of the Earth through the MGA pattern assuming a 5-deg difference between the desired and the actual roll angle. All three of these paths pass primarily through magenta colored regions of the pattern, corresponding to higher gains than blue colored regions.

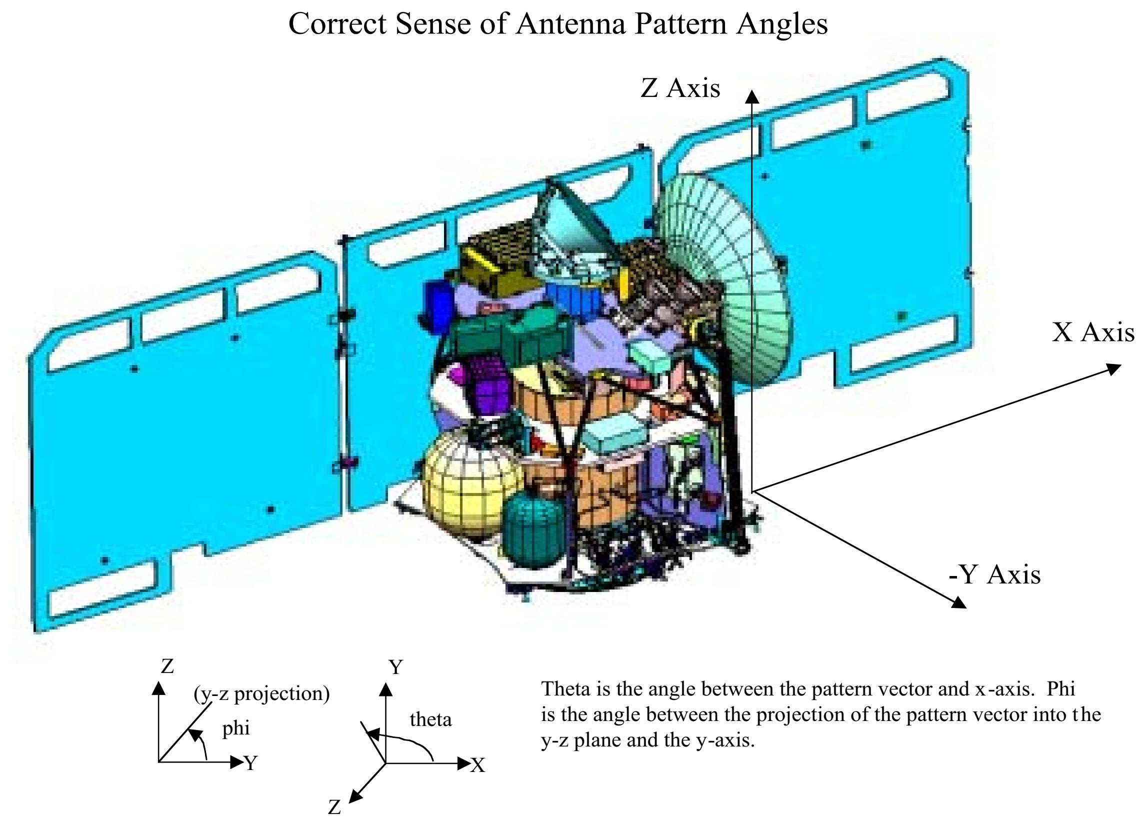


Fig. 5-6. Cone (theta) and clock (phi) with respect to the spacecraft body frame.

Since the downlink was "carrier only"[39] during MOI, telecom prediction and analysis were instrumental in helping to assess the success of the MOI burn before occultation. Good agreement between the signature of the station downlink AGC and the predicted AGC provided a very solid indication that the burn executed nominally. Similarly, the navigation team obtained Doppler residual data that showed the difference in the line-of-sight velocity between the burn and "no burn" scenarios. They were able to compare the Doppler residuals with predicts to assess the success of the burn. The availability of Doppler data depended on the ability to track the downlink carrier.

---

[39] Downlink carrier only means there was no telemetry, no delta-DOR, and no ranging data. However, with Odyssey, downlink ranging modulation is always on, so there was some suppression of the carrier due to modulation by noise in the ranging channel.

