THE ASTROPHYSICAL JOURNAL, 397:420–429, 1992 October 1

THE *COBE*[1] MISSION: ITS DESIGN AND PERFORMANCE TWO YEARS AFTER LAUNCH

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Received 1992 January 31; accepted 1992 April 6

ABSTRACT

COBE, NASA's first space mission devoted primarily to cosmology, carries three scientific instruments to make precise measurements of the spectrum and anisotropy of the cosmic microwave background radiation on angular scales greater than 7° and to conduct a search for a diffuse cosmic infrared background radiation with 0°.7 angular resolution. The mission goal is to make these measurements to the limit imposed by the local astrophysical foregrounds. The *COBE* instruments cover the wavelength range from 1.2 μm to 1 cm. The instruments are calibrated periodically in orbit using internal calibrators and celestial standards. The observing strategy is designed to minimize and allow determination of systematic errors that could result from spacecraft operations, the local environment of the spacecraft, and emission from foreground astrophysical sources such as the Galaxy and the solar system. The mission orbit and the scanning techniques provide full sky coverage, while simultaneously minimizing solar and terrestrial radiation on the instruments and reducing thermal and radiative perturbations of the measurements. The three instruments are complementary in that combined data from all are needed to discriminate cosmological emissions from other astrophysical sources. Operational experience after launch shows that flight performance generally meets or exceeds the design goals. *COBE* has now completed 2 years of flight operations, and a third year has been initiated. Initial *COBE* data products are planned for release in 1993 June.

Subject headings: artificial satellites, space probes — cosmic microwave background

1. INTRODUCTION

The *COBE* mission was motivated by advances in cosmology made within the last several decades that have led to our present understanding of the early universe. Since the discovery of the cosmic microwave background (CMB) in 1964 (Penzias & Wilson 1965), numerous experiments from the ground, rockets, balloons, and spacecraft have been devised to obtain measurements of its spectrum and spatial anisotropies over a wide range of wavelengths and angular scales. Because the CMB, which is interpreted as the relic radiation from the Big Bang, is difficult to measure precisely from within the Earth's atmosphere, it was clear that observations from space would allow a significant improvement in these measurements and thereby in our understanding of conditions in the early universe. Another goal of the *COBE* mission, achievable only by observing from space, is to make a sensitive search for radiation from a cosmic infrared background (CIB), which is expected to result from the cumulative emissions of luminous objects formed after the universe cooled sufficiently to permit the first galaxies and stars to form. A final objective is to enable studies of the Galaxy and solar system over the unprecedented broad spectral range of the *COBE* instruments.

To achieve the full benefit of space observations, a goal of the mission and instrument design was that *COBE* measurements would be limited ultimately by our ability to identify and model the various components of the astrophysical foreground sources, and to discriminate between them and the cosmological emission. This goal drove the design of the mission strategy, the spacecraft and operations, and the choice of instruments. Basic elements in the mission strategy were the requirements for highly redundant full sky coverage and for sufficient time in orbit to achieve necessary sensitivity and evaluate potential sources of systematic errors in the observations. Other elements in the strategy were the needs for onboard instrument calibration and time for frequent checks of calibration stability. To reduce known sources of systematic errors, the mission orbit, spacecraft attitudes, and instrument enclosures were designed to eliminate direct exposure to Sun and Earth radiation and to maintain a well-controlled thermal environment for the instruments. Instrument and spacecraft design included efforts to minimize radio frequency contamination and interference from sources of stray radiation. Finally, the instruments were chosen to measure specific attributes of the cosmological backgrounds and also, through their complementary spectral coverage, to enable the modeling and subtraction of foreground emissions. Early descriptions of the mission concept have been given by Mather (1982) and by Gulkis et al. (1990).

The three scientific instruments are the Far-Infrared Absolute Spectrophotometer (FIRAS), the Differential Microwave Radiometers (DMR), and the Diffuse Infrared Background Experiment (DIRBE). The FIRAS objective is to make a precision measurement of the spectrum of the CMB from 1 cm to

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[1] The National Aeronautics and Space Administration/Goddard Space Flight Center (NASA/GSFC) is responsible for the design, development, and operation of the *Cosmic Background Explorer* (*COBE*), under the scientific guidance of the *COBE* Science Working Group. GSFC is also responsible for the software development and the final processing of the mission data.

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100 μm. The DMR objective is to search for CMB anisotropies on angular scales larger than 7° at frequencies of 31.5, 53, and 90 GHz. The DIRBE objective is to search for a CIB by making absolute brightness measurements of the diffuse infrared radiation in 10 photometric bands from 1 to 300 μm and polarimetric measurements from 1 to 3.5 μm.

In §§ 2–5 of this paper we describe the *COBE* mission and spacecraft concepts central to enabling the mission to achieve its scientific objectives. In § 6 we summarize early scientific results and plans for continuing satellite operations and data analysis.

