2001 MARS ODYSSEY MISSION SUMMARY

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Abstract. The 2001 Mars Odyssey spacecraft, now in orbit at Mars, will observe the Martian surface at infrared and visible wavelengths to determine surface mineralogy and morphology, acquire global gamma ray and neutron observations for a full Martian year, and study the Mars radiation environment from orbit. The science objectives of this mission are to: (1) globally map the elemental composition of the surface, (2) determine the abundance of hydrogen in the shallow subsurface, (3) acquire high spatial and spectral resolution images of the surface mineralogy, (4) provide information on the morphology of the surface, and (5) characterize the Martian near-space radiation environment as related to radiation-induced risk to human explorers.

To accomplish these objectives, the 2001 Mars Odyssey science payload includes a Gamma Ray Spectrometer (GRS), a multi-spectral Thermal Emission Imaging System (THEMIS), and a radiation detector, the Martian Radiation Environment Experiment (MARIE). THEMIS and MARIE are mounted on the spacecraft with THEMIS pointed at nadir. GRS is a suite of three instruments: a Gamma Subsystem (GSS), a Neutron Spectrometer (NS) and a High-Energy Neutron Detector (HEND). The HEND and NS instruments are mounted on the spacecraft body while the GSS is on a 6-m boom.

Some science data were collected during the cruise and aerobraking phases of the mission before the prime mission started. THEMIS acquired infrared and visible images of the Earth-Moon system and of the southern hemisphere of Mars. MARIE monitored the radiation environment during cruise. The GRS collected calibration data during cruise and aerobraking. Early GRS observations in Mars orbit indicated a hydrogen-rich layer in the upper meter of the subsurface in the Southern Hemisphere. Also, atmospheric densities, scale heights, temperatures, and pressures were observed by spacecraft accelerometers during aerobraking as the spacecraft skimmed the upper portions of the Martian atmosphere. This provided the first in-situ evidence of winter polar warming in the Mars upper atmosphere.

The prime mission for 2001 Mars Odyssey began in February 2002 and will continue until August 2004. During this prime mission, the 2001 Mars Odyssey spacecraft will also provide radio relays for the National Aeronautics and Space Administration (NASA) and European landers in early 2004. Science data from 2001 Mars Odyssey instruments will be provided to the science community via NASA's Planetary Data System (PDS). The first PDS release of Odyssey data was in October 2002; subsequent releases occur every 3 months.

1. Introduction

This paper provides an overview of the 2001 Mars Odyssey mission ('Odyssey'). This introduction provides the scientific context and objectives of the mission. Each of the science instruments is then described, and preliminary science results from the cruise and aerobraking phases are presented. Also included are a summary of mission operations, plans for science data archiving, and details on the spacecraft itself (Appendix A). This paper is intended to document the Odyssey mission prior to the main science data collection phase, which is now underway. Companion articles in this volume describe the science instruments in detail (Badhwar, 2004; Boynton *et al.*, 2004; Christensen *et al.*, 2004).

Odyssey is part of a long-term program of Mars exploration conducted by the National Aeronautics and Space Administration (NASA). The scientific objectives of this program are to: (1) search for evidence of past or present life, (2) understand the climate and volatile history of Mars, (3) determine the evolution of the surface and interior of Mars, and (4) prepare for human exploration (McCleese *et al.*, 2001). The Mars Exploration Program is designed to be responsive to scientific discoveries. The guiding objective is to understand whether Mars was, is, or can be, a habitable world. To find out, we need to characterize the planet and understand how geologic, climatic, and other processes have worked to shape Mars and its environment over time.

Among our discoveries about Mars, the possible presence of liquid water, either in the ancient past or preserved in the subsurface today, stands out above all others. Water is critical to life, has likely altered the surface of Mars in the past, and is essential for future exploration. Thus, the common threads of Mars exploration objectives are to understand water on Mars, to identify past and present sources and sinks, and to understand the interaction and exchange between subsurface, surface, and atmospheric reservoirs, as well as the evolution of the volatile composition over time. To accomplish this, lander and/or orbiter spacecraft are launched at each Mars launch opportunity, approximately every 26 months. In 1997, NASA launched the Mars Global Surveyor (MGS), which together with the launch of the Discovery Program's Mars Pathfinder Lander, began a new era of Mars exploration. In the 1998–1999 launch opportunity, NASA launched the Mars Climate Orbiter (which failed to reach Mars orbit) and the Mars Polar Lander (which failed during its landing sequence). The 2001 Mars mission originally consisted of an orbiter and lander; both scheduled for launch in the spring of 2001. However, NASA decided to cancel the Mars 2001 lander and proceed only with the orbiter. This 2001 element of the Mars Exploration Program is focused on mapping the elemental and mineralogical composition of the surface, and monitoring the radiation environment (Saunders 2000, 2001a, 2001b; Saunders and Meyer, 2001; Saunders *et al.*, 1999; Jakosky *et al.*, 2001).

The 2001 Mars Odyssey mission contributes directly to the Mars Exploration Program goals by a direct search for water in the near surface of Mars at present and a search for evidence of past water in the surface mineralogy and morphology. In particular, 2001 Mars Odyssey carries instruments that will observe the Martian surface at infrared and visible wavelengths to determine surface mineralogy and morphology, provide global gamma ray and neutron observations for a full Martian year, and study the Mars radiation environment from orbit. The science objectives of the 2001 Mars Odyssey mission are to:

(1) globally map the elemental composition of the surface.
(2) determine the abundance of hydrogen in the shallow subsurface.
(3) acquire high spatial and spectral resolution images of the surface mineralogy.
(4) provide information on the morphology of the surface.
(5) characterize the Martian near-space radiation environment as related to radiation-induced risk to human explorers.

To accomplish these objectives, the science payload on 2001 Mars Odyssey consists of a gamma ray spectrometer, a multi-spectral thermal and visible imager, and a radiation detector as described in Table I. 2001 Mars Odyssey fills important niches in Mars exploration as a follow-on to the Mars Global Surveyor, and as a predecessor to the 2003 Mars Exploration Rovers (MERs), the 2003 European Mars Express orbiter, and the 2005 Mars Reconnaissance Orbiter (MRO). The Gamma Ray Spectrometer is a reflight of the instrument lost on Mars Observer. The Thermal Emission Imaging System (THEMIS) expands upon the results from MGS's Thermal Emission Spectrometer (TES) by examining the Martian surface in a similar spectral region, but with a resolution of 100 meters (30 times better than TES). THEMIS will also collect visible images at 18-meter resolution, bridging the gap between the few meter resolution of MGS's Mars Orbiter Camera (MOC) and the resolutions of many 10's to 100's of meters of the Viking Orbiter images. MARIE provides the first measurements of radiation in the Martian environment as a precursor to possible future human exploration of Mars.

Coordinated planning and implementation of science observations is provided by the Odyssey Project Science Group (PSG) that is comprised of the Principal Investigators (PIs), Instrument Team Leaders, and Interdisciplinary Scientists (IDS) (Table II). The PSG, which is chaired by the JPL Project Scientist and the NASA Program Scientist, establishes science policy for the project and adjudicates conflicts between instruments. Additional scientists (Odyssey Participating Scientists)

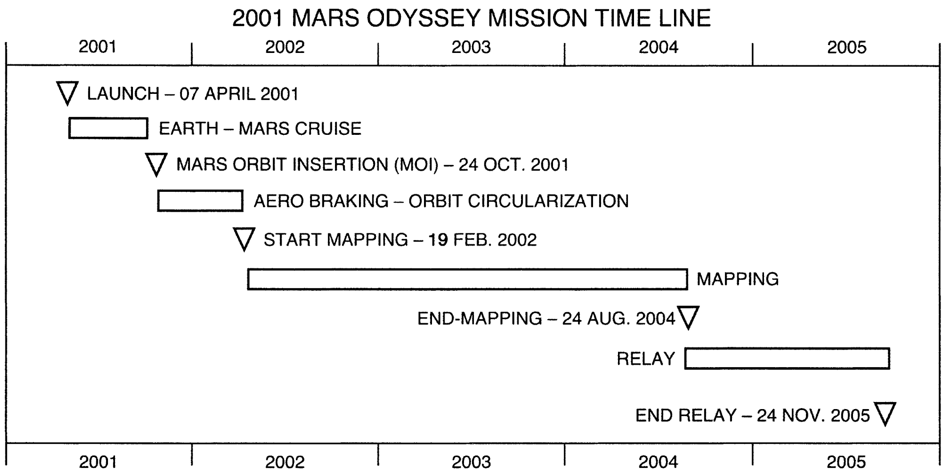

Figure 1. 2001 Mars Odyssey Mission Timeline. The primary mapping phase will be from February 2002 until August 2004, followed by a telecommunications relay phase until November 2005. Science observations in the relay phases beyond the mapping phase are currently undefined and depend on a number of factors, including spacecraft and instrument health as well as operational resources.

were competitively selected early in 2002 to assist with science operations and to augment the scientific expertise of the science teams. Data from the instruments will be distributed to the science community under the auspices of the IDS for data and archiving as well as the Odyssey Data Products Working Group (DPWG), a subgroup of the PSG. The DPWG has developed an archive plan that is compliant with Planetary Data System (PDS) standards and will oversee generation, validation, and delivery of integrated archives to the PDS. In addition, the 2001 Mars Odyssey mission will provide regular public release of images and other science and technology data via the Internet for public information purposes (see http://mars.jpl.nasa.gov/odyssey/, http://themis.asu.edu/, http://grs.lpl.arizona.edu/, http://marie.jsc.nasa.gov/, http://wwwpds.wustl.edu/missions/odyssey/; Klug and Christensen, 2001; Klug *et al.*, 2002).

The 2001 Mars Odyssey mission timeline is shown in Figure 1. Odyssey's prime mission extends for 917 days from the start of mapping in February 2002 (following orbit circularization via aerobraking) to August 2004. During this prime science mission, Odyssey will also serve as a communications relay for U.S. and international landers in early 2004. After the prime science mission, Odyssey will continue to serve as a telecommunications asset for an additional 457 days. Thus, the total mission duration will be two Mars years (1,374 days). As a goal, an additional Mars year of relay operations is planned. Spacecraft resources may be available for extended mission science observations during the later relay phases of the mission. Observations beyond the prime mission could provide data on interannual phenomena, as well as global high resolution visible imaging and improved elemental concentration maps.