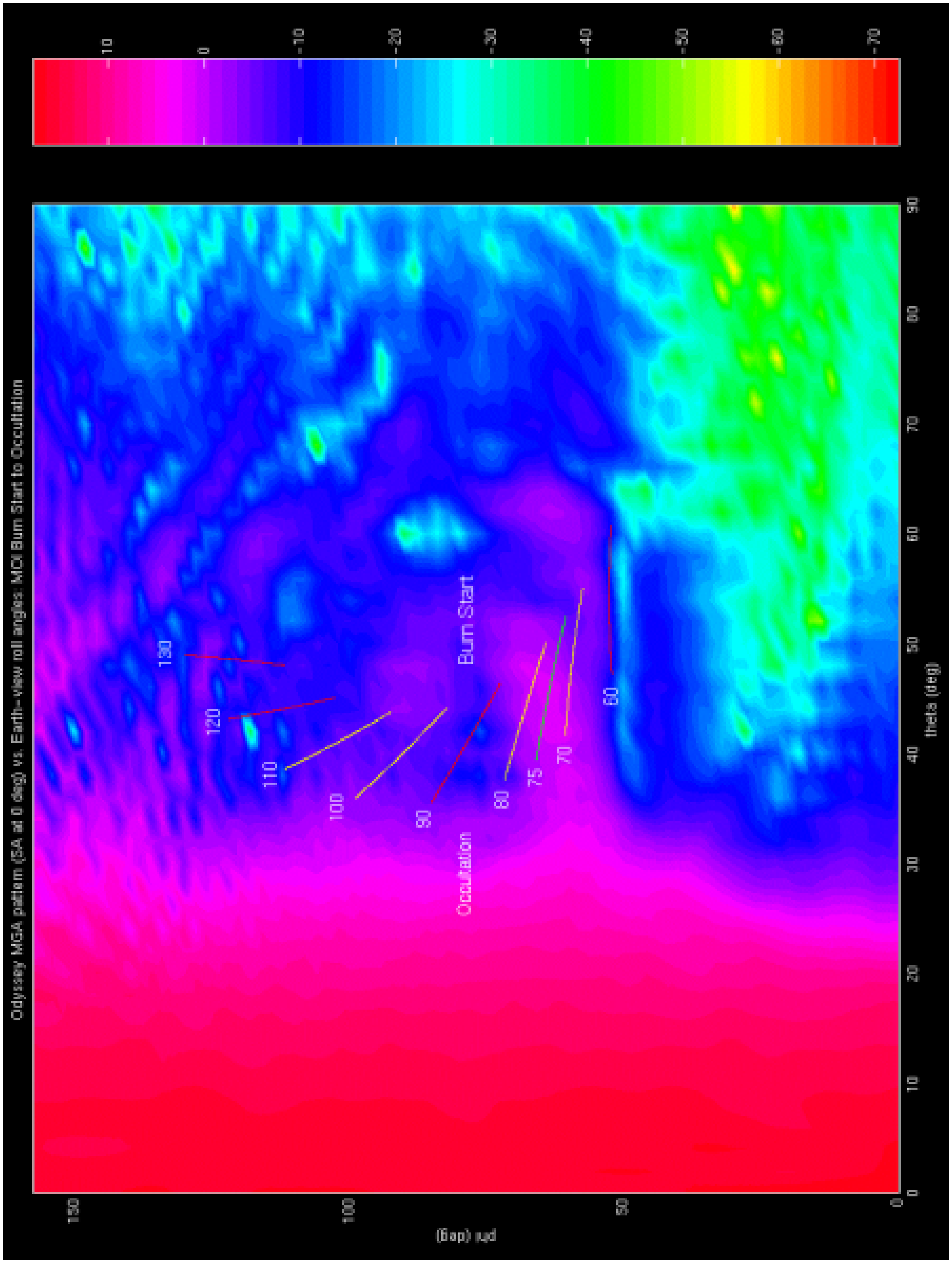


Fig. 5-7. Earth vector in MGA pattern for various roll angles.

A timeline of important MOI events is in Table 5-4, and a sketch of when Odyssey was visible to Earth is in Fig. 1-6. Prior to MOI, communications links were via the HGA at 125 b/s (uplink) and 28,440 b/s (downlink). At approximately 8 minutes before the burn, the spacecraft was configured for MOI with the LGA (uplink only) and the MGA (downlink carrier only). A minute later, the slew to the MOI attitude began.

About 10 minutes after the start of the burn, Odyssey went into Earth occultation behind Mars. During occultation, the burn ended, and the spacecraft slewed to point the +x-axis (HGA and MGA) at the Earth. During the first 3 minutes after occultation exit, the downlink remained carrier only via the MGA, and then switched to 40 b/s telemetry. After an assessment of spacecraft health and status by the flight team, the ground commanded the spacecraft to return to the normal cruise configuration, and a replay of MOI data was started. Normal cruise mode is via the HGA at 125 b/s (uplink) and 28440 b/s (downlink).

Table 5-4. Timeline of important telecom events during the Odyssey MOI.

MOI Relative Time	ERT	Event Description
–00:08:04	10/24/2001 02:18:15	Configure telecom for MOI (MGA carrier-only downlink, LGA uplink); signal returns in 2-way mode after 10 second LOS, at –143 dBm (70m)
–00:07:06	10/24/2001 02:19:13	Start slew to MOI attitude; signal level decreases; brief LOS during turn
–00:04:37	10/24/2001 02:21:42	Inertial hold at MOI attitude; signal level at –165 dBm (70 m)
00:00:00	10/24/2001 02:26:19	Start of MOI burn; possible 1 min LOS
+00:09:37	10/24/2001 02:35:56	Enter Earth occultation; LOS
+00:19:44	10/24/2001 02:46:03	Approximate end of MOI maneuver
+00:20:36	10/24/2001 02:46:55	Start slew to Earth-point attitude
+00:29:24	10/24/2001 02:55:43	Exit Earth occultation; AOS, approximately –143 dBm
+00:32:02	10/24/2001 02:58:21	Configure telecom for post-MOI checkout (MGA 40 b/s downlink, LGA uplink); BVR AGC will drop 5.5 dB for telemetry modulation, 25 kHz subcarrier

The downlink carrier margin during MOI was severely limited. At Goldstone and Canberra, both 70-m stations (DSS 14 and DSS 43) and both 34-m HEF stations (DSS 15 and DSS 45) were scheduled to provide support.

Using the spacecraft SPK file from the navigation team and the predicted CK file corresponding to the roll angle of 75, the TFP generated predicts of MOI downlink signal levels.

A plot of predicted MOI downlink carrier-loop SNR[40] (with a threshold of 10 dB) is shown in Fig. 5-8. Even at the 70-m stations and with a carrier-loop bandwidth set to a narrow bandwidth, 3 Hz, the link margin was very limited. The large initial downward slope in the plot corresponds to the spacecraft slew to the burn attitude. During this slew, loss of signal (LOS) was expected at all stations at 02:23 UTC as the carrier-loop SNR dropped below threshold. At the 70-m stations, the LOS period was expected to be brief (less than 1 minute). Following reacquisition, the 70-m antennas were expected to track the downlink AGC continuously until occultation. At the 34-m HEF stations, a longer LOS period (1–2 minutes) was expected, followed by a second LOS period (2 minutes) at 02:25 UTC, and possibly a third brief LOS period (less than 1 minute) at 02:35 UTC. A brief LOS (up to 1 minute) was possible at all stations at the start of the MOI burn (02:26:19 UTC) due to attitude and Doppler transients.

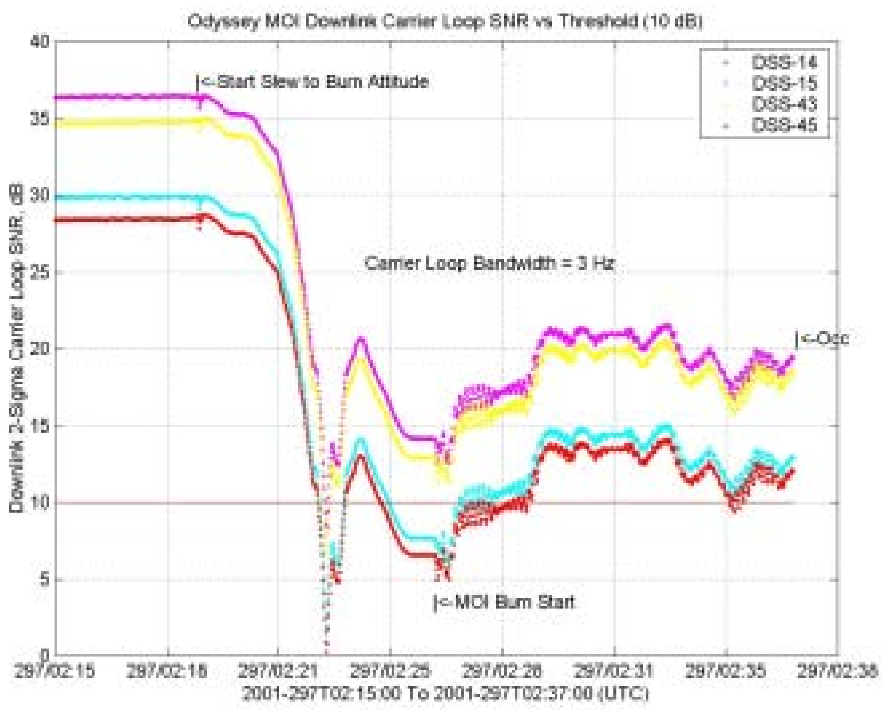


Fig. 5-8. Predicted downlink carrier loop SNR (3-Hz bandwidth).