2. MISSION DESIGN

The need to control and measure potential sources of systematic errors required an integrated design and operations concept. It led to the requirements for an all-sky survey and a minimum time in orbit of 6 months, and imposed constraints on the permitted amount of radiative interference from local sources such as the Earth, Sun, Moon, and radio interference from the ground, *COBE* spacecraft, and other satellites. The instruments required temperature stability to maintain gain and offset stability and a high level of cleanliness to reduce the entry of stray light and thermal emission from particulates. The control of systematic errors in the measurement of the CMB anisotropy and the need for measuring the zodiacal cloud at different solar elongation angles for subsequent modeling required that the satellite rotate. The choice of orbit, within the constraint of available launch vehicles, was also an important consideration in minimizing systematic errors. In this section of the paper we describe the elements of the design.

The major components of the satellite are the instrument module and the spacecraft module. The instrument module contains the scientific instruments and some of their electronics, a superfluid He dewar, and a Sun-Earth shield. The spacecraft module includes most of the instrument electronics, spacecraft subsystems including the attitude control system, command and data-handling system, power system, solar panels, two omnidirectional antennas, and necessary support structures. These components are shown schematically in Figure 1.

2.1. *The Orbit*

The overriding considerations in choosing the orbit were the need for full sky coverage, the need to eliminate stray radiation from the instruments, and the need to maintain thermal stability of the dewar and the instruments. In near-Earth orbit, the Sun and Earth are the primary sources of thermal emission, and it is necessary to ensure that neither the instruments nor the dewar are exposed to their radiation. A circular Sun-synchronous orbit can satisfy these requirements throughout the year. In a Sun-synchronous orbit, the inclination and altitude are chosen so that the orbital plane precesses 360° in 1 year due to the Earth's gravitational quadrupole moment. For *COBE* a 900 km altitude orbit was chosen, requiring a 99°

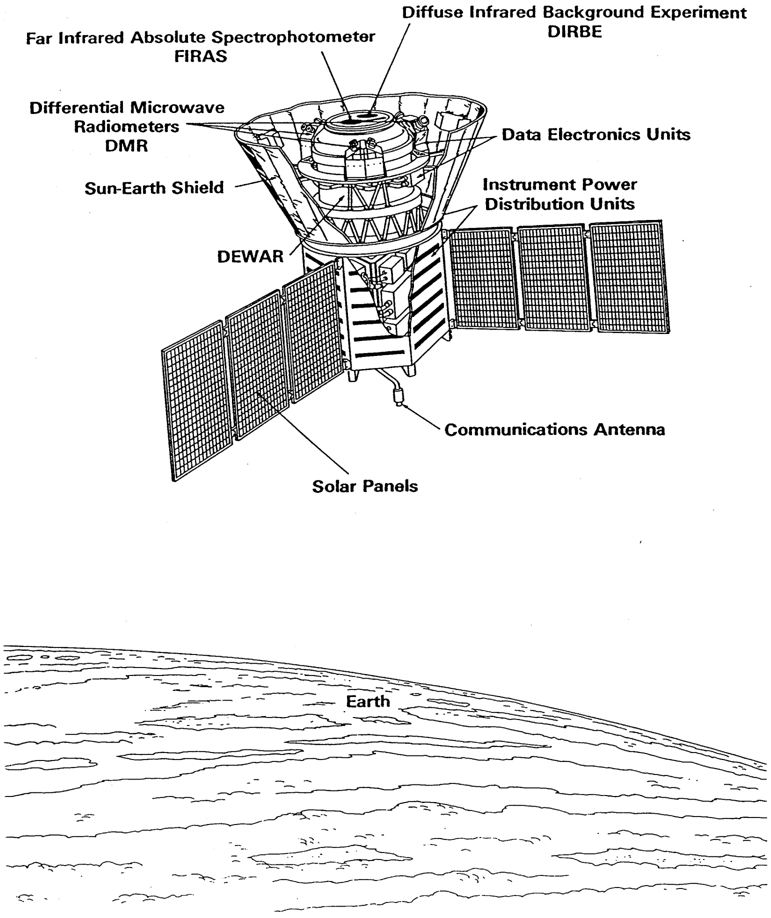

FIG. 1.—Artist cutaway drawing of the major components on *COBE*, showing the locations of the three scientific instruments

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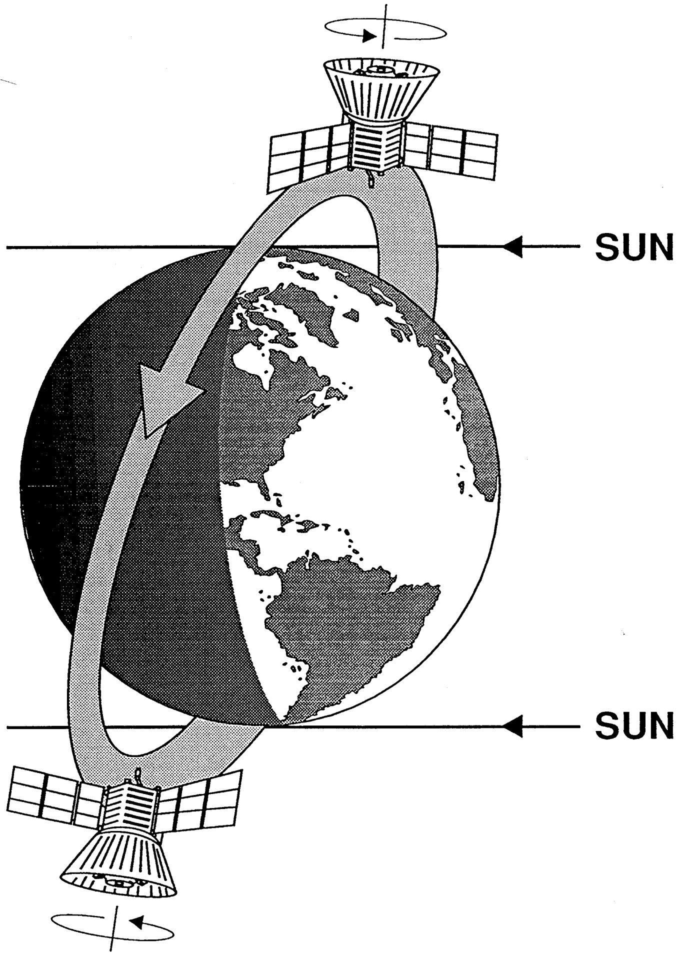