TABLE I
2001 Mars Odyssey Instruments

Instrument	Description	Principal Investigator
THEMIS (Thermal Emission Imaging System)	Will determine the mineralogy of the Martian surface using multispectral, thermal-infrared mages that have 9 spectral bands between 6.5 and 14.5 μm. Will also acquire visible-light images with 18-m pixel resolution in either monochrome or color.	Philip Christensen, Arizona State University
GRS (Gamma Ray Spectrometer)	Will perform full-planet mapping of elemental abundance, at a spatial resolution of about 600 km, by remote gamma ray spectroscopy, and full-planet mapping of the hydrogen (with depth of water inferred) and CO_2 abundances by combined gamma ray and neutron spectroscopy.	William Boynton, University of Arizona (GRS Team Leader) William Feldman, Los Alamos National Laboratory (Team Member for Neutron Spectrometer) Igor Mitrofanov Institute of Space Research (PI, High Energy Neutron Detector)
MARIE (Martian Radiation Environment Experiment)	Will measure the accumulated absorbed dose and tissue dose rate as a function of time, determine the radiation quality factor, determine the energy deposition spectrum from 0.1 keV/μm to 40 keV/μm, and separate the contribution of protons and of high charge and energy (HZE) particles to these quantities.	Gautam Badhwar, Johnson Space Center (PI, deceased) Cary Zeitlin, PI National Space Biomedical Research Institute

2. Odyssey Science Instruments

The 2001 Mars Odyssey science payload (as previously noted) consists of a Thermal Emission Imaging System (THEMIS), a Gamma Ray Spectrometer instrument suite (GRS), and a Martian Radiation Environment Experiment (MARIE). The GRS instrument suite includes the Gamma Subsystem (GSS), the Neutron Spectrometer (NS), and the High-Energy Neutron Detector (HEND). The locations of these instruments on the spacecraft are shown in Figure 2. Note that the GRS

TABLE II
2001 Mars Odyssey Project Science Group (PSG) Members

Raymond Arvidson (IDS for Data and Archiving) Washington University St. Louis, Missouri
Gautam Badhwar (MARIE PI, deceased) NASA Johnson Space Center Houston, Texas
William Boynton (GRS Team Leader) University of Arizona Tucson, Arizona
Philip Christensen (THEMIS PI) Arizona State University Tempe, Arizona
Cary Zeitlin (MARIE PI) National Space Biomedical Research Institute Houston, Texas
William Feldman (GRS Team Member for NS) Los Alamos National Laboratory Los Alamos, New Mexico
Bruce Jakosky (Interdisciplinary Scientist) University of Colorado, Boulder Boulder, Colorado
Michael Meyer (Program Scientist) NASA Headquarters Washington, DC
Igor Mitrofanov (HEND PI) Institute for Space Research (IKI) Moscow, RUSSIA
Jeffrey Plaut (Project Scientist after October 2002) Jet Propulsion Laboratory Pasadena, California
R. Stephen Saunders (Project Scientist until October 2002) Jet Propulsion Laboratory Pasadena, California

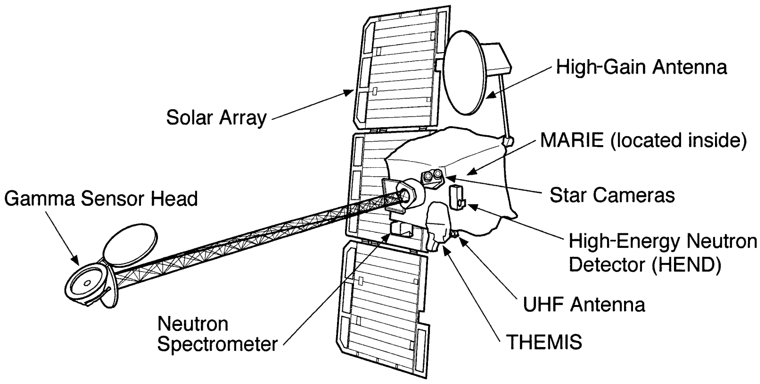

Figure 2. 2001 Mars Odyssey Spacecraft in Mapping Configuration. The Odyssey spacecraft as described in Appendix A consists of a central spacecraft bus with a 6-m boom for the gamma sensor head, and articulated solar arrays and high-gain antenna. Electrical power is provided by solar arrays. Communication to and from Earth is provided by low- and medium-gain antennas mounted on the spacecraft bus and an articulated high-gain antenna pointed toward Earth. Science instruments onboard the Odyssey spacecraft include a Thermal Emission Imaging System (THEMIS), a Gamma Ray Spectrometer (GRS) instrument suite, and a Martian Radiation Environment Experiment (MARIE). The GRS instrument suite includes the Gamma Subsystem (GSS), the Neutron Spectrometer (NS), and the High-Energy Neutron Detector (HEND). All of these instruments, except the gamma sensor head, are located on the spacecraft bus, with THEMIS pointed at nadir.

gamma sensor head is located on a 6-m boom, which is perpendicular to the orbit plane. All other instruments are located on the spacecraft bus, with THEMIS pointed at nadir. MARIE has a 68-degree field of view, which is pointed in the anti-velocity direction. Its field-of-view does not include Mars. The NS and HEND observe neutrons in all directions. A detailed description of the 2001 Mars Odyssey spacecraft is given in Appendix A.

2.1. Thermal Emission Imaging System (THEMIS)

THEMIS addresses the 2001 Mars Odyssey objectives of acquiring high spatial and spectral resolution images of surface mineralogy, and providing information on the morphology of the Martian surface. These mineralogical and morphological measurements will help to determine a geologic record of past liquid environments and will help map future potential Mars landing sites. Specific THEMIS science objectives are to:

(1) determine the mineralogy and petrology of localized deposits associated with hydrothermal or sub-aqueous environments, and to identify sample return sites likely to represent these environments.

(2) provide a direct link to the global hyper-spectral mineral mapping from the Mars Global Surveyor (MGS) Thermal Emission Spectrometer by utilizing the same infrared spectral region at high (100 m) spatial resolution.

TABLE III
Thermal Emission Imaging System (THEMIS) Science Team Members

Team Member	Title	Organization
Philip Christensen	Principal Investigator	Arizona State University
Bruce Jakosky	Co-Investigator	University of Colorado, Boulder
Hugh Kieffer	Co-Investigator	U.S. Geological Survey, Flagstaff
Michael Malin	Co-Investigator	Malin Space Science Systems
Harry McSween	Co-Investigator	University of Tennessee
Kenneth Nealson	Co-Investigator	University of Southern California
Anton Ivanov	Participating Scientist	Jet Propulsion Laboratory
Melissa Lane	Participating Scientist	Planetary Science Institute
Alfred McEwen	Participating Scientist	University of Arizona
Mark Richardson	Participating Scientist	California Institute of Technology
James Bell	Participating Scientist	Cornell University
Greg Mehall	THEMIS Mission Manager	Arizona State University
Steven Silverman	Project Engineer	Santa Barbara Remote Sensing

(3) study small-scale geologic processes and landing site characteristics using morphologic and thermo-physical properties.
(4) search for pre-dawn thermal anomalies associated with active subsurface hydrothermal systems.

The THEMIS Principal Investigator is Philip Christensen of Arizona State University. THEMIS team members are given in Table III. Further description of THEMIS is given later in this issue (Christensen *et al.*, 2003).

To accomplish the THEMIS objectives, this instrument will determine surface mineralogy using multi-spectral thermal-infrared images in 9 spectral bands from 6.5–14.5 μm with 100-m pixel resolution. THEMIS will also acquire visible images at 18 m/pixel in up to 5 spectral bands for morphology studies and landing site selection. The THEMIS thermal-infrared spectral region contains the fundamental vibrational absorption bands that provide the most diagnostic information on mineral composition, as all geologic materials, including carbonates, hydrothermal silica, sulfates, phosphates, hydroxides, silicates, and oxides have strong absorptions in the 6.5–14.5 μm region. Thus, silica and carbonates, which are key diagnostic minerals in thermal spring deposits, can be readily identified using THEMIS thermal-infrared spectra. Remote sensing studies of terrestrial surfaces, together with laboratory measurements, have demonstrated that 9 spectral bands are sufficient to detect minerals at abundances of 5–10%. The use of long wavelength infrared data has additional advantages over shorter-wavelength visible and near-infrared data because it can penetrate further through atmospheric dust

TABLE IV
Thermal Emission Imaging System (THEMIS) Mapping Observations

Mineral mapping (daytime IR) during clearest periods and warmest time of day	~50% of total mission data
Nighttime temperature mapping throughout the year	~15% of total mission data
Visible imaging during late afternoon periods when shadows are better and IR data of lower quality	~30% of total mission data
Color imaging for targets of opportunity	~5% of total mission data

and surface coatings with absorption bands that are linearly proportional to mineral abundance, even at very fine grain sizes.

THEMIS was designed as the follow-on to the Mars Global Surveyor Thermal Emission Spectrometer (TES), which produced a hyper-spectral (286-band) mineral map of the entire planet. THEMIS covers much of the same wavelength region as TES. Furthermore, the THEMIS filters were optimized utilizing knowledge of Martian surface minerals determined from TES data, and TES global maps will allow targeting of areas with known concentrations of key minerals. THEMIS will achieve infrared signal-to-noise ratios of 33 to 100 for surface temperatures (235 –265 K) typical for Odyssey's late afternoon (about 3:00 to 6:00 p.m.) orbit. In addition, Odyssey's orbit is ideally suited to the search for pre-dawn temperature anomalies associated with active hydrothermal systems, if they exist. The visible imager will have a signal-to-noise ratio greater than 100 for Odyssey's late afternoon orbit. The THEMIS instrument weighs 10.7 kg, is 28 cm wide × 30 cm high × 31 cm long, and consumes an orbital average power of 5.1 W.

The THEMIS observation strategy given in Table IV shows that about half of the THEMIS data will be devoted to daytime, infrared mapping for minerals. The first few months of THEMIS operation, as shown in Table V, were devoted primarily to acquiring data for selection of MER landing sites and other targets of interest to the public and the scientific community.

2.2. Gamma Ray Spectrometer (GRS) Suite

The GRS instrument suite consists of three instruments: a Gamma Subsystem (GSS), a Neutron Spectrometer (NS), and a High-Energy Neutron Detector (HEND). These instruments address the 2001 Mars Odyssey objectives of globally mapping the elemental composition of the surface, and of determining the abundance of hydrogen in the shallow subsurface. Thus, this instrument suite plays a lead role in determining the elemental makeup of the Martian surface.