---

40 Downlink carrier loop SNR is a function of downlink AGC.

A comparison of the predicted versus observed AGC at DSS 14 during MOI is shown in Fig. 5-9. The DSN carrier-loop bandwidth was inadvertently set to 30 Hz instead of the planned 3 Hz, effectively shifting the carrier-loop SNR curves down by 10 dB in Fig. 5-8. This explains a slight delay in AOS 1 following LOS 1. The cause of LOS 2, at the start of the MOI burn, was initially thought to be MOI attitude or Doppler transients. When AOS 2 didn't happen as expected about 1 minute after LOS 2, the too-wide carrier-loop bandwidth was discovered. Adjustments were requested and made in real time to narrow the loop bandwidth on some of the Block V Receivers. Narrowing the loop bandwidth allowed DSS 14 to acquire the signal about 3 minutes after LOS 2. DSS 14 was able to track the carrier for another 6 minutes until occultation. The excellent agreement between predicted and observed AGC was a strong indication the burn was executing normally.

The post-MOI data replay included quaternions representing the actual attitude of the spacecraft during MOI. The telecom assessment of MOI now included predicts rerun using a CK file built from these quaternions and compared with the original predicts and the AGC actuals. This comparison makes it more likely that LOS 2 was caused by the too-wide carrier-loop bandwidth than by MOI transients. The rerun predicts also confirmed that nothing unusual happened to the spacecraft between LOS 2 and AOS 2 that would have prevented the ground from tracking the signal.

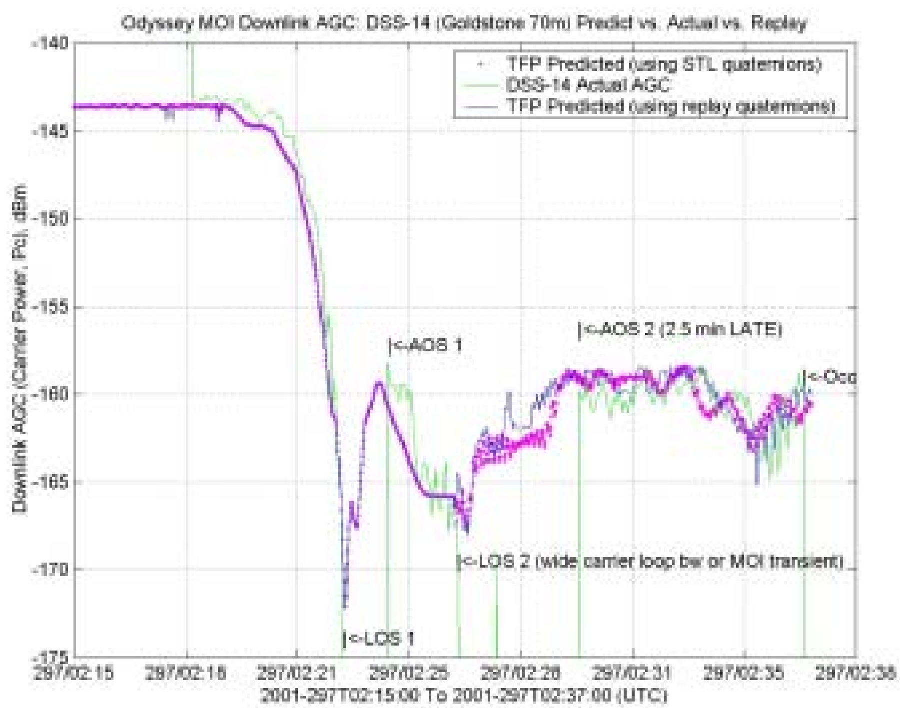


Fig. 5-9. Post-MOI assessment: downlink $P_{carrier}$ (AGC) predict versus actual versus replay.

5.1.5 Aerobraking (Using Body-Fixed HGA, Earth-Pointed)

Following MOI, Odyssey spent about 3 months aerobraking in preparation for the science and relay phase. During aerobraking, shallow drag passes through the upper atmosphere of Mars removed energy from the orbit, lowered the apoapsis, and reduced the orbital period. The aerobraking phase culminated in January 2002 with a final periapsis-raise maneuver to initiate the transfer to the desired near-circular 400-km science orbit.

During aerobraking, both the HGA and the solar panel remained in a stowed configuration, as is shown in Fig. 5-10. As during normal cruise, communications during the aerobraking phase was via the HGA at 125 b/s (uplink) and 28,440 b/s (downlink). The spacecraft x-axis (parallel to the HGA boresight) remained Earth-pointed except during the atmospheric drag pass, about a half-hour each orbit. During the drag passes, Fig. 5-10, the –y-axis was aligned with the velocity vector, and the –z-axis was toward nadir.[41]

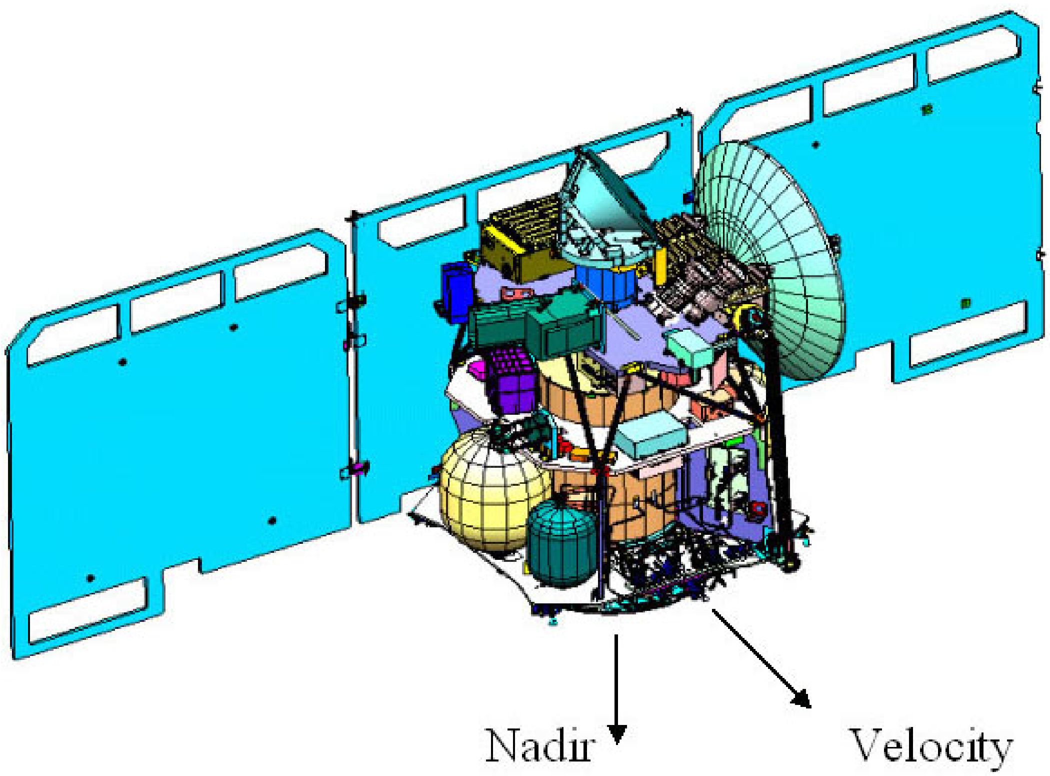


Fig. 5-10. Odyssey configuration during aerobraking drag passes.