FIG. 2.—Schematic drawing of *COBE* in orbit. *COBE* is shown in a high-inclination orbit with its axis of rotation always pointing away from the Earth and about 90° from the Sun.

inclination. A 900 km altitude was within the launch capabilities of the Shuttle (with an auxiliary propulsion system on *COBE*) or a Delta rocket. This altitude is a good compromise between contamination from the Earth's residual atmosphere, which increases at lower altitude, and interference due to charged particles in the Earth's radiation belts at higher altitudes. A 6 PM ascending node was chosen for the *COBE* orbital plane; this node follows the terminator (the boundary between sunlight and darkness on the Earth) throughout the year. By continuously reorienting the spacecraft spin axis at about 94° from the Sun and close to the local zenith, it became possible to keep the Sun and Earth below the plane of the shield. In this observing mode, the spacecraft central axis scans the full sky every six months. The orbit is shown schematically in Figure 2. The orbital period is 103 minutes, giving almost exactly 14 orbits per day.

2.2. *Spin Rate and Orientation of the Spacecraft*

It is necessary to spin the spacecraft to attain the scientific objectives of measuring the CMB anisotropy and searching for a CIB. As will be discussed in more detail below (and illustrated in Fig. 3), the FIRAS optical axis points along the spin axis while the DIRBE and DMR beams point 30° from the axis. The spin allows DIRBE to measure the emission and scattering by the zodiacal dust cloud over a range of solar elongation angles for each celestial direction, which aids in the discrimination and subsequent modeling of zodiacal radiation. For the DMR, the spin causes a short-term interchange of the two beams associated with a single differential radiometer and thereby gives a modulation of the differential sky signal at the spin rate. The 0.8 rpm spin rate is chosen to be fast enough to reduce the noise and systematic errors that could otherwise arise from radiometer gain and offset instabilities. The spin axis is tilted back from the orbital velocity vector as a precaution against possible deposition of residual atmospheric gas on the cold optics and against a possible infrared glow that would

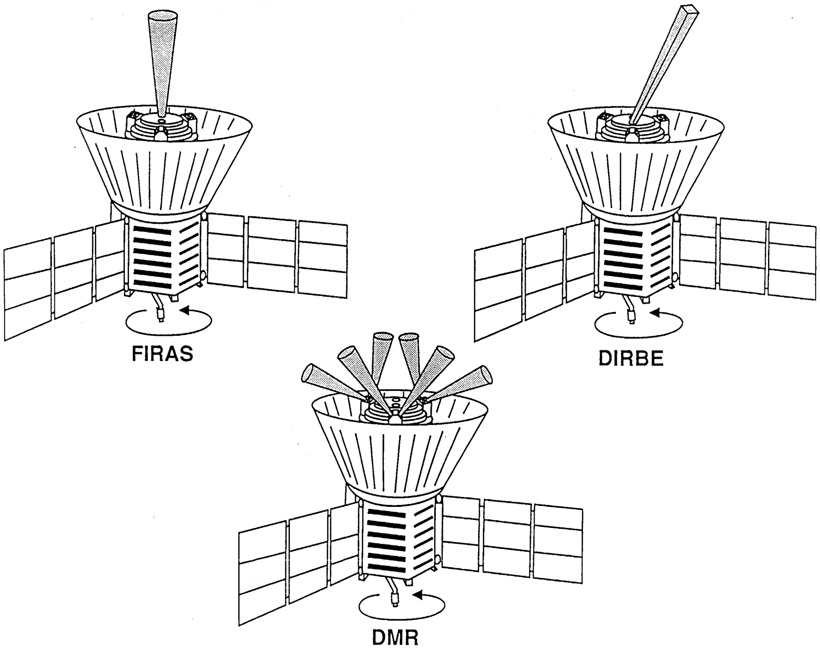

FIG. 3.—Schematic drawing of the viewing direction for each of the three instruments with respect to the spin axis of the spacecraft

arise from fast neutral particles hitting surfaces at supersonic speeds. (The tilt-back varies a few degrees about 96° during each orbit.) The axis of the spacecraft is also tipped to angles between 92° and 94° from the Sun to reduce the amount of sunlight reflected or scattered from the edge of the shield into the instrument apertures and dewar.