When exposed to cosmic rays, chemical elements in the Martian near-subsurface (in uppermost meter) emit gamma rays with distinct energy levels. By measuring gamma rays coming from the Martian surface, it is possible to calculate surface

TABLE V

Thermal Emission Imaging System (THEMIS) Early Observation Priorities

MER Landing Sites	Day/Night IR; VIS; whenever possible Meridiani Melas Isidis Eos Gusev Crater
Viking 1, 2, & Pathfinder Sites	Day/night IR; VIS; whenever possible
Valles Marineris layered deposits	Day/night IR; VIS; 6 observations
Southern hemisphere young gullies	Day/night IR; VIS; 6 observations
Putative shorelines	Day/night IR; VIS; 6 observations
Polar caps	Day/night IR; VIS; 6 observations
Geometric calibration sites	Day/night IR; VIS; 4/day
IR drift calibration sequences	Day/night IR; 3/day; Equatorial, polar, night
General interest	Outflow channels, southern hemisphere dunes, Arsia, Pavonis, Ascraeus, Olympus, Elysium Mons, polar dunes, Elysium flows, Day/night IR; VIS; 1/orbit

elements' distributions and abundances. In addition, measuring both gamma rays and neutrons provides a measurement of hydrogen abundance in the upper meter of subsurface, which in turn allows inferences about the presence of near-surface water.

The GRS objective is to determine the composition of Mars' surface by full-planet mapping of elemental abundance with an accuracy of 10% or better and a spatial resolution of about 600 km by remote gamma ray spectrometry, and full-planet mapping of the hydrogen abundance (with depth of water inferred) and seasonal CO_2 frost thickness. The GRS team leader is William Boynton of the University of Arizona. The GRS team shown in Table VI will operate this suite of instruments from the University of Arizona. Further description of the GRS instrument suite is given later in this issue (Boynton, *et al.* 2003).

The GRS will also address astrophysical problems such as gamma ray bursts, the extragalactic background and solar processes by measuring gamma ray and particle fluxes from non-Martian sources. For example, GRS data from extragalactic gamma ray bursts (GRBs) will be used with the data from Ulysses and near-Earth satellites (High Energy Transient Explorer-2, Wind, etc.). Interplanetary triangulation, a technique involving accurate timing of burst arrival times, allows the sky positions of the sources of GRBs to be determined with accuracy of several minutes of arc. GRS data can also provide insight into solar flares. The simultaneous measurement of gamma rays and high-energy neutrons from powerful solar flares at

TABLE VI
Gamma Ray Spectrometer (GRS) Team Members

Team Member	Title	Organization
William Boynton	Team Leader	University of Arizona
Igor Mitrofanov	HEND PI	Space Research Institute, Russia Academy of Sciences
William Feldman	Team Member for NS	Los Alamos National Laboratory (LANL)
James Arnold	Team Member	University of California, San Diego
Claude d'Uston	Team Member	CESR, Toulouse
Peter Englert	Team Member	University of Miami
Albert Metzger	Team Member	Jet Propulsion Laboratory
Robert Reedy	Team Member	LANL/University of New Mexico
Steven Squyres	Team Member	Cornell University
Jacob Trombka	Team Member	Goddard Space Flight Center
Heinrich Wänke	Team Member	Max-Planck-Institut für Chemie
Johannes Brückner	Team Member	Max-Planck-Institut für Chemie
Darrell Drake	Team Member	Techsource, Inc.
Larry Evans	Team Member	Computer Sciences Corporation
John Laros	Team Member	University of Arizona
Richard Starr	Team Member	Catholic University
Kevin Hurley	Participating Scientist	University of California, Berkeley
Thomas Prettyman	Participating Scientist	Los Alamos National Laboratory
G. Jeffrey Taylor	Participating Scientist	University of Hawaii, Manoa

Mars, combined with those from the vicinity of Earth, allows a stereoscopic image of the active region on the Sun. These stereoscopic observations of powerful flares will provide a three-dimensional model of the sources of hard-electromagnetic radiation and corpuscular emission in active regions on the Sun.

The GRS (as noted above) consists of several components. The gamma sensor head is separated from the rest of the spacecraft by a 6-m (20-ft) boom, which was extended after Odyssey entered its mapping orbit. This minimizes the interference from gamma rays coming from the spacecraft itself. An initial GRS calibration was performed during the first 100 days of mapping. Then the boom was deployed, and it will remain in this position for the rest of the mission. The NS and the HEND components of the GRS are mounted on the main spacecraft structure and will operate continuously throughout the mission. The entire GRS instrument suite weighs 30.2 kg and uses 32 W of power. The GSS measures 46.8 cm long, 53.4 cm tall, and 60.4 cm wide. The NS is 17.3 cm long, 14.4 cm tall, and 31.4 cm wide. The

HEND measures 30.3 cm long, 24.8 cm tall, and 24.2 cm wide. The instrument's central electronics box is 28.1 cm long, 24.3 cm tall, and 23.4 cm wide.

2.3. Gamma Subsystem (GSS)

The GSS will detect and count gamma rays emitted from the Martian surface. By associating the energy of gamma rays with known nuclear transitions and by measuring the number of gamma rays emitted from a given portion of the Martian surface, it is possible to determine surface elemental abundances and discern their spatial distribution. While the energy in these emissions determines which elements are present, the intensity of the spectrum reveals the elements' concentrations. These energies will be collected with 600-km resolution over time and will be used to build up a full-planet map of elemental abundances and their distributions. The GSS uses a high-purity germanium detector cooled below 100 K to measure gamma ray flux. GSS performance is a strong function of its temperature, which in turn constrains the spacecraft orbit beta angle (angle between orbit normal and direction to Sun) to insure that the GSS cooler is shaded from the Sun. Thus, the orbit beta angle must be less than $-57.5°$ ($-56°$ to shade the cooler and a pointing uncertainty of 1.5°) in order to acquire useful GSS data. Furthermore, annealing of the germanium detector on the GSS may be required to recover performance, with each annealing cycle taking approximately 10 days.

2.4. Neutron Spectrometer (NS)

The NS measures neutrons liberated from the near-subsurface of Mars by cosmic rays. Since Mars has a thin atmosphere and no global magnetic field, cosmic rays pass unhindered through the atmosphere and interact with the surface. Cosmic ray bombardment of nuclei of subsurface material down to about 3 m produces secondary neutrons. These neutrons in turn propagate through the subsurface and interact on their way out with subsurface nuclei. Fast neutrons produced by the cosmic rays may in turn be moderated by collisions with nuclei before they escape from the subsurface, resulting in neutrons with thermal or epithermal energies. The flux of secondary neutrons from the surface, as a function of energy, provides information primarily on the concentration of H and C in the uppermost meter of the surface material.

The NS sensor consists of a cubical block of borated plastic scintillator that is segmented into four equal volume prisms. In the mapping orbit, one of the prisms faces forward into the spacecraft velocity vector, one faces backward, one faces down toward Mars, and one faces upward. Neutrons coming directly from Mars will be separated from those coming from the spacecraft using a combination of velocity filtration (because the spacecraft in orbit about Mars travels faster than a thermal neutron) and shielding of one prism by the other three. Fast neutrons are separated from thermal and epithermal neutrons electronically. Details of the instrument and the Doppler filter technique for separating thermal and epithermal neutrons are described by Feldman *et al.*, 2001. The NS is provided and operated by the Los Alamos National Laboratory (LANL). William Feldman at LANL is the NS team leader within the GRS Team.

2.5. High-Energy Neutron Detector (HEND)

The HEND complements the NS as it measures the higher energy neutrons liberated from the Martian surface by cosmic rays. HEND consists of a set of five particle sensors and their electronics boards. The sensors include three proportional counters and a scintillation block with two scintillators. The proportional counters and an internal scintillator detect neutrons with different energies. With these sensors, HEND is able to measure neutrons over a broad energy range from 0.4 eV up to 10.0 MeV. HEND also helps calibration of the Gamma Subsystem. HEND is provided and operated by the laboratory of Space Gamma Ray Spectroscopy at the Russian Aviation and Space Agency's Institute for Space Research (IKI) in Moscow, Russia. Igor Mitrofanov is the Principal Investigator.

2.6. Martian Radiation Environment Experiment (MARIE)

MARIE addresses the 2001 Mars Odyssey objective of characterizing the Martian near-space radiation environment as related to radiation-induced risk to human explorers. As space radiation presents a serious hazard to crews of interplanetary missions, MARIE's goal is to measure radiation doses that would be experienced by future astronauts and determine possible effects of Martian radiation on human beings. Hazardous space radiation comes from two sources: energetic particles from the Sun and galactic cosmic rays from beyond our solar system. Both kinds of radiation can trigger cancer and damage the central nervous system. A spectrometer inside MARIE measures the total energy from these radiation sources; both in interplanetary cruise from Earth to Mars and in orbit at Mars. As the spacecraft orbits Mars, the spectrometer sweeps through the sky and measures the radiation field coming from different directions. Specifically, MARIE goals are to:

(1) characterize specific aspects of the Martian near-space radiation environment.
(2) characterize the surface radiation environment as related to radiation-induced risk to human exploration.
(3) determine and model effects of the atmosphere on radiation doses at the surface.

The Principal Investigator for the MARIE experiment originally selected by NASA was Gautam Badhwar, who unfortunately died just before Odyssey reached Mars (this issue, Cucinotta, 2003). The MARIE Principal Investigator is now Cary Zeitlin of the National Space Biomedical Research Institute, Baylor College of Medicine in Houston. The MARIE team members are shown in Table VII. Further description of MARIE is provided later in this issue (Badhwar, 2003).

The MARIE instrument was provided by NASA's Human Exploration and Development of Space (HEDS) Program in order to characterize the radiation envir-

TABLE VII
Martian Radiation Environment Experiment (MARIE) Team Members

Team Member	Title	Organization
Cary Zeitlin	Principal Investigator	National Space Biomedical Research Institute
Francis Cucinotta	Co-Investigator	Johnson Space Center
Kerry Lee	Co-Investigator	University of Houston
Timothy Cleghorn	Co-Investigator	Johnson Space Center
Ronald Turner	Participating Scientist	ANSER Corporation

onment at Mars. The instrument, with a square field of view 68 degrees on a side, is designed to continuously collect data during Odyssey's cruise from Earth to Mars and in Mars orbit. It can store large amounts of data for downlink whenever possible, and will operate throughout the entire science mission. The instrument weighs 3.3 kg and uses 7 W of power. It measures 29.4 cm long, 23.2 cm tall, and 10.8 cm wide.