[41] The nadir direction is along the line from the spacecraft to the center of the planet.

5.1.6 Science (HGA Gimballed to Track the Earth)

The nominal science mission began February 1, 2002, at the end of aerobraking. This phase of the mission lasts 917 days and will end in August 2004. A near-circular science orbit of 400 km provides the observational geometry desired by the Odyssey instruments. The orbit period of just under 2 hours results in 12.5 spacecraft revolutions around Mars per sol. The 93.1-deg. inclination of the orbit was chosen to produce a nearly Sun-synchronous[42] orbit. This allows the local mean solar time (LMST) of the orbit to slowly drift at a constant rate, which is part of the orbit design strategy.

Mars Odyssey carries several kinds of spectrometers:

- THEMIS: The Thermal Emission Imaging System is a camera that images Mars in the visible and infrared parts of the spectrum in order to determine the distribution of minerals on the surface of Mars;[43]
- GRS: The Gamma Ray Spectrometer uses the gamma-ray part of the spectrum to look for the presence of 20 elements from the periodic table (e.g., carbon, silicon, iron, magnesium, etc.). Its neutron detectors look for water and ice in the soil by measuring neutrons;
- MARIE: The Martian Radiation Experiment is designed to measure the radiation environment of Mars using an energetic particle spectrometer.

The science mission design balances the observational desires of two of the instruments, THEMIS and GRS. For THEMIS, collecting high-quality infrared data is only possible when the local true solar time (LTST) is earlier than 5 P.M. For GRS, collecting high-quality data is only possible for solar beta angles less than (more negative than) –57.5 deg. As shown in Fig. 5-11, the strategy allows for a full Martian year[44] of GRS data acquisition spread over two opportunities, and two opportunities for THEMIS observations. The third instrument, MARIE, will operate continuously during the entire science phase.

Figure 5-12 depicts the nominal spacecraft configuration. Figure 1-7 shows the nominal spacecraft attitude during the science phase with respect to the velocity and nadir pointing vectors: to minimize the effects of gravity gradient torques, Odyssey is canted 17 deg off nadir about the +z-axis (orbit normal).

---

[42] In a Sun-synchronous orbit, the Local Mean Solar Time of the ascending node is fixed.

[43] THEMIS will take infrared images to study the distribution of minerals of the Martian surface and will acquire visible images with a resolution of approximately 18 meters to determine the geological record of past liquid environments. These will help identify landing site candidates for future missions to Mars.

[44] A Martian year is 687 days.

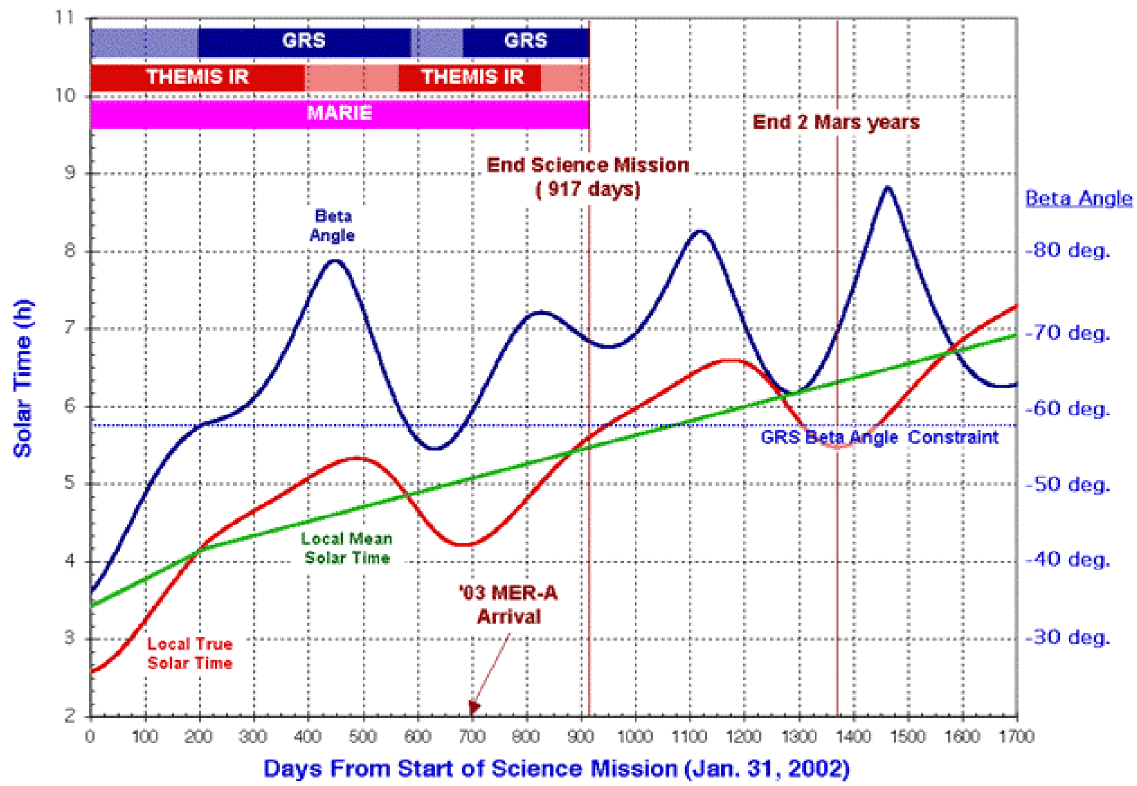


Fig. 5-11. Odyssey science orbit and instrument opportunities.

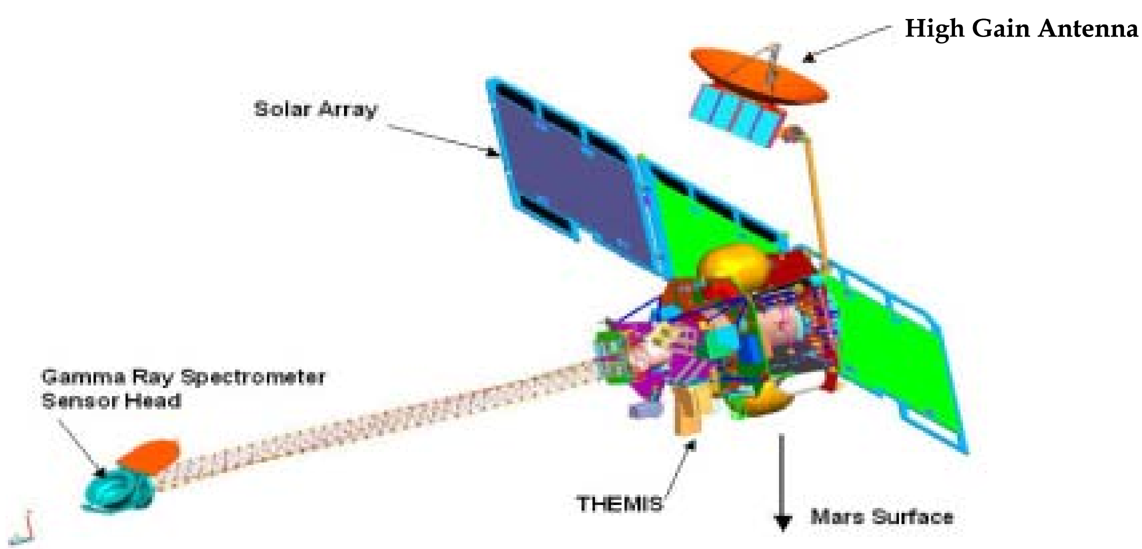


Fig. 5-12. Odyssey mapping configuration during the science phase.