A sophisticated attitude control system meets the unique requirements of slow rotation and three-axis control. This was implemented by using a pair of inertia wheels (yaw angular momentum wheels), with their axes oriented along the spacecraft spin axis. These wheels carry an angular momentum opposite that of the entire spacecraft to create a zero net angular momentum system. The spacecraft orientation is controlled by three reaction wheels with spin axes 120° apart in the plane perpendicular to the spacecraft spin axis and by electromagnetic coils (torquer bars) that interact with the Earth's magnetic field.

The attitude of the spacecraft is measured and maintained by a redundant set of sensors and servo systems. Earth and Sun sensors (one of each on each of the three transverse control axes) provide control signals to point the spin axis away from the Earth and at least 90° from the Sun. Rate damping and fine-resolution attitude sensing are provided by six gyros, one on each transverse control axis and three on the spin axis. The system is redundant in that stable operation is achievable with one or perhaps two of the transverse control axes disabled, and with only one spin axis gyro operable.

Coarse attitude parameters are calculated by using telemetered data from the attitude control sensors. The Sun and Earth directions are measured in spacecraft body coordinates and are transformed to inertial coordinates using the spacecraft ephemeris. These are then used to compute quaternions and rotation matrices describing the spacecraft orientation. The data are smoothed and interpolated using the gyro signals to produce attitude solutions good to 4′ (1 σ), adequate to meet the initial requirements for the FIRAS and DMR. The DIRBE with its smaller beam size (0°.7 rather than 7°) requires a more accurate attitude solution. This fine aspect is determined by using gyro data to interpolate between the positions of known stars detected in the short-wavelength bands of the DIRBE instrument. The fine-aspect solution has an accuracy of 1′.5 (1 σ) and is now used in the analysis of data from all three instruments.

There is an unavoidable radiative perturbation to the instruments from the Earth in the chosen orbit and spacecraft attitude. At 900 km altitude, Earth's limb is 118° from the zenith. Since the altitude control system maintains the axis of the satellite pointing away from the Earth and 94° from the Sun, the Earth limb does not rise above the plane of the Sun-Earth shield for most of the year. However, since the Earth's axis is tilted 23°.5 from the ecliptic pole, the angle between the plane of *COBE*'s orbit and the ecliptic plane varies through the seasons from −14°.5 to +32°.5. As a consequence, the combination of the tilt of the Earth's axis, the orbit inclination, and the offset of the spacecraft spin axis from the Sun brings the Earth limb above the shield for up to 20 minutes per orbit near the June solstices. During this period the Earth's limb rises a few degrees above the plane of the shield for part of each orbit, while on the opposite side of the orbit the spacecraft goes into the Earth's shadow. A strategy to minimize risk was to place this "eclipse" season as far as possible after launch, so that the ascending node occurs over the evening terminator, causing eclipses to occur near the south pole around the June solstices.

2.3. *Sky Scan Strategy*

The scan strategy is governed by the requirement for all-sky coverage and the need for many scans of each pixel on the sky. Many scans build up the signal-to-noise ratio and allow tests for systematic errors by multiple measurements of the same part of the sky under different environmental conditions, instrument parameters, and observing times.

The scientific instruments, oriented on the satellite in different ways, result in scan patterns unique to each instrument (Fig. 3). The three pairs of DMR receivers are spaced 120° apart around the aperture plane of the dewar. Each radiometer channel measures the difference in sky signal from a pair of horns defining 7° fields of view separated by 60°, each beam being 30° from the spin axis. The DIRBE, located inside the dewar, views 30° from the spin axis to provide data over a range of solar elongation angles during each spacecraft rotation. DMR and DIRBE trace out a pattern of epicycles that enable them to scan half of the sky every day and obtain multiple measurements for each pixel of the sky. The FIRAS, also located inside the dewar, views along the spin axis with its 7° field of view.

2.4. *Power*

Three solar array wings, deployed after launch, provide power for the spacecraft and instrument electronics. Each wing consists of three panels with solar cells on both sides. The arrays were designed for a minimum lifetime of 1 year to maintain a peak capacity of approximately 1280 W at launch and an average capacity of 750 W at the end of the first year. The actual performance at the end of the first year had diminished by about 3%. The nominal spacecraft and instrumental power load is 542 W.

Power generated in the solar arrays is supplied directly to the spacecraft and instrument subsystems through a regulated +28 V. bus. The power system operates at close to 100% efficiency by taking advantage of the nearly constant solar illumination provided by the orbit and spacecraft spin. Bus voltages are maintained by shunt regulators which radiate excess power into space. The 20 minute power transients during the eclipse season are smoothed by batteries.

A significant effort was made in developing space-worthy low-noise and RF-free power supplies and power distribution systems for the instruments. The low-noise sections have their own DC-DC power converters with separate grounds, multiple shields, and nested subregulators.

2.5. *Satellite Commanding and Data Communication*

COBE requires a special design for satellite commanding, tracking, and data retrieval. It has two antennas, one to communicate with the Tracking and Data Relay Satellite System (TDRSS), and the other to transmit data stored on tape recorders directly to the ground. The antennas are located on a mast at the bottom of the spacecraft deployed after launch.