3. Odyssey Operations: Launch, Interplanetary Cruise, Aerobraking, and Early Mapping

The 2001 Mars Odyssey spacecraft was launched from Cape Canaveral on April 7, 2001 at 11:02 a.m., EDT, during its first launch opportunity. One hour after launch, Odyssey's signals were received at the Deep Space Network (DSN) complex near Canberra, Australia. Odyssey's cruise from Earth to Mars was accomplished in 200 days, on a Type 1 trajectory taking less than 180° around the Sun. Further details of spacecraft activities from launch through cruise, arrival and aerobraking are given in Appendix B. Cruise navigation was done with two-way Doppler and ranging data as well as a series of delta differential one-way ranges (ΔDORs). These ΔDOR measurements established Odyssey's position in the plane-of-the-sky complementing line-of-sight ranging provided by the two-way Doppler and ranging data. There were four trajectory course maneuvers (TCMs); the first and second at 46 and 86 days after launch; the third and fourth at 37 and 13 days before arrival. The Odyssey spacecraft arrived at Mars on October 24, 2001 within 1 km of its aim point. The initial orbit period was 18.6 hours, well within the expected range of 15–24 hours. Then aerobraking was used to transition from this initial elliptical orbit to the desired near circular mapping orbit.

Aerobraking was conducted in three phases: walk-in, main phase, and walk-out. Walk-in, which was initiated 4 days after arrival and accomplished in eight orbits, lowered the periapsis altitude to 110 km. Then during the main phase, small

TABLE VIII
2001 Mars Odyssey Mapping Orbit Parameters

Epoch: (SCET – UTC)	12-SEP-2002 05:15:27
Index Altitude	392 km
Semi-Major Axis	3785 km
Inclination	93.2 deg
Eccentricity	0.0115
Orbit Period	1.964 hr
Longitude of Ascending Node	173.7 deg
Argument of Periapsis	268 deg
LTST of Descending Node (hh:mm:ss)	16:21:33
LMST of Descending Node (hh:mm:ss)	16:16:05
Solar Beta Angle	−59.0 deg

thruster firings at apoapsis kept the drag pass periapsis altitude to heights where atmospheric heating and drag on the spacecraft were within limits. The transition from aerobraking to a mapping orbit (the walk-out phase) was done with three maneuvers in mid-to-late January 2002. In total, aerobraking was done without incident during 330 orbits in 75 days.

At the end of aerobraking, the Odyssey spacecraft was in its near circular science-mapping orbit of 370 to 432 km, some 18 km above that of MGS. The science orbit as shown in Table VIII has an inclination of 93.1 degrees, which results in a nearly Sun-synchronous orbit. The orbit period is just under two hours. Successive ground tracks are separated in longitude by approximately 29.5 degrees and the entire ground track nearly repeats every 30 days. After achieving this science orbit, the final major spacecraft event before the start of mapping was the deployment of the High-Gain Antenna (HGA), which was successfully performed on February 4, 2002.

3.1. Start of Mapping and Expected Orbit Evolution

The science-mapping mission began on February 19, 2002, 118 days after arrival. THEMIS was turned on and began imaging. A day later, GRS was turned on. The GRS's gamma sensor head had accumulated radiation damage during cruise. This necessitated a 'warm anneal' process, where it was warmed up and allowed to cool back to its normal operating temperature. The GRS warm anneal was completed on March 22, 2002 and improved the instrument performance. Although the GRS bands are somewhat broader than at launch, they were within specification. The GRS boom deployment occurred in early June 2002. Another in-orbit GRS anneal was performed in early November 2002.

A major success story at the start of mapping was the recovery of the MARIE instrument. MARIE experienced an apparent loss of 'heartbeat' in August 2002, two months before arrival. At that time, attempts to revive MARIE were unsuccessful. Once the mapping orbit was achieved, more extensive troubleshooting of the MARIE instrument began. Memory dumps were performed to determine the last states of the instrument. After that, MARIE's 'heartbeat' was re-established on March 6, 2002, and MARIE started returning science data from Mars orbit. The instrument has continued to return science data since then, and its prognosis for a long life is good.

The science orbit design is optimized to provide a balance between THEMIS and GRS observations; MARIE investigations do not directly affect the orbit design. At the start of the mapping orbit, the local true solar time (LTST) of approximately 3:15 p.m. allows high-quality THEMIS observations, but the beta angle of −44 degrees affects GRS data quality. High quality THEMIS infrared data are only obtained at LTST earlier than 5:00 p.m. while high quality GRS data are only obtained for beta angles less than −57.5 degrees. The first THEMIS opportunity started at the beginning of mapping and will continue for about 300 days. The second THEMIS opportunity starts at about 550 days and continues until the end of the mapping phase. THEMIS and GRS observations may continue outside of their optimal solar geometry, as power and telecommunication constraints allow.

The time-history of LTST and beta angle are controlled by changing the spacecraft orbit nodal precession rate (the rate at which the orbit plane rotates in inertial space). Figure 3 shows the expected time history of LTST and beta angle for the mapping and relay phases of the orbiter mission. The figure also includes local mean solar time (LMST), Mars-to-Earth range, and Mars-centered solar longitude L_S. LMST is a fictitious solar time that assumes that Mars moves in a circular orbit about the Sun with a period equal to the actual elliptical Mars orbit. LMST is constant for a Sun-synchronous orbit; differences between LTST and LMST are due to Mars' orbital eccentricity.

The nodal precession rate is controlled by slight changes to orbit inclination. The inclination of the science orbit (see Table VIII) is biased slightly higher than that required for Sun-synchronous precession to cause the beta angle to decrease (go more negative) so that GRS observations can commence early in the science mission. During the first 670 days of the mapping phase, the LMST drifts at a constant rate from its initial value of 3:54 p.m. to 5:00 p.m. At that time a maneuver using 8 m/s of delta-V will lock LMST to 5 p.m.

The Mars-to-Earth range is the dominant factor in determining the return data rate. This range is near the maximum during the first THEMIS opportunity, but is near the minimum at the beginning of the second THEMIS opportunity. Thus, more THEMIS data will be transmitted to Earth during the second THEMIS opportunity. Quality GRS data acquisition commences 154 days into the mapping phase and continues until the end of the mapping phase. During this GRS observation period, which spans more than one Mars year, the maximum beta angle is −54.5 degrees. MARIE will operate throughout the entire mapping phase of 917 days.

4. Odyssey Science Observations in Interplanetary Cruise, Aerobraking, and Early Mapping

4.1. Science Observations During Interplanetary Cruise

Odyssey science instrument operations during interplanetary cruise provided an opportunity to operate and calibrate the instruments. THEMIS obtained an Earth-Moon image that was the first to show the Earth and Moon in a single frame at nearly their true separation (i.e., perpendicular to the Earth-Moon line). MARIE operated from the beginning of interplanetary cruise until mid August 2001, when MARIE failed to respond to commands. This anomaly terminated MARIE observations until after orbit insertion and aerobraking were completed. In the four months MARIE was operating, it met its cruise science goals and two large solar particle events were observed. The interplanetary radiation environment, as a function of time and distance from the Sun, was measured and agreed with models (Cucinotta *et al.*, 2002; Vuong *et al.*, 2002; Saganti *et al.*, 2003, this issue).

All three of the GRS instruments were operated and obtained useful data. The GSS was operated during cruise and obtained nearly 1000 hours of data. The spectra from these cruise GSS observations will be used to remove the spacecraft signature from the gamma ray spectra at Mars. The NS was also operated during cruise and performed as expected (Feldman *et al.*, 2001). This showed that the flux of fast neutrons generated by cosmic-ray interactions with spacecraft material is about 1/3 of that expected from Mars. The HEND was operated for a large fraction of the cruise phase and detected many cosmic, solar, and soft-gamma ray events. From May 5 through September 24, 2001, HEND detected 25 gamma ray bursts (GRBs), which were confirmed by other spacecraft observations. Also, HEND detected six powerful solar flares, which were also confirmed by other spacecraft. The most intense solar flare event took place September 24, 2001 in the last four hours of HEND operations during interplanetary cruise.

4.2. Science Observations During Aerobraking

Odyssey science instrument operations during aerobraking were multifaceted. The GRS acquired a large amount of data, while THEMIS was used sparingly, and MARIE remained turned off after the anomaly occurred late in interplanetary cruise. In addition, significant atmospheric observations using the spacecraft accelerometers were collected during aerobraking.

Spacecraft geometries during aerobraking were not compatible with THEMIS operation. A spacecraft slew would have been required, and data downlink capability was extremely limited. However, a THEMIS atmospheric monitoring test