Following aerobraking, the HGA boom was deployed to allow it to track the Earth. Normal communications during the science mission are via the gimballed HGA. For simplicity, the uplink bit rate is 125 b/s, even when the link could support a higher rate. Downlink bit rates are selected based on link margin and are between 28,440 b/s and 110,600 b/s for 70-m passes, and between 3,950 b/s and 110,600 b/s for 34-m passes. THEMIS data volumes require 70-m coverage, but GRS opportunities only need 34-m coverage. DSN support during the science phase averages 14 hours of coverage per day. As shown in Fig. 1-11, the average DSN pass length during the science phase is greater than 10 hours.

5.1.7 Relay

The relay phase requires orientations and configurations similar to the science phase. It will last for 457 days following the end of the science phase to complete the 2 full Martian years in orbit. The normal attitude for relay is the same as for the science phase, which was shown in Fig. 5-12. Figure 5-13 shows the spacecraft configuration during the relay phase. Odyssey's UHF quadrifilar helix antenna (Fig. 3-11) is mounted with its boresight along the –x-axis, which is canted 17 deg off nadir. In the cover picture, the UHF antenna is pointed vertically upward from its location at the top left edge of the main spacecraft body.

The planned end of the mission is in November 2005, 2 Martian years after the start of the science phase. This allows Odyssey to serve as a UHF relay orbiter for both of NASA's Mars Exploration Rovers and ESA's Beagle 2 Lander, which are scheduled to arrive at Mars in 2003 and 2004. During the relay phase, DSN coverage will be scaled back to one 4-hour 34-m pass per day.

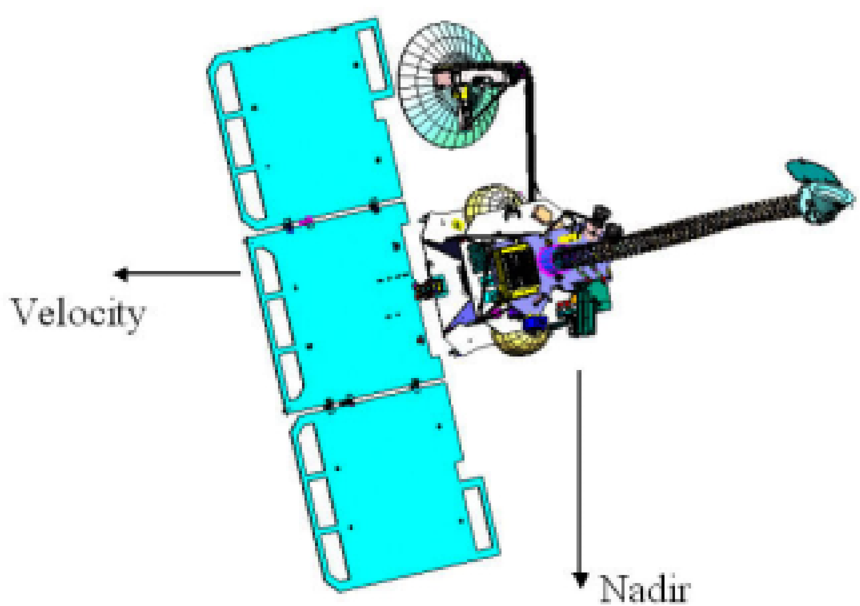


Fig. 5-13. Odyssey configuration during the relay phase.

5.2 UHF

5.2.1 Data Volume with MER

Odyssey will support relay of data from the Mars Exploration Rovers during their surface missions. The UHF link will nominally be used for all non-time-critical data (most of the science data) and as a functional backup to the MER direct-to-Earth (DTE) link.

MER has the same type of UHF transceiver as Odyssey. The MER UHF antenna is a monopole mounted on the Rover equipment deck. Due to its linear polarization and the presence of many vertical structures on the deck (low- and high-gain antennas, panoramic camera mast, etc.) the antenna pattern is asymmetrical in azimuth for both the forward (rover receive) link and the return (rover transmit) link. This will cause the data volume returned via Odyssey to be strongly dependent on the rover orientation on Mars' surface relative to the orbiter's path above it. See Fig. 5-14 for a preliminary transmit frequency antenna pattern measured on the rover mock-up.

A preliminary analysis has been performed to evaluate the data volume that can be transferred between MER and Odyssey. Figure 5-15 shows the data volume in Mbits returned per sol at 128 kb/s in the reliable bit-stream mode where the forward link is used to send frame acknowledgments at 8 kb/s. Minimum, average, and maximum data volume per sol are calculated over 8 different orientations of the rover spaced 45 deg apart.[45]

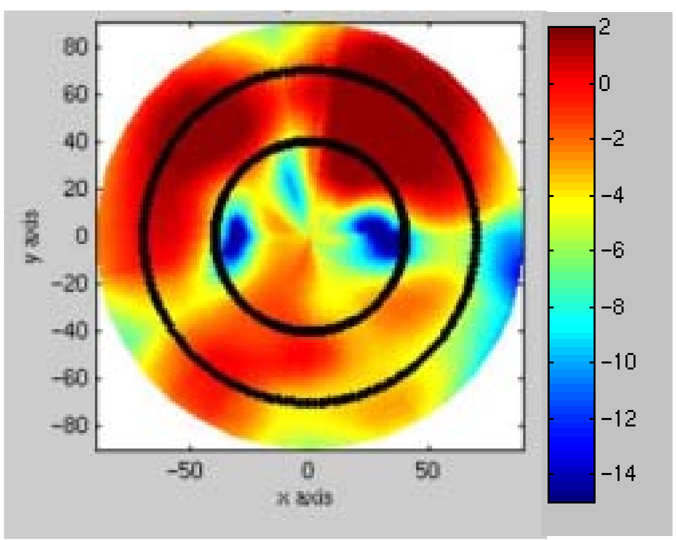


Fig. 5-14. MER 401-MHz transmit antenna pattern, gain in dB.

---

[45] The rover antenna pattern is highly asymmetrical at both receive and transmit frequencies. The transmit (return) link typically has a lower link margin because of its higher bit rate. Most Odyssey passes have a north–south overflight.