The TDRSS link transmits commands for tracking, spacecraft attitude maneuvers, and control of the instruments. It is also used to establish a short (10–20 minutes) real-time data flow, approximately every other orbit, from the satellite to the operations control center at GSFC via the ground station at White Sands, NM.

The primary data flow is stored on one of two on-board tape recorders and read out daily directly to the NASA receiving station at the Wallops Flight Facility. The *COBE* near-polar orbit provides a minimum of two morning and two evening opportunities for transmission of the stored data. Both the stored and real-time data are relayed to the Payload Operations Control Center at GSFC for satellite health and safety monitoring and engineering trend analysis. The data are also relayed to the analysis center for quick-look processing. An edited tape of the tape-recorder dump is received 24–48 hr after contact, and these data are used for final science data processing.

The spacecraft electronics include a command and data-handling system that stores and decodes the commands received from the ground, collects data from the instruments and spacecraft at the rate of 4 kbps, and prepares data for transmission to the ground. The on-board tape recorders and data system allow 24 hr of data to be transmitted to the ground in 9 minutes. Each instrument has a separate data stream located within a fixed part of the telemetry format. The data rate allocations for DIRBE, FIRAS, and DMR are 1716, 1362, and 250 bps, respectively. The remainder of the telemetry is assigned to spacecraft subsystems.

2.6. *Launch Vehicle*

COBE, as initially proposed, was to have been launched by a Delta rocket. However, once the design was underway, the Shuttle was adopted as the launch vehicle. After the Challenger accident occurred in 1986, the spacecraft was redesigned to fit within the weight and size constraints of the Delta. The final *COBE* satellite had a total mass of 2270 kg, length of 5.49 m, and diameter of 2.44 m with Sun-Earth shield and solar panels folded (8.53 m with the solar panels deployed), all consistent with the mission requirements and Delta launch constraints.

2.7. *Scope and Nature of Ground Testing*

The ground testing of *COBE* posed significant challenges. The mission involved a constellation of difficult technologies, among which cyrogenics and the manipulation of low-level signals stand out. Moreover, it was necessary to demonstrate that the individual subsystems, and ultimately the entire spacecraft and instrument assembly in its flight configuration, could-satisfy both the sensitivity and systematic error requirements.

Major tests after *COBE* was fully integrated were performed to simulate the space environments, including vacuum and temperature; susceptibility to vibration, acoustic excitation, and acoustic shock; electromagnetic interference (EMI) self-compatibility and radio frequency interference (RFI) susceptibility; and overall tests to determine the interaction between instruments and spacecraft. Special tests were also performed to simulate the thermal and power conditions that would occur during eclipse periods.

All parts of the spacecraft and instruments requiring deployment—Sun-Earth shield (including dust covers on the DMR horns), antenna boom, solar panels, dewar cover, FIRAS external calibrator and moving mirror transport—were tested in orientations and with supports to simulate (as much as possible) zero gravity. The instruments were characterized and calibrated extensively on the ground, first in their own special test environments, then in the full flight assembly, and finally again in orbit.

Numerous technical papers on various aspects of *COBE* have been published. Papers not specific to the instruments are referenced here. These include papers on contamination control (Barney 1991); test facility requirements for thermal balance tests (Milam 1991); design of the dewar (Hopkins & Castles 1985); optical alignments (Sampler 1990); thermal performance of the dewar prior to launch and in orbit (Hopkins & Payne 1987; Volz & Ryschkewitsch 1990; Volz et al. 1990; Volz et al. 1991; Volz & Dipirro 1992); thermal design of the cryogenic optical assembly (Mosier 1991); cryogenic cooldown tests (Coladonato et al. 1990); and attitude control (Bromberg & Croft 1985).

3. THE INSTRUMENT MODULE

Major components of the intrument module are shown in the cutaway artist's drawing of Figure 1. Prominent features in the drawing are the dewar that houses FIRAS and DIRBE, the three DMR radiometers around the dewar aperture, and the Sun-Earth shield.

3.1. *The Instruments*

A brief description of the scientific instruments is given in this section, and their characteristics are summarized in Table 1. The instrument designs are described in detail in separate papers and will not be repeated here. Smoot et al. (1990) describe the DMR; papers describing FIRAS and DIRBE are in preparation. The three instruments overlap in wavelength coverage, providing both a consistency check on measurements in the regions of spectral overlap and assistance in discriminating the signal contributions from our galaxy, solar system, and the cosmological backgrounds.

The FIRAS instrument is a polarizing Michelson interferometer (Mather 1982) with two separate spectral channels. The low-frequency channel, extending from 0.5 mm to 1 cm, was designed to obtain a precision comparison between the CMB spectrum and a Planckian calibration spectrum. The objective was to attain, in each 5% wide spectral element and each 7° pixel, an accuracy and sensitivity of $\nu I_\nu \cong 10^{-9}$ W m^{-2} sr^{-1} which is 0.1% of the peak brightness of a 2.7 K blackbody. The high-frequency channel, with a useful spectral range from 0.12 to 0.5 mm, was designed to measure the emission from dust and gas in our galaxy and to remove the effect of Galactic radiation on the measurements of the CMB made in the low-frequency channel.