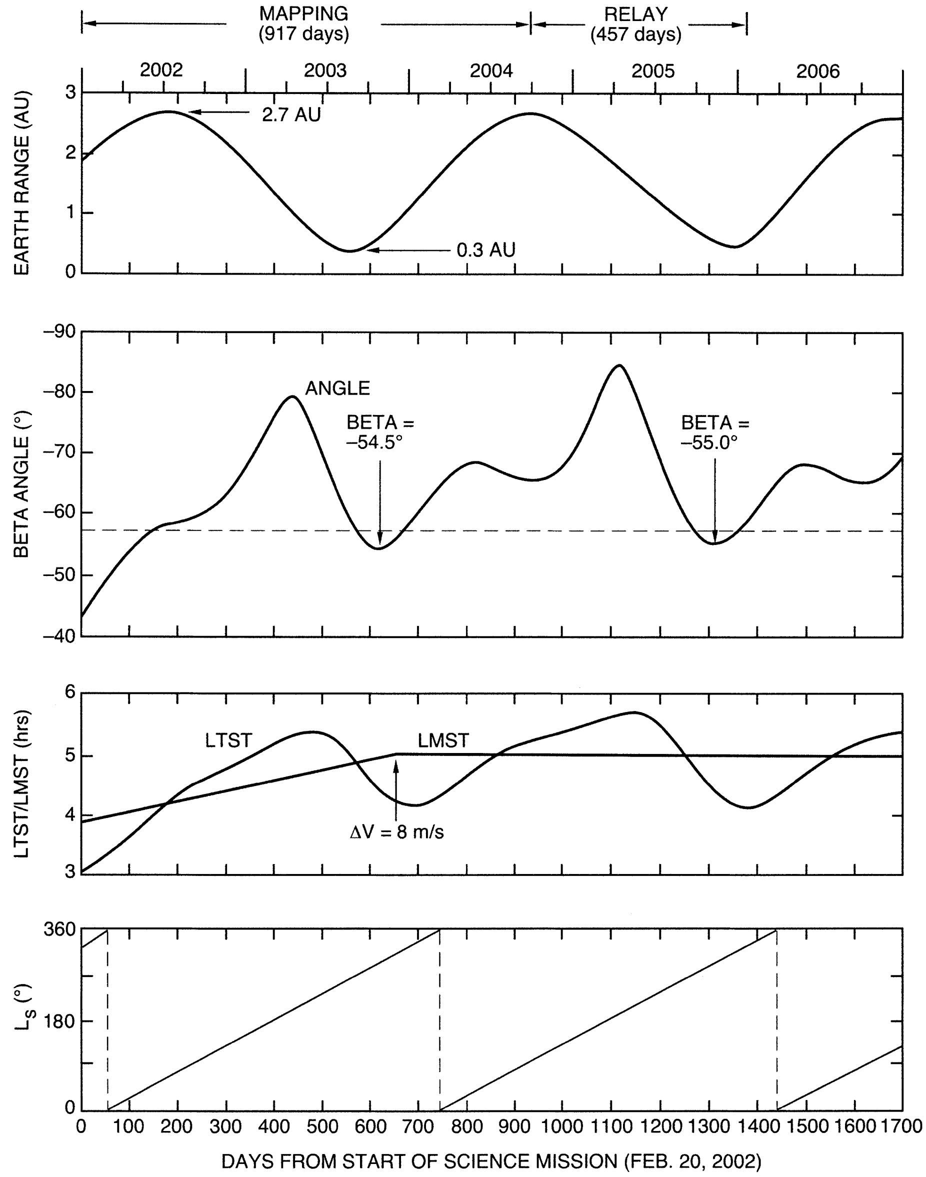

Figure 3. Expected Evolution of 2001 Mars Odyssey Mapping Orbit with Time. Earth-Mars range will vary between a minimum of 0.3 AU and 2.7 AU, with high data downlink volumes at the Earth-Mars range minima, and low data downlink volumes at the Earth-Mars range maxima. Beta angle varies between −44 degrees at the start of mapping with two minima near −80 degrees. The Gamma Subsystem (GSS) acquires quality data when the Beta angle is less than −57.5 degrees. Local mean solar time (LMST) varies from near 4 p.m. at the start of mapping and drifts up to 5 p.m. at about 670 days into the mapping mission. Local true solar time (LTST) varies from 3:00 p.m. to 5:45 p.m. over the mission. L_S is the Mars-centered solar longitude; 0° represents the start of northern spring. Thus, Odyssey's mapping phase started in late northern winter.

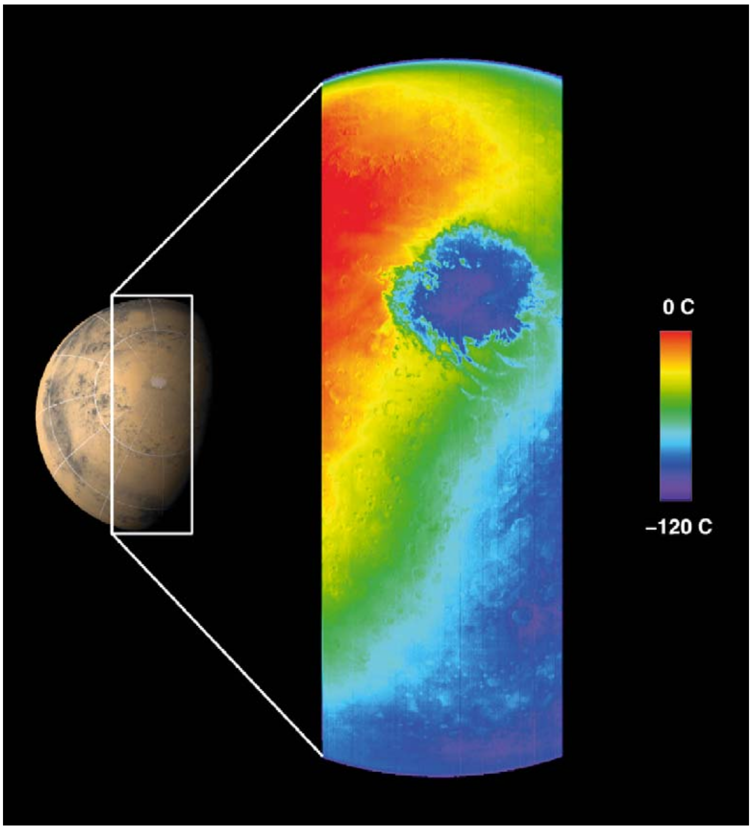

Figure 4. First THEMIS Infrared Image of Mars. This image of the south polar region was acquired during an atmospheric monitoring test just a few days after arrival using a single infrared filter centered at 10.1 μm. The prominent cold circular feature is the south polar carbon dioxide ice cap, about 300 km across. (JPL Public Release Photo PIA 03459)

was conducted following Mars orbit insertion (MOI) in order to demonstrate a capability for atmospheric monitoring in the event of an MGS TES failure during aerobraking (see Appendix B). The THEMIS atmospheric monitoring test on October 30, 2001 acquired THEMIS's first infrared image of Mars, at apoapsis (29,000 km) during the 9^{th} orbit at Mars (Figure 4). This image was obtained when the spacecraft was looking toward the South Pole of Mars. The season on Mars was mid-summer in the Southern Hemisphere. The extremely cold (blue), circular feature in the center of the image is the Martian south polar carbon dioxide ice cap at a temperature of $-120°$C. The polar cap was more than 300 km in diameter at that time. The image spans the morning terminator covering a length of 6,500 km from limb to limb, with a resolution of approximately 7.7 km/pixel (4.6 mi/pixel). The cold region in the lower right portion of the image is associated with Argyre Basin.

Two of Odyssey's GRS instruments, the HEND and the NS, were turned on immediately after arrival at Mars and operated during most of the aerobraking phase. HEND operated continuously during aerobraking until the periapsis altitude was lowered to 180 km. Then, the HEND high voltage was cycled off/on at 20 minutes before/after periapsis. This protected against the possibility of arcing across the high voltage components in the electronics. HEND was also operated during the transition from aerobraking to mapping after the periapsis was raised above 180 kilometers. The NS was operated continuously and all NS channels detected the expected neutron signal from Mars until the periapsis altitude dropped to 180 km, at which time the NS was turned off. The NS was turned on again and operated during the transition from aerobraking to mapping, providing additional calibration for this instrument. HEND and NS observations immediately after arrival at Mars yielded indications that these two instruments were seeing neutrons from the surface. During the first two periapses at orbital altitudes of 300 km above the Martian North Pole, HEND detected large fluxes of neutrons from the surface of Mars. At the same time, the NS saw large variations in neutrons, varying with latitude for about three orbits at Mars after orbital insertion on October 24–25, 2001 (Feldman *et al.*, 2002; Tokar *et al.*, 2002).

A significant finding by the NS and HEND after aerobraking was the discovery that the flux of epithermal neutrons coming from the region of Mars poleward of 60° south latitude is depressed by at least a factor of 2 from that coming from the more equatorial latitudes. These results, shown in Figure 5, are consistent with near-surface polar terrain being rich in hydrogen within 30° of the pole (Feldman, 2002a). This new result for Mars can be placed in context by comparing it with the lunar epithermal flux measured by the NS on the Lunar Prospector spacecraft. Whereas the entire epithermal neutron flux from the Moon varies by only 15%, that measured along a single orbital track of Mars Odyssey varies by more than a factor of 2.

Another significant finding was provided by Odyssey's accelerometers, which measured atmospheric densities, scale heights, temperatures, and pressures over time as the spacecraft skimmed the upper portions of the Martian atmosphere during aerobraking. This provided the first in-situ evidence of winter polar warming in the Mars upper atmosphere (Keating *et al.*, 2002 a,b). This warming may be due to a cross-equatorial meridional flow in the thermosphere from the summer hemisphere, which subsides in the winter polar region, bringing strong adiabatic heating. These data also showed winter polar temperatures rising with decreasing altitude, which agrees with some recent Mars atmospheric models. Also, temperatures at altitudes of 100 km near the winter pole were discovered to be twice as high as those predicted by earlier models.

In summary, the GRS, MARIE, and THEMIS operations in Earth-to-Mars planetary cruise and in the aerobraking transition phases before mapping demonstrated that these instruments were operating as planned and ready for routine opera-

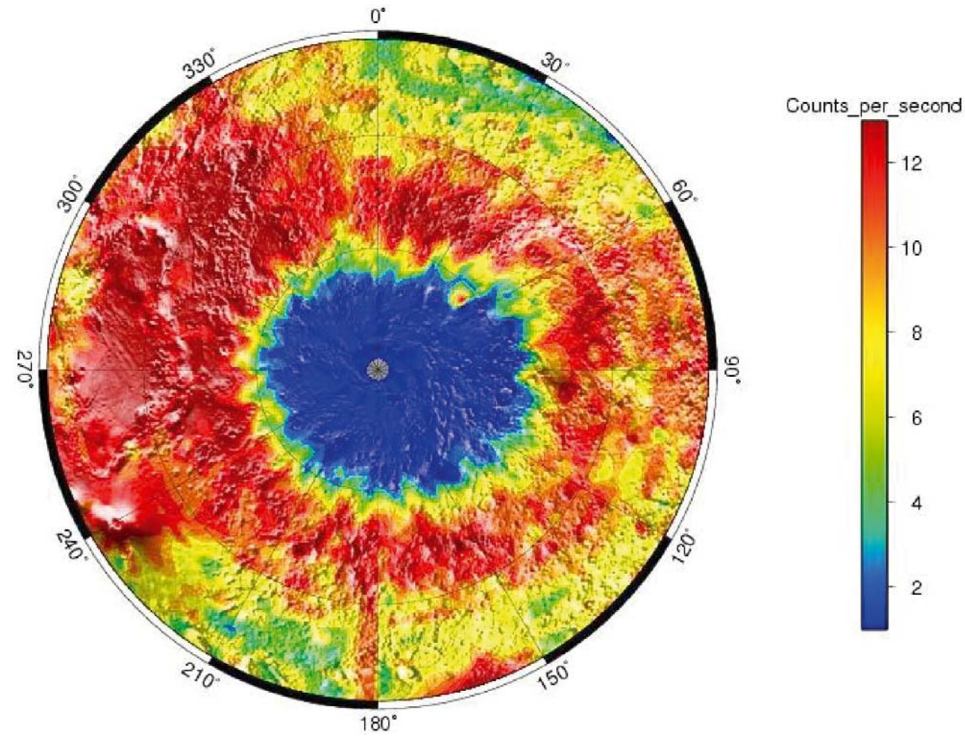

Figure 5. Epithermal Neutron Data for the Martian South Pole. Early Neutron Spectrometer (NS) and High-Energy Neutron Detector (HEND) observations indicate that the flux of epithermal neutrons coming from the region of Mars poleward of $\sim$ 60° south latitude is depressed from that coming from the more equatorial latitudes by at least a factor of two. These results are consistent with near surface polar terrain within 30 degrees of the pole being rich in hydrogen. See Feldman *et al.*, 2002a. (JPL Public Release Photo PIA 03487)

tions. In addition, atmospheric observations during aerobraking provided valuable insights into the dynamics of Mars upper atmosphere.