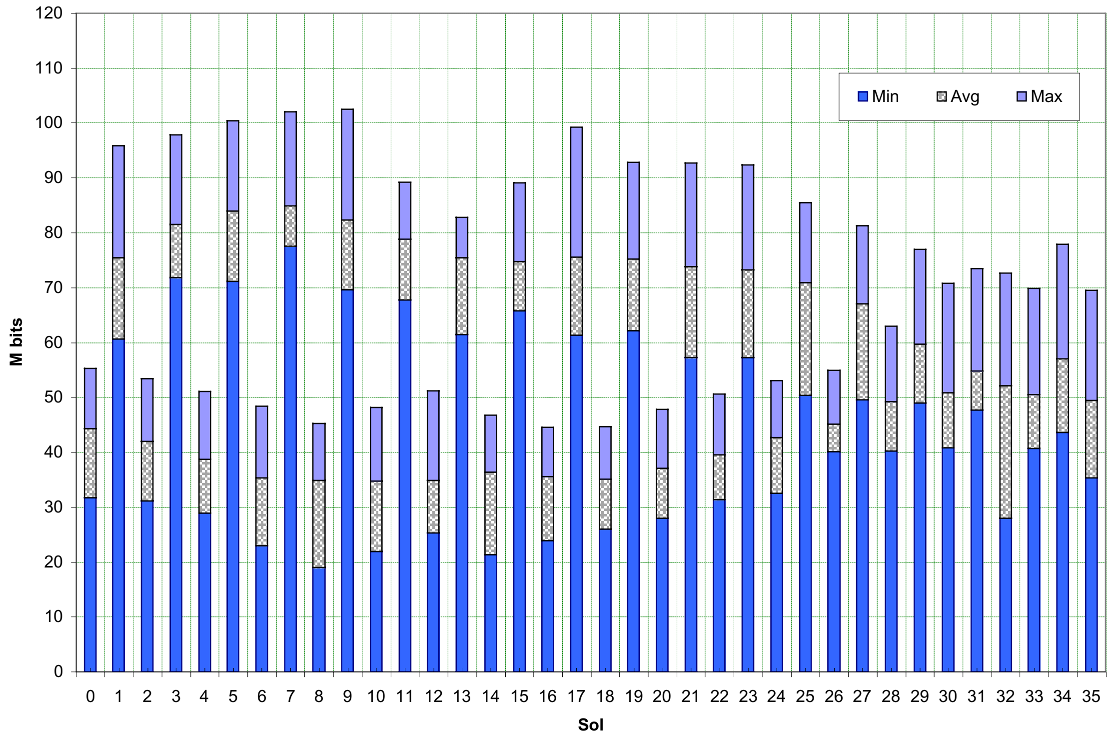


Fig. 5-15. Data volume per sol in return link between MER and Odyssey for different rover orientations.

The estimated data volumes include tolerances and expected degradations.[46] The link is considered closed (carrier and data both above threshold) when the channel bit-error rate (BER) is less than 10^{-6}. Given the maximum frame size of 1024 bytes, this BER results in a very small frame-error rate (FER) and a protocol efficiency (limited by the overhead) of approximately 97 percent. The average of 56 Mbits per sol satisfies the MER requirement for data volume return via Odyssey.

An estimate of data volume in the forward link at 8 kb/s can be obtained by scaling the chart by 8/128 and additionally by accounting for an protocol efficiency degraded to approximately 55 percent due to a smaller frame size. The worst-case forward link is adequate to meet the MER requirement of 1 Mbit per sol.

5.2.2 Odyssey In-Flight UHF Tests

The in-flight UHF tests were made in June 2001 while the spacecraft was in the cruise phase. The objectives of these tests were to

---

[46] As described in the next section, Odyssey performance was assessed during the June 2001 in-flight test, and unexpected degradations were found. Losses of 2 dB in the return link and 6 dB in the forward link to account for these test results have been included in the estimate. The tolerances are accounted for by including a 2-sigma statistical margin on the received power estimate. The test results are documented in [13].

- Verify that the UHF subsystem and other payloads remained electromagnetically compatible with one another after launch;
- Obtain points on the UHF antenna radiation pattern at both the receive and transmit frequencies;
- Verify the performance of the UHF forward and return links at the boresight.

Transmission from a vehicle on the surface of Mars was simulated by using the antenna at Stanford University, operated by the Stanford Research Institute (SRI), known as the Big Dish (Fig. 5-16). The Big Dish is a 45.7-m parabolic antenna, having both transmit and receive capabilities at Odyssey's UHF frequencies. The RF signal transmitted from Stanford was generated in an engineering development model of the MER UHF transceiver and amplified to an RF power as high as 40 kW by a klystron.

With the spacecraft more than 20 million km away, the signal level received at Stanford was too low to demodulate the Odyssey 8 kb/s forward data stream. Instead, measurements of received carrier-to-noise ratio were made. Return link performance was assessed from the telemetered return link AGC at the Odyssey transceiver. Using the UHF AGC, the BER could be calculated for the data sent from Stanford and then relayed by Odyssey at X-band to the DSN.

The Odyssey subsystem is electromagnetically compatible with the spacecraft and performed its functions. However, there was some degradation in link performance. The signal received at Stanford from Odyssey was about 6 dB lower than expected, and the signal received by Odyssey from Stanford was approximately 2 dB short of expectations.[47] The expected performance was based on link budgets using data from UHF component acceptance tests, subsystem and system tests, and measurements of the UHF radiation pattern on a mock-up of the spacecraft. Table 5-5 presents the forward link budget for the nominal case of the antenna pointed to the ground; Table 5-6 compares expected versus observed performance.

Fig. 5-16. SRI 46-m dish at Stanford.

[47] The 2-dB return link shortfall is within the measurement accuracy of the test.

Table 5-5. Link budget for forward link (Odyssey transmits).

Observation Date	6/6/01					6/8/01	6/21/01
Observation Time [ERT]	07:00 UTC					07:00 UTC	04:50 UTC
Transmission Station (Odyssey)	**Nominal**	**Fav**	**Adv**	**Avg**	**Var**	**Nominal**	**Nominal**
Frequency [Hz]	437100000.0						
Wavelength [m]	0.6859						
Modulation	**CW**						
Transmit Power [W]	12.0						
Transmit Power [dBm]	40.8	0.50	–0.5	40.8	0.083		
Circuit Losses [dB]	–1.0	0.2	–0.2	–1.0	0.013		
Antenna Gain [dBi]	4.8	1.0	–1.0	4.8	0.333		
EIRP [dBm]	*44.6*			*44.6*			
Range [m]	2.02E+10					2.11E+10	2.82E+10
Space Losses [dB]	–231.4	0.0	0.0	–231.4	0.000	–231.8	–234.3
Atmospheric Losses [dB]							
Receiving Station (Stanford)							
Antenna Diameter [m]	45.7						
System Efficiency	0.60						
Antenna Effective Area [m2]	985.0						
Antenna Gain [dB]	44.2	0.3	–0.3	44.2	0.030		
Feed Losses [dB]	–0.7	0.1	–0.1	–0.7	0.003		
Polarization Losses [dB]	–0.1	0.1	–0.1	–0.1	0.003		
Misc Losses [dB]	–0.2	0.1	–0.1	–0.2	0.003		
Received Power [dBm]	*–143.6*			*–143.6*		*–144.1*	*–146.5*
System Temperature [K]	110.0	–55	55	110.0			
Sky Temperature [K]	70.0	–14	14	70.0			
Noise Density No[dBm/Hz]	*–177.0*	*–2.4*	*1.5*	*–177.4*	*1.313*		
Expected Pt/No [dB-Hz]	**33.4**			**33.9**	**1.783**	**32.9**	**30.4**
Sigma [dB]				1.3			
2*Sigma [dB]				2.7			
Expected Pt/No - 2*Sigma [dB-Hz]				**32.2**			

Table 5-6. Observed versus expected performance.