The instrument directly measures the difference between the sky signal in its 7° beam and that from a temperature-controlled internal reference body. The best apodized spectral resolution is 0.2 cm^{-1} (6 GHz). The in-orbit absolute calibration of FIRAS was accomplished by inserting an external blackbody calibrator periodically into the mouth of the horn. The calibrator is a precision temperature-controlled blackbody, with an emissivity greater than 0.999. The FIRAS uses bolometric detectors in both channels.

The DMR consists of six radiometers, two at each freqency, designed to search for anisotropies with a mean sensitivity better than 0.15 mK rms (at frequencies of 53 and 90 GHz), and 0.3 mK (at 31.5 GHz), per 7° pixel on the sky after 1 year of observation. The 31.5 GHz radiometers are operated at 300 K, and those at higher frequencies are radiatively cooled to 140 K. Each radiometer has two beams oriented 60° apart; the received powers from each beam are differenced to obtain high-sensitivity measurements of anisotropies. The slow rotation of *COBE* about its spin axis interchanges the beams on the sky to reduce systematic errors as discussed in § 2.2. The multiple frequencies were selected to bracket the region where Galactic synchrotron emission, free-free emission, and radiation by interstellar dust are least, and to distinguish these sources from the CMB. Gain calibrations are obtained from

TABLE 1

COBE INSTRUMENT CHARACTERISTICS

PARAMETER	INSTRUMENT		
	DIRBE	DMR	FIRAS
Wavelength bands	1.25 μm[a] 15–30 μm 2.2 μm[a] 40–80 μm 3.5 μm[a] 80–120 μm 4.9 μm 120–200 μm 8–15 μm 200–300 μm	3.3 mm 5.7 mm 9.6 mm	0.5–10 mm 0.1–0.5 mm
Spectral resolution	$\lambda/\Delta\lambda = 1$–10	550 MHz (9.6 mm) 850 MHz (5.7 mm) 850 MHz (3.3 mm)	$\Delta\nu > 0.2$ cm^{-1} ($\nu < 20$ cm^{-1}) $\Delta\nu > 1.$ cm^{-1} ($\nu > 20$ cm^{-1})
Field of view	0°.7 square	7° FWHM	7° circular diameter
Instrument type	Multiband filter photometer/ polarimeter	6 Dicke-switched differential microwave radiometers	Polarizing Michelson interferometer
Flux collector	Off-axis Gregorian telescope 19 cm primary	Dual corrugated horns separated by 60°	Flared horn
Look direction[b]	30° off spin axis	Opposing pairs each 30° off spin axis	On spin axis
Instrument temperature	1.55 K (at bolometers)	300 K (9.6 mm) 140 K (5.7 and 3.3 mm)	1.55 K (at bolometers)
Detector	Photovoltaics bands 1–4 Photoconductors bands 5–8 Composite bolometers bands 9, 10	Diode mixers	Composite bolometers
Sensitivity	rms noise per FOV in 10 months[c] Band νI_ν (10^{-9} W m^{-2} sr^{-1}) 1.25 μm 1.0 2.2 μm 0.9 3.5 μm 0.6 4.9 μm 0.5 8–15 μm 0.3 15–30 μm 0.4 40–80 μm 0.4 80–120 μm 0.1 120–200 μm 11.0 200–300 μm 4.0	rms noise for a 1 s integration period (mK Hz$^{-1/2}$) 31 GHz Ch A 43. Ch B 42. 53 GHz Ch A 15.2 Ch B 16.4 90 GHz Ch A 27.5 Ch B 19.2	rms noise per FOV in 10 months for 3–20 cm^{-1} $\Delta T = 0.24$ mK $\Delta\nu I_\nu = 10^{-9}$ W m^{-2} sr^{-1}

[a] Linear polarization also measured.

[b] Spin axis is approximately normal to the Sun, directed away from the Earth.

[c] Based on instrument dark noise in orbit; actual performance is reduced by sky confusion noise.

the Moon, internal secondary reference noise sources, and the modulation of the CMB dipole by the Earth's motion around the Sun (Bennett et al. 1992).

The DIRBE optical system is a cryogenic, well-baffled, off-axis Gregorian telescope with a 19 cm diameter primary mirror. This design eliminates any obstruction in the beam. The DIRBE was designed to make an absolute measurement of the spectrum and angular distribution of the diffuse infrared background and therefore must have extremely strong rejection of stray light. The instrument covers the wavelength range from 1 to 300 μm in 10 bands with a design sensitivity per field of view on the sky of $\lambda I_\lambda = 10^{-9}$ W m^{-2} sr^{-1} in each band after 1 year of observation. The instrument also measures two perpendicular components of linear polarization in its short-wavelength bands at 1.2, 2.2, and 3.5 μm. The polarization measurements were included to help distinguish the contribution to the infrared background from sunlight scattered by interplanetary dust and to help in modeling the spatial distribution of the interplanetary dust cloud. Since the DIRBE optical axis is oriented 30° from the spin axis of the spacecraft, it views half the sky every day with many redundant scans at solar elongation angles ranging from 64° to 124°. Over the course of 6 months, every celestial direction is redundantly sampled at all possible elongation angles in this range.