4.3. Science Results–Early Mapping

Odyssey observations in the first few months of mapping operation provided evidence for ice in the near-polar regions of Mars, discovered water ice at the surface near the south pole of Mars, and showed that radiation at Mars agrees with current models. GRS measurements showed that the uppermost meter of the Martian regolith near the poles (from latitudes of 60 degrees to the poles) was enriched in hydrogen. This was consistent with models that indicate this ice-rich layer underlies a hydrogen poor layer, and that water ice constitutes $35\% \pm 15\%$ of the ice-rich layer by mass. For regions near the South Pole, column densities of the hydrogen poor layer were about 150 grams per square centimeter at -42 latitude thinning to about 40 grams per square centimeter at -77 degrees south latitude

(Boynton *et al.*, July 2002, Feldman *et al.*, 2002b, and Mitrofanov *et al.*, 2002). Early THEMIS observations combined with earlier TES and Viking observations indicate that water ice is exposed near the edge of the perennial south polar cap of Mars (Titus *et al.*, 2003). Also, THEMIS visible images combined with images from the Mars Global Surveyor (MGS) suggest that melting snow may cause of the numerous eroded gullies first observed on Mars by the MGS's Mars Orbiting Camera (MOC) in 2000 (Christensen, 2003). Early MARIE observations indicate that the radiation dose rate at Mars is in good agreement with a model of the Galactic Cosmic Rays (Saganti *et al.*, 2003, this issue). Also, several Solar Particle Events (SPEs) were observed after March 2002 at Earth–Sun–Mars angles of 100° to 180°.

5. Odyssey Science Data Archiving and Distribution

A key requirement of the 2001 Mars Odyssey project is to provide data to the science community via the auspices of NASA's Planetary Data System (PDS). The instrument science teams are responsible for retrieving science packets (science telemetry), spacecraft planet instrument C-matrix events (SPICE) files, and other relevant information from the appropriate project databases, and transferring the files to their respective home institutions. Principal investigators (PIs) and their teams are responsible for generating engineering data records (EDRs) and reduced data records (RDRs) at each PI's home institution. Once EDR and RDR data products have been validated and released to the PDS as archives, the data and associated information will be made available to the research, education, and public communities.

Standard products form the core of the archives produced by Odyssey and released to the PDS for distribution to the science community and others. Standard products are well-defined, systematically generated data products, such as the EDRs and RDRs. These products and associated supporting information (e.g., documentation and index tables) will be validated and delivered to the PDS at regular intervals. The processes and schedules for generation and validation of standard products and archives, delivery to the PDS, and distribution to the science and other communities are described in greater detail in this section.

5.1. Generation, Validation and Delivery of Archives

The generation and validation of data products for the archives combines information from instrument science packets, spacecraft engineering packets, and other engineering information and data. In addition, SPICE kernels are generated and archived by the Navigation and Ancillary Information Facility (NAIF). Principal investigators access instrument science and engineering packets, and ancillary information such as spacecraft position and orientation in SPICE file format, from

TABLE IX
2001 Mars Odyssey EDR and Higher-Level Standard Data Products

Investigation	Product	Description
MARIE	MARIE-REDR	Raw times series of counts and radiation levels for MARIE detectors
	MARIE-RDR	Time series of radiation levels reduced to geophysical units
THEMIS	THM-VISEDR	Image cube of visible bands
	THM-IREDR	Image cube of infrared bands
	THM-VISRDR	Visible-band image cubes in radiance units
	THM-IRRDR	Infrared-band image cubes in radiance units
GRS	GRS-EDR	Raw gamma, NS, and HEND spectra
	GRS-IDR	Binned counts from GSR, NS, and HEND data
	GRS-RDR	Maps of element ratios and/or concentrations
SPICE	SPK	SPK (spacecraft) kernels
	PcK	PcK (planetary ephemeris) kernels
	IK	I (instruments) kernel
	CK	C (spacecraft rotations) kernels
	EK	E (experiment explanation/experimenter’s notebook) kernels
Radio Science	ATDF	Archive Tracking Data Files
	ODF	Orbit Data Files
	RSR	Radio Science Receiver Records
Accelerometer	Altitude EDR	Constant Altitude Data

the project databases. All of these are used to generate NASA Level 1A experiment data records and higher-level derived products given in Table IX. These data products, along with supporting materials such as documentation, index tables, calibration files, algorithms, and/or software, form the Mars Odyssey science data archives. These archives are assembled under the auspices of the PIs and Instrument Team Leads with guidance and assistance (as needed) from the Mars Odyssey Interdisciplinary Scientist for data and archiving, and the Mars Odyssey Data and Products Working Group (DPWG). The DPWG helps by generating plans for the archives and by providing oversight during the archiving phase of the mission.

PDS policy requires that science archives be validated for scientific integrity and for compliance with PDS standards. This validation is done at several points along the path from receipt of raw packets to delivery of standard products using a combination of instrument team, mission, and PDS personnel. The instrument teams conduct primary validation of standard products and associated information as an integral part of their data analysis work. After validation, these standard products are assembled with supporting materials such as labels, index tables, documentation and software to form archives. Broad oversight of this validation work is done via the Science Data Validation Team (SDVT), a multi-mission team that ensures that all Mars Exploration Program projects are maintaining archiving quality and schedules. In addition, the Odyssey DPWG works on a detailed level to ensure that validation steps are accomplished.

An important step here is the validation of standard product archives before delivery to the PDS. Before the first archive delivery from an instrument, the standard products and supporting materials undergo a formal PDS peer review with participation of mission personnel, PDS personnel, as well as reviewers invited from the science community. The archives are examined for integrity of scientific content, compliance with the applicable data product Software Interface Specification (SIS) and archive SIS, and compliance with PDS standards. These peer reviews may result in requests for changes or additions to the supporting material in the archive ('liens'). The liens will be resolved before the archive can be accepted by PDS. Subsequent deliveries of archives throughout the mission are not required to undergo further peer review, as long as they do not vary substantially from the first delivery. They are, however, required to pass a validation check for PDS compliance. If minor errors are found, they may simply be documented in an errata file that accompanies the archive. Major errors will be corrected before the archive is accepted by PDS. After an instrument data archive has passed peer review and the PDS validation check, it is released ('delivered') to the PDS.

The PDS is also responsible for maintaining copies of its science archives on permanent physical media and for delivering copies of science archives to the National Space Science Data Center (NSSDC). As archives are released to the PDS, the receiving PDS Node will generate copies on appropriate physical media for long-term storage by PDS and NSSDC. During the six-month validation period before delivery and the interval following delivery during which the PDS Nodes are writing the archives to physical media, the data products will exist only as online archives. To reduce the risk of data loss, the Mars Odyssey Project is responsible for conducting periodic backups and maintaining redundant copies of online archives until they are permanently stored with PDS.

5.2. Release and Distribution of Data Products

The distribution of Odyssey data products is a two-step process. The 2001 Mars Odyssey project is responsible for making data products available to its own personnel and the instrument teams. The PDS is responsible for making data products available to the rest of the science community and the public. Whereas the data archives from previous missions have often been distributed to the science community on a set of physical media (e.g., CD ROMs), the large volume of data expected from Mars Odyssey makes this form of distribution expensive and impractical. Instead, distribution will be accomplished primarily by Internet access in ways that take advantage of the capabilities and expertise associated with PI home institution systems.

Because of differences in instrument data volumes and the facilities at the PI institutions, the distribution of Odyssey data products varies from instrument to instrument. In particular:

(a) The MARIE archives will be transferred to the PDS Planetary Plasma Interaction (PPI) Node at UCLA for online access once the archives have been validated and released.

(b) GRS archives will be transferred to the PDS Geosciences Node for online access. Custom-generated GRS products will be distributed online from the GRS facility at the University of Arizona, which will become a PDS Data Node for the duration of the mission and sometime beyond. When this Data Node is eventually dissolved, the custom product capability will be transferred to the PDS Geosciences Node.

(c) THEMIS archives will be distributed online from the THEMIS facility at Arizona State University, which will become a PDS Data Node for the duration of the mission and sometime beyond. When this Data Node is eventually dissolved, the THEMIS archives will be transferred to the PDS Imaging Node.

For all of these instruments, the PDS will generate hard copy volumes (primarily DVDs) as needed.

The 2001 Mars Odyssey Project releases integrated archives within six months of receipt of the last raw data included in the archives, in compliance with the Mars Exploration Program data release policy. During the six-month interval between receipt and release, the data are processed to standard products, validated through analyses, assembled into archives (online), and checked for compliance with PDS standards. The first Odyssey data release occurred in October 2002, six months after the first six weeks of the science mission and consisted of data acquired during those first six weeks of mapping. Thereafter, data releases will occur every three months. Each of the remaining deliveries will include three months worth of data acquired six to nine months previously.

In conclusion, these public PDS archives of Odyssey science data provide the general public and Mars science communities with a significant data set that fits into the current progression of Mars missions and fills important gaps in our knowledge of the planet.

Acknowledgements

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Many have contributed to the success of the 2001 Mars Odyssey mission. The 2001 Mars Odyssey mission is managed by the Jet Propulsion Laboratory (JPL). Lockheed Martin Astronautics (LMA) built the Odyssey Orbiter in their Denver, Colorado facilities. Both JPL and LMA have jointly operated the spacecraft from launch through interplanetary cruise and into orbit at Mars.

The Gamma Ray Spectrometer (GRS) instruments were integrated by the Lunar and Planetary Laboratory, University of Arizona, under the leadership of Prof. William Boynton, GRS Team Lead. The High-Energy Neutron Detector (HEND) was constructed by the Laboratory of Space Gamma Ray Spectroscopy at the Space Research Institute (Moscow, Russia) under the leadership of Igor Mitrofanov. The Neutron Spectrometer (NS) instrument was constructed by the Los Alamos National Laboratory (LANL) under the leadership of William Feldman. The Gamma Subsystem (GSS) was constructed by the Lunar and Planetary Laboratory, University of Arizona.