Observation Date	6/6/01	6/21/01
Expected Pt/No, Nominal [dB-Hz]	**33.4**	**30.4**
Expected Pt/No, Avg -2*Sigma [dB-Hz]	**31.2**	**28.2**
Observed S+N [dB]		5.0
Observed N [dB]		0.0
Observed (S+N)/N [dB]		5.0
Observed S/N [dB]		3.3
Search Bandwidth [Hz]		125.0
Observed Pt/N [dB-Hz]	**26.8**	**24.3**
Observed-Nominal Expected Pt/No [dB]	**–6.6**	**–6.1**
Observed-Avg Expected Pt/No [dB] -2*Sigma	**–4.4**	**–3.9**

A post-test anomaly investigation team found no provable cause (smoking gun) for the 6-dB deficiency in the Odyssey-to-Stanford link. The cause is possibly a combination of several factors, the most likely of which are

- Accuracy of the measurement;
- Accuracy of the antenna pattern measurement on the mock-up and its fidelity with respect to the spacecraft;
- UHF antenna mismatch loss.[48]

While outright transceiver failure is considered unlikely (mainly because the RF power detected by the transceiver itself was close to nominal), a failure during acceptance test of the MER transceiver transmit-band filter at the output of the power amplifier might be related. In late 2002, the connection with the in-flight test anomaly is still being investigated.

Further tests to improve the understanding of the performance are planned during September 2003 (which is during MER's cruise to Mars), when Mars and Earth range will be at the next minimum.

[48] Ground testing after launch found that mismatch losses between the Odyssey antenna and the rest of the subsystem might have contributed to up to 1 dB of loss.

Section 6

Lessons Learned

6.1 X-Band Development

These observations come from the Odyssey pre-launch design, development, and test phases and are offered by one of the authors, Andre Makovsky.

- The teamwork between JPL and LMA was excellent. The frequent technical interchange led to better understanding and greater appreciation for the capabilities of both teams. That respect in turn led to yet more open interchange. Therefore, we can say that this openness and the resulting cooperation were extremely productive: difficult technical problems were recognized and resolved more quickly.
- Technical supervision and interaction with a subcontractor should occur from the beginning; contracts are not "fire and forget." In the example of EMS (the SSPA subcontractor), much re-work and technical supervision (from LMA and JPL) was necessary late in the development phase. In a severely cost-constrained environment, one may try to cut costs by reducing this technical interaction but then may end up having to spend more time, money, and people to re-do it.
- Generating high-quality telecom performance predictions (using TFP) was made possible by three factors:
  - Characterizing the MGA gain pattern carefully in two dimensions, with solar panel mock-ups. The MGA gain varies significantly with roll orientation (7–10 dB fades) beyond 40 degrees off-point.
  - The LMA STL (Spacecraft Test Laboratory) generated high-fidelity spacecraft attitude predicts for critical spacecraft maneuvers (such as MOI).
  - High-accuracy telecom performance predicts were generated by TFP (Telecom Forecaster and Predictor), a software tool developed at JPL.
- Because Odyssey had a southerly declination shortly after launch, it required two different tracking stations in the Southern hemisphere. One was the DSN complex at Canberra, the other was a non-DSN site in Santiago, Chile. There again, frequent technical interchanges (early enough in the planning process not to require massive commitment of resources) and several pre-launch tests ensured a very successful delivery of telemetry and Doppler data to both JPL (Pasadena) and LMA (Denver) from Santiago (Chile).

6.2 UHF Development

The need for thorough subsystem testing before delivering separate components to assembly, test, and launch operations (ATLO) became apparent.

- Although the UHF transceiver and diplexer had been tested separately and met their specifications, they did not function as a subsystem; an impedance mismatch due to wrong cable lengths made the diplexer not see the impedance to which it was designed, hence it didn't isolate as expected. It was necessary to optimize the length of the cables connecting the diplexer and transceiver to match the impedances of the entire UHF system. The UHF subsystem had to be removed from the orbiter and shipped to Cincinnati Electronics (CE) for the re-work. (CE was not originally contracted by LMA to produce the UHF system, only the transceiver.)
- Once that impedance matching was completed at CE, carrier acquisition tests with the transmitter operating showed that the receiver was not acquiring over the specified search bandwidth and signal level. We eventually isolated the cause to a transmitter harmonic that mixed with the image frequency in the receiver and caused the PLL to false lock; only a strong enough signal would pull it out of such a false lock. It happened only at some temperatures. We fixed that problem by inserting a filter to attenuate the offending transmitted spur.
- C&DH's emissions at UHF exceeded limits required for the UHF receiver early in the ATLO flow. This leakage had to be isolated and remedied, and the consequence was a delay in ATLO testing. It was apparent that the UHF's requirements were not well understood by the other subsystems.

The physical placement of the UHF antenna on the spacecraft needs to be settled early because interaction of nearby objects with the antenna's RF field can significantly affect the resulting antenna pattern. Placement is determined by the required fields of view of the science instruments, solar array, and antenna. Assessment of the multipath caused by nearby structures requires both modeling with better software tools than were available and testing with a higher fidelity mock-up of the spacecraft and solar array.

References

[1] *Mars Odyssey Baseline Reference Mission*, Rev. B, MSP01-99-0195, JPL D-20592 (internal document), LMA, Denver, March 30, 2001.

[2] Robert A. Mase, *Mars Odyssey Navigation Plan and Trajectories Characteristics*, PD 722-202, JPL D-16001 (internal document), July 1999.

[3] *Mars Surveyor Program '01 Orbiter System Requirements*, Rev. G, MSP01-97-0011, JPL D-16356 (internal document), LMA, Denver, April 2001.

[4] Guy Beutelschies, *Mars Surveyor 2001 Project Flight System Requirements and Targets*, PD 722-401, JPL D-16181 (internal document), Rev. 3, November 1999.

[5] *CCSDS Blue Book,* CCSDS 201.0-B-1, Telecommand, Part 1 Channel Service, http://www.ccsds.org/documents/pdf/CCSDS-201.0-B-3.pdf (current June 2000), *CCSDS Blue Book*, CCSDS 101.0-B-3, Telemetry Channel Coding, http://www.ccsds.org/documents/pdf/CCSDS-101.0-B-5.pdf (current June 2001).