The DIRBE is an absolute photometer which measures the difference between the sky brightness and a zero-flux internal surface using a tuning-fork chopper running at 32 Hz. The synchronously demodulated signal is averaged for 0.125 s before transmission to the ground. A cold shutter can be closed to block the sky signal to measure instrumental offsets. DIRBE uses celestial objects and internal thermal reference sources for monitoring response stability, and celestial sources for absolute response calibration. The instrument design, together with the mission and spacecraft capabilities, were chosen to facilitate discrimination of emissions from the solar system and our galaxy from that of an isotropic CIB.

3.2. *The Dewar*

The dewar is a 650 liter superfluid helium cryostat designed to keep the FIRAS and DIRBE instruments cooled to less than 1.8 K for a minimum of 6 months. The *COBE* dewar is similar to that flown on the *IRAS* mission (Neugebauer et al. 1984). An aperture cover, sealing the dewar, permitted calibration and performance testing of the cryogenic instruments prior to launch. A contamination shield attached to the inside of the dewar cover protected the DIRBE primary mirror from particulate or gaseous contamination. It also protected DIRBE from emission from warm parts of the cryostat during ground testing. In orbit, the helium effluent was vented along the spin axis near the communication atennas.

3.3. *The Sun-Earth Shield*

The conical Sun-Earth shield protects the scientific instruments from direct solar and terrestrial radiation and provides thermal isolation for the dewar. The shield also provides the instruments with isolation from Earth-based RFI and from the spacecraft transmitting antenna. The shield is made of 12 honeycomb panels covered with multilayer insulating (MLI) blankets, alternating with flexible MLI segments. The outer layer of the MLI is aluminized Kapton to resist degradation due to the orbital bombardment by monatomic oxygen. The upper portion of the inner surface of the shield is covered with low-emissivity aluminum foil to provide a high-quality surface viewing the instrumentation. The shield was designed to be flexible and folded to fit within the Delta rocket fairing for launch. Contamination covers attached to the Sun-Earth shield were placed over the DMR horn antennas and were pulled away in orbit by the deployment of the shield.

4. SPACECRAFT MODULE

The exterior of the spacecraft module, located below the instrument module is sketched in Figure 1. It includes the power system, the attitude control system, the command and data-handling system, the two on-board tape recorders, instrument electronic boxes, communication atennas, and solar panels. The design requirements and functions of the spacecraft components were described in § 2.

The rebuild of the new spacecraft module for launch on a Delta rocket was a major effort. The spacecraft, scientific instruments, and dewar had been completed before the Challenger explosion in 1986. The total mass of the satellite had to be reduced from 4540 to 2270 kg, which was accomplished without compromising the scientific objectives.

The major weight savings were in the spacecraft structure (which became much smaller) and the hydrazine propulsion system, which was no longer needed on the Delta. Battery size, which had been set by requirements for ascent from the Shuttle orbit, was reduced. The previously fixed solar panels were redesigned to deploy after launch. Redesign was also required for the power supply electronics, attitude control electronics, torquer bars, momentum wheels, and main electrical harnesses. An electronically switched steerable antenna was eliminated, and an antenna boom holding the two omni antennas was designed to deploy after launch.

The Sun-Earth shield was also completely redesigned. The original shield was a fixed cone with a diameter that filled the Shuttle bay. The new shield had to unfold in orbit, while retaining all its exacting thermal, RF, and stray light control requirements.

Although the major changes were confined to those given above, the scientific instruments did not completely escape modifications. The DMR radiometer heads had to be completely redesigned mechanically to fit without the Delta shroud and were attached directly to the dewar to save space. The vibration loads for a Delta, different from those for the Shuttle, required that the DIRBE chopping mechanism be redesigned.

5. OPERATIONS IN ORBIT

COBE was launched aboard Delta rocket No. 189 at 1434 UT on 1989 November 18 from the Western Space and Missile Center at the Vandenberg Air Force Base in California into the desired orbit. The spacecraft and orbital characteristics are given in Table 2.

The DMR receivers began operating the day after launch. The dewar cover was ejected 3 days after launch, and the FIRAS and DIRBE instruments began obtaining science data on the same day. During the first month in orbit, various tests were undertaken to evaluate the performance of the instruments and spacecraft and to optimize instrument parameters.

COBE operated in a routine survey mode. During the cryogenic lifetime, the satellite was periodically tilted a few degrees further away from the Sun than the nominal 94° at the beginning and end of each FIRAS calibration. This maneuver

TABLE 2

COBE SPACECRAFT AND ORBITAL CHARACTERISTICS

Orbit	
Altitude at insertion	900.2 km
Inclination	99°.3
Eccentricity at launch	0.0006
Mean eccentricity over 1 yr	0.0012
Time of ascending node	6 pm
Dimensions of spacecraft	
Total mass	2270 kg
Length	5.49 m
Diameter	8.53 m (with solar panels deployed) 2.44 m (with solar panels folded at launch)
Orbital period	103 minutes (nominal)
Spacecraft rotation rate	0.8 rpm (nominal)
Power available	750 W
Data rate	4 kbps
Dewar	
Capacity available	650 liters
At launch:	
Fill	100%
Fill after pump down	92.7%
Internal temperature	1.7 K
In orbit:	
Internal temperature	1.4 K
Sun-Earth shield	
Inner side temperature	180 K
Lifetime of helium in orbit	307 days

ensured that the external blackbody calibrator was not in direct sunlight as it moved above the plane of the Sun-Earth shield during insertion into the entrance horn of FIRAS.