The Thermal Emission Imaging System (THEMIS) was supplied by the Arizona State University under the leadership of Prof. Philip Christensen. The Martian Radiation Environment Experiment (MARIE) instrument was supplied by the Johnson Space Center under the leadership of the late Gautam Badhwar.

The Planetary Data System (PDS) is acknowledged for guiding the Odyssey mission in developing plans for data archiving and for making Mars data available to the public and the science community.

Comments provided by reviewers contributed to a significant improvement of this report.

Appendix A. Odyssey Spacecraft–Details and Description

This appendix provides a detailed overview of the 2001 Mars Odyssey spacecraft. This orbiter was constructed to meet a number of requirements including providing power to the spacecraft systems via a solar array, providing a 6-m boom to separate the GRS from the spacecraft, providing communication to Earth via low-, medium-, and high-gain antennas, and providing a bus for all of the other science instruments, as well as normal spacecraft housekeeping components. The spacecraft bus, as shown in Figure 2, is a box measuring 2.2 m long, 1.7 m tall, and 2.6 m wide, composed mostly of aluminum and some titanium. At launch, Odyssey weighed 725.0 kg, including the 331.8-kg dry spacecraft with all of its subsystems, 348.7 kg of fuel and 44.2 kg of instruments.

A.1. Command and Data Handling Subsystem

All of Odyssey's computing functions are performed by the command and data handling subsystem. The heart of this subsystem is a small onboard computer, a radiation-hardened version of the chips used on most personal computers. The subsystem runs Odyssey's flight software and controls the spacecraft through interface electronics with 128 MB of random access memory (RAM) and 3 MB of nonvolatile memory, which allows the system to maintain critical data even without power. Interface electronics make use of computer cards to communicate with external peripherals. These cards slip into slots in the computer's main board, giving the system specific functions it would not have otherwise. For redundancy purposes, there are two identical strings of these computer and interface electronics so that if one fails, the spacecraft can switch to the other.

There are a number of spacecraft interface cards with different functions. An interface card supports internal spacecraft communication with Odyssey's orientation sensors and its science instruments. A master input/output card collects signals from around the spacecraft and also sends commands to the electrical power subsystem. The uplink/downlink card provides an interface to Odyssey's telecommunications subsystems. There are two other boards in the command and data handling subsystem, both internally redundant. The module interface card controls when the spacecraft switches to backup hardware and serves as the spacecraft's time clock. A converter card takes electricity produced by the power subsystem and converts it into the proper voltages for the rest of the command and data handling subsystem components. The last interface card is a single, non-redundant, 1GB mass memory card that is used to store imaging data. The entire command and data handling subsystem weighs 11.1 kg.

A.2. Telecommunications

Odyssey's telecommunications subsystem is composed of a radio system which operates in the X-band microwave frequency range and in the ultra high frequency (UHF) range. This provides communication capability throughout all phases of the mission. The X-band system is used for communications between Earth and Odyssey, while the UHF system will be used for communications between the Odyssey orbiter and future Mars landers. The telecommunication subsystem weighs 23.9 kg.

A.3. Electrical Power

All of the spacecraft's power is generated, stored and distributed by the electrical power subsystem. The system obtains its power from an array of gallium arsenide solar cells on a panel measuring 7 m^2. A power distribution and drive unit contains switches that send power to various electrical loads around the spacecraft. Power is also stored in a 16-amp-hour nickel-hydrogen battery. The electrical power subsystem operates the gimbal drives on the high-gain antenna and the solar array. It also contains a pyro initiator unit, which fires pyrotechnically-actuated valves, activates burn wires, and opens and closes thruster valves. The electrical power subsystem weighs 86.0 kg.

A.4. Guidance, Navigation, and Control

The guidance, navigation, and control subsystem consists of three redundant pairs of sensors, which determine the spacecraft's orientation. A Sun sensor detects the position of the Sun as a backup to the star camera, while a star camera looks at star fields. Between star camera updates, the inertial measurement unit provides information on spacecraft orientation. This system also includes the reaction wheels, gyro-like devices used along with thrusters to control the spacecraft's orientation. There are a total of four reaction wheels, with three used for primary control and one as a backup. Odyssey's orientation is held fixed in relation to space ('three-axis stabilized') as opposed to being stabilized via spinning. The guidance, navigation, and control subsystem weighs 23.4 kg.

A.5. Propulsion

The propulsion subsystem consists of a set of thrusters and a main engine. The thrusters are used to perform Odyssey's attitude control and trajectory correction maneuvers, while the main engine is used only once to place the spacecraft in orbit around Mars. The main engine, which uses hydrazine propellant with nitrogen tetroxide as an oxidizer, produces a minimum thrust of 695 Newtons. Each of the four thrusters used for attitude control produce a thrust of 0.9 Newtons. Four 22-Newton thrusters are used for turning the spacecraft. The propulsion subsystem also includes a single gaseous helium tank used to pressurize the fuel and oxidizer tanks, as well as miscellaneous tubing, pyro valves, and filters. The propulsion subsystem weighs 49.7 kg.

A.6. Structures

The spacecraft's structure consists of two modules: the propulsion module and the equipment module. The propulsion module contains tanks, thrusters, and associated plumbing. The equipment module is composed of an equipment deck and supports engineering components and the radiation experiment, and a science deck connected by struts. The topside of the science deck, in turn, supports the thermal emission imaging system, gamma ray spectrometer, the high-energy neutron detector, the neutron spectrometer and the star cameras. The underside of the science deck supports engineering components and the gamma ray spectrometer's central electronics box. The structure's subsystem weighs 81.7 kg.

A.7. Thermal Control and Mechanisms

The thermal control subsystem is responsible for maintaining the temperatures of the spacecraft components to within their allowable limits. This subsystem is a combination of heaters, radiators, louvers, blankets and thermal paint. The thermal control subsystem weighs 20.3 kg.

In addition to the thermal control subsystem, there are a number of mechanisms, several of which are associated with its high-gain antenna. Three retention and release devices are used to lock the antenna down during launch, cruise and aerobraking. Once the science orbit was attained, the antenna was released and deployed with a motor-driven hinge. The antenna's position is controlled with a two-axis gimbal assembly. There are also four retention and release devices used for the solar array. The three panels of the array are folded together and locked down for launch. After deployment, the solar array is also controlled using a two-axis gimbal assembly. The last mechanism is a retention and release device for the deployable 6-m boom for the Gamma Subsystem. All of these mechanisms combined weigh 24.2 kg.

A.8. Flight Software

Odyssey receives its commands via radio from Earth and translates them into spacecraft actions. To support this, the flight software is capable of running multiple concurrent sequences, as well as executing 'immediate' commands as soon as they are received. The software responsible for the data collection is extremely flexible. It collects data from the science and engineering devices and puts them in a number of holding bins, which can be modified via ground commands. The flight software is also responsible for a number of autonomous functions, such as attitude control and fault protection. If the software senses a fault, it will automatically perform a number of preset actions to put the spacecraft in a safe standby attitude, awaiting further direction from ground controllers.

A.9. Launch Vehicle

Odyssey was launched on a variant of Boeing's Delta II rocket, the 7925, which included nine strap-on solid-fuel motors. Each of the nine solid fuel boosters was 1 m in diameter and 13 m long; each contained 11,765 kg of fuel and provided a total thrust of 485,458 N at liftoff. The casings on these solid rocket motors were lightweight graphite epoxy. The first stage housed a main engine and two vernier engines. The vernier engines provided roll control during main engine burn and attitude control after main engine cutoff before the second stage separation. The main engine burned 96,000 kg of liquid fuel (a highly refined form of kerosene) and used liquid oxygen as an oxidizer.

The second stage was 2.4 m in diameter and 6 m long, which used 3,929 kg of liquid fuel, a 50/50 mixture of hydrazine and unsymmetric dimethly hydrazine. The oxidizer was 2,101 kg of nitrogen tetroxide. The second-stage engine performed two separate burns during the launch sequence.

The third and final stage of the Delta II 7925 provided the final thrust needed to place Odyssey on a trajectory to Mars. This upper stage was 1.25 m in diameter and consisted of a solid-fuel rocket motor with 2,012 kg of propellant and a nutation control system that provided stability after the motor ignited. A spin table attached to the top of the Delta's second stage supported and stabilized the Odyssey spacecraft and upper stage before it was separated from the second stage. The Odyssey spacecraft was mounted to the third stage by a payload attachment fitting. A yo-yo despin system decreased the spin rate of the spacecraft and upper stage before they

TABLE A1

2001 Mars Odyssey Spacecraft, Launch Vehicle, Mission and Web Site Information

Spacecraft	Dimensions: Main structure 2.2 m long, 1.7 m tall and 2.6 m wide; wingspan of solar array 5.7 m tip to tip Weight: 725 kg total, composed of 331.8 kg dry spacecraft, 348.7 kg of fuel of science instruments and 44.2 kg Science instruments: Thermal Emission Imaging System (THEMIS), Gamma Ray Spectrometer (GRS), Martian Radiation Environment Experiment (MARIE) Power: Solar array providing up to 1,500 W just after launch; 750 W at Mars
Launch Vehicle	Type: Delta II 7925 Weight: 230,983 kg
Mission	Launch window: April 7–27, 2001 (launched on first opportunity–April 7, 2001) Earth-Mars distance at launch: 125 million km Total distance traveled Earth to Mars: 460 million km Mars arrival date: October 24, 2001 Earth-Mars distance at arrival: 150 million km One-way speed of light time Mars-to-Earth at arrival: 8 minutes, 30 seconds Science mapping phase: February 2002–August 2004 Relay phase: August 2004–November 2005
Web Sites	Information on 2001 Mars Odyssey Mission http://mars.jpl.nasa.gov/odyssey/ Information on THEMIS and latest released THEMIS Images http://themis.asu.edu/ Information on GRS suite and results http://grs.lpl.arizona.edu/ Information on MARIE and results http://marie.jsc.nasa.gov/ Odyssey Data Archives site http://wwwpds.wustl.edu/missions/odyssey/

separated from each other. During launch and ascent through Earth's atmosphere, the Odyssey spacecraft and upper stage was protected from aerodynamic forces by a 2.9-m-diameter payload fairing, which was jettisoned from the Delta II during second-stage powered flight at an altitude of 136 km.

A summary of information on the 2001 Mars Odyssey Spacecraft, Launch Vehicle, Mission and Web Sites is given in Table A-1.