[6] *LMA Environmental Requirements*, MSP01-98-0029, JPL D-16351 (internal document), September 28, 1998.

[7] *DSMS Telecommunications Link Design Handbook*, 810-005, Rev. E, Jet Propulsion Laboratory, Pasadena, California, January 2001. http://eis.jpl.nasa.gov/deepspace/dsndocs/810-005/

[8] *Mars 2001 Odyssey Telecommunications Operations Handbook*, PD 622-802, JPL D-19010 (JPL internal document), Jet Propulsion Laboratory, Pasadena, California, March 27, 2001.

[9] *SDST Functional Spec*, Motorola 12-P43596N (internal Odyssey project contract document), October 15, 1999.

[10] *UHF Transceiver Theory of Operation/User's Manual*, Rev. 1.2, CE document 648855 (internal Odyssey project contract document), CMC Electronics Cincinnati, May 4, 2001.

[11] *Telecom Forecaster Predictor/Unified Telecom Predictor (TFP/UTP) User's Guide*, DSMS 887-000036, JPL D-21499 (internal document), V2.1, Jet Propulsion Laboratory, Pasadena, California, February 21, 2002.

[12] Joseph Yuen, editor, *Deep Space Telecommunications Systems Engineering*, New York: Plenum Press, 1983.

[13] Stan Butman, *June 2001 UHF Anomaly Test Report*, JPL D-22615 (JPL internal document), Jet Propulsion Laboratory, Pasadena, California, June 2001.

[14] *Santiago Satellite Tracking Station*, CEE/TOP/GEN/UG, Issue 3, Rev. 1, Centro de Estudios Espaciales Universidad de Chile, May 1998. http://www.unispace3.co.cl/cee.html

Abbreviations and Acronyms

ACK	acknowledgment
ACS	attitude control subsystem
A/D	analog-to-Digital (converter)
AGC	automatic gain control (value of P_{carrier})
AMMOS	Advanced Multi-Mission Operations System
AOS	acquisition of signal
ASIC	application-specific integrated circuit
ASM	attached synchronization marker
ATLO	assembly, test and launch operations
ARQ	automatic repeat request
AU	astronomical unit
az	azimuth
BER	bit-error rate
BPF	bandpass filter
BPSK	binary phase-shift keying
BVR	Block V Receiver
BW	bandwidth
BWG	beam-waveguide (antenna)
CBE	current best estimates
CCSDS	Consultative Committee for Space Data Systems
C&DH	command and data handling subsystem
CDS	command and data subsystem
CE	CMC Electronics Cincinnati (also known as Cincinnati Electronics)
CK	camera kernel
CNR	carrier signal-to-noise ratio
CRC	cyclic redundancy code
CSOC	Coordinated Space Operations Contract
CTS	coaxial transfer switch
CW	continuous wave
dB	decibel
dBi	dB above isotropic
DCT	design control table
DOFF	degrees off boresight
DOR	differential one-way ranging
DS1	Deep Space 1
DSN	Deep Space Network
DSS	Deep Space Station
DTE	direct-to-earth (link)
E_b	energy per bit
EIRP	effective isotropic radiated power
el	elevation

EMC	electromagnetic compatibility
EME	Earth mean equatorial
EMS	Electromagnetic Sciences (manufacturer of the SSPA)
ERD	environmental requirements document
ERT	Earth received time
ETR	eastern test range
ESA	European Space Agency
FEC	forward error correction
FER	frame-error rate
FSK	frequency shift keying
FSS	frame synchronizer
G2	generator polynomial for the second convolutional symbol
GDS	ground data system
GRS	Gamma Ray Spectrometer
G/T	ratio of antenna gain to system noise temperature
GUI	graphical user interface
HCD	hardware command decoder
HEF	high efficiency (antenna)
HGA	high gain antenna
ICD	Interface Control Document
ID	identification number
IND	Interplanetary Network Directorate
IR	infrared
JPL	Jet Propulsion Laboratory
Ka-band	deep-space frequency band: 31.9 to 32.1 GHz (down)
LCP	left circular polarization
LGA	low-gain antenna
LMA	Lockheed Martin Astronautics
LMST	local mean solar time
LNA	low-noise amplifier
LOS	loss of signal
LTST	local true solar time
MARIE	Martian Radiation Experiment
MCD	maximum-likelihood convolutional decoder
MCO	Mars Climate Orbiter (one of the Mars'98 missions)
MEL	master equipment list
MER	Mars Exploration Rover (scheduled to launch end of May 2003)
MGA	medium gain antenna
mod	modulation
MOI	Mars orbit insertion
MPL	Mars Polar Lander
MSP	Mars Surveyor Program (of which Odyssey is one mission)
MSP'01	the early name for the Odyssey mission, which launched in 2001
NAIF	Navigation and Ancillary Information Facility
NASA	National Aeronautics and Space Administration
NAV	navigation

NCO	numerically controlled oscillator
NF	notch filter
N_o	noise spectral density
NOP	network operations plan
NRZ	non-return-to-zero
NRZ-L	NRZ-level
NSP	Network Simplification Project
ODPD	orbiter design performance document
OTM	orbiter trim maneuver
OWLT	one-way light time
P_c	received carrier power (also written as $P_{carrier}$)
P_d	received data power
P_t	received total power
PCM	Pulse code modulation
PLL	phase-locked loop
PM	phase modulation
POR	power-on reset
Proximity-1	a CCSDS protocol for SE–Orbiter communications
PSK	phase shift keying
RCP	right circular polarization
Rcv	receive
RF	radio frequency
RS	Reed–Solomon
S1	RF switch 1, a WTS
S2	RF switch 2, a CTS
S/C	spacecraft
S-band	deep-space frequency band: 2.1 GHz (up) and 2.3 GHz (down)
SDST	small deep-space transponder
SE	surface element
SN	serial number
SNR	signal-to-noise ratio
SNT	system noise temperature
sol	a Mars day (~1.02749 Earth days; ~24.6 hr; 24 h 39 m, 36 s)
SPE	Sun–probe (orbiter)–Earth (angle)
SPK	spacecraft kernel
SRA	sequential ranging assembly
SRI	Stanford Research Institute
SSPA	solid-state power amplifier
SSO	sufficiently stable oscillator
STL	Spacecraft Test Laboratory (at LMA)
TCM	trajectory correction maneuver
telecom	telecommunications
TFP	Telecom Forecaster Predictor
THEMIS	Thermal Emission Imaging System
Tlm	telemetry
TMI	telemetry modulation index

tx	transmit
UHF	ultra-high frequency (approximately 401 MHz–437 MHz for Odyssey)
UHF1	Proximity-1, a CCSDS protocol for SE-Orbiter communications
USO	ultra-stable oscillator
UTC	universal time coordinated
VCO	voltage controlled oscillator
VSWR	voltage standing wave ratio
WTS	waveguide transfer switch
X-band	deep-space frequency band: 7.1 GHz (up) and 8.4 GHz (down)
XTR	transmit–receive