Appendix B. Odyssey Spacecraft Operations: Launch, Interplanetary Cruise, and Aerobraking

This appendix provides details of Odyssey spacecraft operations from launch through interplanetary cruise and aerobraking.

B.1. Launch, Lift-Off, Insertion into a Parking Orbit

2001 Mars Odyssey was launched from Cape Canaveral on April 7, 2001 at 11:02 a.m. EDT during its very first launch opportunity. Odyssey lifted off from Space Launch Complex 17 at Cape Canaveral Air Station, Florida. Sixty-six seconds after launch, the first three solid rocket boosters were discarded followed by the next three boosters one second later. The final three boosters were jettisoned 2 minutes, 11 seconds after launch. About 4 minutes, 24 seconds after liftoff, the first stage stopped firing and was discarded 8 seconds later. About 5 seconds later the second stage engine ignited. The fairing or nose cone was discarded 4 minutes, 41 seconds after launch. The first burn of the second stage engine occurred at 10 minutes, 3 seconds after launch.

At this point the vehicle was in low Earth orbit at an altitude of 189 km and the second stage was restarted at 24 minutes, 32 seconds after launch. Small rockets were then fired to spin up the third stage on a turntable attached to the second stage. The third stage separated and ignited its motor, putting the spinning spacecraft on its interplanetary cruise trajectory. A nutation control system (a thruster on an arm mounted on the side of the third stage) was used to maintain stability during this third stage burn. After that, the spinning upper stage and the attached Odyssey spacecraft was despun so that the spacecraft could be separated and acquire its proper cruise orientation. This was accomplished by a set of weights that are reeled out from the spinning vehicle on flexible lines that act in a manner similar to spinning ice skaters slowing themselves by extending their arms. Odyssey separated from the Delta II third stage about 33 minutes after launch. Remaining spin was removed using the orbiter's onboard thrusters. At 36 minutes after launch, the solar array was unfolded and 8 minutes later it was locked into place. Then the spacecraft turned to its initial communication attitude and the radio transmitter was turned on. One hour after launch, the 34-m-diameter antenna at the Deep Space Network (DSN) complex near Canberra, Australia, acquired Odyssey's first signal.

B.2. Interplanetary Cruise

Odyssey's interplanetary cruise phase from Earth to Mars was accomplished in 200 days. Engineering activities during the cruise included checkout of the spacecraft in its cruise configuration, checkout and monitoring of the science instruments, and navigation activities necessary to determine and correct Odyssey's flight path to Mars. Science activities in this cruise phase included payload health and status checks, instrument calibrations, as well as data collection by the science instruments as spacecraft limitations allowed.

Odyssey's flight path from Earth to Mars was a Type 1 trajectory, taking less than 180 degrees around the Sun. During the first two months of interplanetary cruise, only the DSN station in Canberra was capable of viewing the spacecraft. Late in May, California's Goldstone station came into view, and by early June the Madrid station was also able to track the spacecraft. A small tracking station in Santiago, Chile was used during the first seven days following launch to fill in tracking coverage. During early Earth-to-Mars cruise, Odyssey transmitted to Earth using its medium-gain antenna and received commands on its low-gain antenna during the early portion on its flight. Later in cruise, Odyssey communicated via its high-gain antenna. Cruise command sequences were generated and uplinked every four weeks during regularly scheduled DSN passes.

The spacecraft determined its orientation in space during the interplanetary cruise phase via a star camera augmented with an inertial measurement unit. The spacecraft was oriented with its medium- or high-gain antenna pointed toward the Earth, while keeping the solar panels pointed toward the Sun. Spacecraft orientation was controlled by reaction wheels; devices similar to gyroscopes. These devices were occasionally 'desaturated', when their momentum was unloaded by firing the spacecraft's thrusters.

Navigation activities during interplanetary cruise involve the collection of two-way Doppler and ranging data as well as a series of delta differential one-way ranges (ΔDORs). The ΔDOR measurements were interferometric measurements between two radio sources: one of the radio sources being the differential one-way range tones from Odyssey and the second radio source was either a quasar (known, stable natural radio source) or the telemetry signal from the Mars Global Surveyor spacecraft. Both radio sources were recorded simultaneously at two earth-based radio antennas separated by about 120 degrees of longitude. Odyssey's position in the plane-of-the-sky was determined by triangulation of the ΔDOR signals, complementing the line-of-sight ranging provided by two-way Doppler and ranging data.

During interplanetary cruise, Odyssey conducted four trajectory course maneuvers (TCMs) by firing its thrusters to adjust its flight path. The first trajectory correction maneuver occurred 46 days after launch and corrected launch injection errors to adjust the Mars arrival aim point. It was followed by a second TCM 86 days after launch. The remaining two TCMs were 37 days and 13 days before arrival. The spacecraft was tracked by the DSN antennas for 24 hours before and after all of the TCMs. These maneuvers were conducted in a 'constrained turn-and-burn' mode in which the spacecraft turned to the desired burn attitude and fired the thrusters, while remaining in contact with Earth.

Science instruments were powered on, tested and calibrated during cruise. The THEMIS thermal imaging system took a picture of the Earth-Moon system 12 days after launch. Also, a THEMIS star calibration imaging was done 76 days after launch. There were two GRS calibration periods during which each of the suite's three sensors was operated. The MARIE was operated constantly during cruise until mid August, when it stopped responding to commands from Earth. This ended MARIE observations until after orbit insertion and aerobraking were completed.

Also, a test of the orbiter's UHF radio system was performed after launch. The 45-meter antenna at California's Stanford University was used to test the UHF system ability to receive and transmit. This UHF radio system will be used during Odyssey's relay phase to support future landers; it is not used as part of the orbiter's science mission. This test was successfully performed.

B.3. Mars Arrival, Orbit Insertion, and Aerobraking

Odyssey arrived at Mars on October 24, 2001. As it neared its closest point to the planet over the northern hemisphere, the spacecraft fired its 695-N main engine for 22 minutes allowing its capture in an elliptical orbit. Mars orbit insertion (MOI) performance was excellent. Navigation delivery was within 1 km of the target altitude. The post-MOI orbit period was 18.6 hours (the expected range was 15 –24 hours). Oxidizer burn-to-depletion was detected and triggered the burn cutoff as planned. The main engine thrust level was somewhat lower than expected (due to a better balanced spacecraft), resulting in a burn time of 1219 seconds versus an expected value of 1183 seconds. No period reduction maneuver following MOI was required.

Aerobraking provided a means of transitioning from the initial elliptical orbit immediately after arrival to the desired near circular mapping orbit. This technique was first demonstrated at Venus by Magellan and subsequently, at Mars by Mars Global Surveyor. It slows the spacecraft incrementally, orbit by orbit, by using frictional drag as it flies through the upper part of the planet's atmosphere. Friction from the atmosphere on the spacecraft and its wing-like solar array caused the spacecraft to lose some of its orbital energy during each periapsis, known as a 'drag pass'. As the spacecraft was slowed during each drag pass, the orbit was gradually lowered and circularized.

The Thermal Emission Spectrometer (TES) instrument on the Mars Global Surveyor spacecraft provided monitoring of the Mars atmosphere during Odyssey aerobraking. One important aspect of the TES observations was the potential to provide warning should a large dust storm have erupted. A dust storm could have increased the temperature of the atmosphere and resulted in a 'blooming' upward of the atmosphere. If this had occurred, the Odyssey spacecraft would have experienced a larger than expected drag force which could have overheated the spacecraft. With warning from TES, the Odyssey mission teams could adjust the height of orbit periapsis, raising Odyssey to a safe height. The THEMIS Mission Operations Team was prepared to turn on THEMIS and support atmospheric monitoring if the TES data were not available. Both the TES and THEMIS Atmospheric Science teams supported Odyssey's Atmospheric Advisory Group data interpretation. Fortunately, no significant dust storms occurred during aerobraking.

Aerobraking was conducted in three phases: walk-in, the main phase, and walk-out. The walk-in phase occurred during the first eight orbits following Mars arrival. The main aerobraking phase began once the point of the spacecraft's periapsis had been lowered to within 110 km above the Martian surface. As the spacecraft's orbit was reduced and circularized during 330 drag passes in 75 days, the periapsis moved northward, almost directly over Mars' North Pole. Small thruster firings when the spacecraft was at its apoapsis kept the drag pass altitude at the proper level to limit heating and dynamic pressure on the orbiter. The walk-out phase occurred during the last few days of aerobraking as described below. Aerobraking was completed with no major anomalies. Aerobraking was initiated 4 days after MOI and was completed after 75 days. Daily analyses of Mars atmosphere during aerobraking was done by the 2001 Mars Odyssey Atmospheric Advisory Group – led by Richard Zurek, JPL, assisted by Gerald Keating, George Washington University, and others at NASA's Langley Research Center in Hampton, Virginia.

The primary transition from aerobraking to a mapping orbit (the aerobraking walkout phase) was conducted in a series of three maneuvers in mid-January 2002. The first, aerobraking exit maneuver (ABX1) was conducted on January 11, 2002 to raise the orbit periapsis and terminate drag passes throughout the atmosphere. This ABX1 maneuver was performed at apoapsis and raised the periapsis altitude to about 200 km using a delta velocity (ΔV) of 20 m/s. The second aerobraking exit maneuver (ABX2), conducted on January 15, 2002, raised periapsis and changed the inclination. This was done when the argument of periapsis had drifted to the equator. This ABX2 maneuver raised periapsis altitude to 387 km and yielded an inclination that provided the proper local solar time drift for science mapping orbit. This maneuver was also conducted at apoapsis using a ΔV of 56 m/s. The third aerobraking exit maneuver (ABX3), conducted on January 17, 2002, reduced the orbit period and froze the orbit. This lowered apoapsis altitude to 450 km and rotated the argument of periapsis to the South Pole ($\omega = 270°$). This maneuver was conducted at apoapsis using a ΔV of 27 m/s.

Following these three aerobraking exit maneuvers, there were small orbit adjustments as well as the deployment of the high-gain antenna (HGA). Small, final orbit clean-up maneuvers on January 28 and 30, 2002 corrected residual biases and execution errors from the rocket burns associated with the three aerobraking exit maneuvers (ABX1, ABX2 and ABX3). These maneuvers adjusted both the periapsis and apoapsis altitudes using a ΔV of about 4 m/sec. After the final orbit was achieved, the last major spacecraft event before the start of mapping was the deployment of the HGA, which was successfully performed on February 4, 2002.

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