The spacecraft altitude decreased at the rate of 30 m per day during the first 10 months of flight, due largely to the thrust from the efficient helium. (The pitch-back of the spacecraft from the velocity vector to minimize residual air impinging on the dewar caused the venting helium to apply a small thrust opposite to the velocity.) This loss of altitude did not present problems to the mission but needed to be considered in the attitude reconstruction.

The three instruments completed their first full sky coverage by 1990 mid-June and returned high-quality data until the depletion of the liquid helium at 0936 UT 1990 September 21. The FIRAS, which had surveyed the sky 1.6 times, ceased operating when the helium ran out, but the DMR is still operating normally in all of its six channels. By 1991 November (over 1 year after helium depletion) the dewar temperature at the DIRBE detectors was about 50 K. The six longest wavelength bands were turned off in 1990 September, but the four short-wavelength bands of the DIRBE continue to acquire data, although at reduced sensitivity. The detector system responsivity in the short-wavelength bands decreased about an order of magnitude following cryogen depletion (largely due to the change in load resistance). However, sky maps of the large-scale interplanetary dust signals continue to be of adequate quality to permit searching for evidence of temporal changes on annual time scales.

The continuing operation of the satellite will reduce the random noise in the CMB anisotropy measurements and will provide additional data for the control and measurement of systematic errors. The data from the four operating DIRBE bands are providing 2 full years of zodiacal light and emission mapping. These data will aid in modeling the zodiacal dust, in particular its evolution and dynamics, which will prove useful in the search for the CIB.

An unanticipated problem with FIRAS occurred after launch. A position sensor in the mirror transport mechanism of the interferometer was triggered by energetic charged particles trapped in Earth's magnetic field, especially during passages through the South Atlantic Anomaly (SAA). As a result, the transport mechanism went to its end-of-travel and continued to drive against its stop, dissipating excess power into the dewar. Once understood, the problem was largely overcome by commanding the transport mechanism to cease scanning on entry to the SAA and to resume normal operation on leaving the SAA. This anomaly somewhat shortened the lifetime of the helium.

The dewar performed thermally better than expected. In flight the helium temperature inside the main cryogen tank was 1.40 K (the design requirement was 1.6 K). The temperature of the inner surface of the Sun-Earth shield was 180 K (the requirement was 220 K), allowing the outer dewar wall and cryogenic instruments to operate at colder temperatures. As expected, the Earth limb rose a few degrees above the Sun-Earth shield for a part of every orbit during a 3 month period starting in May. Earth's radiation produced thermal transients in the instruments and adversely affected data for a portion of each orbit, but some of these data are still usable after careful calibration. The 10 month lifetime of the cryogen is consistent with the detailed prelaunch model of the cryostat after taking into account Earth limb heating near the solstice, the FIRAS mirror transport anomaly, and the heat dissipated in normal operation and calibration cycles of the instruments.

All of the spacecraft systems operate well, achieving the mission design requirements. One of *COBE*'s gyros for a transverse control axis failed electrically on the fourth day after launch. The attitude control electronics on the failed gyro were cross-strapped out that same day, and no science data were lost. The nominal spin rate of 0.8 rpm was achieved on November 27, after increasing the rate from 0.4 rpm in several small steps, as planned. The remaining gyros and all other spacecraft systems performed flawlessly during the lifetime of the cryogen.

On 1991 September 7, one of the three gyros on the spin-axis failed, but again no data were lost. Fine-aspect solutions were not carried out for 3 days while changes in gyro use were implemented. Since that date there have been no further problems, and operations continue as planned.

6. EARLY RESULTS, FUTURE PLANS

6.1. *Scientific Results*

Since launch, preliminary analyses of *COBE* data have led to several major cosmological advances. The results to date have firmly established the thermal nature of the CMB spectrum and have added more stringent limits on the large-scale structure of the primeval universe. It is particularly difficult to reconcile the known large-scale distribution of galaxies with the apparent smoothness of the CMB. A brief summary is given here of the results obtained during the first 2 years after launch.

The FIRAS data confirmed the prediction of the Big Bang model that the CMB must have a thermal spectrum. Initial results based on 9 minutes of data showed that there is no deviation from a blackbody spectrum $B_\nu(T)$ as large as 1% of the peak brightness (Mather et al. 1990a) over the spectral range from 500 μm to 1 cm. The temperature of the CMB in the direction of the north Galactic pole is 2.735 ± 0.060 K, where 60 mK is the initial conservative uncertainty in the calibration of the thermomemtry of the absolute calibrator. These data also have ruled out the existence of a hot smooth intergalactic medium that could emit more than 3% of the observed X-ray background. The thermal character of the CMB spectrum was subsequently confirmed by Gush, Halpern, & Wishnow (1990), who obtained virtually the same temperature.

More recently Shafer et al. (1991) and Cheng et al. (1991) have examined FIRAS spectra in a direction known previously to be very low in interstellar material ($l = 142°$, $b = 55°$). In this direction, known as Baade's Hole, the temperature is 2.730 ± 0.060 K, and there is no deviation from a blackbody spectrum greater than 0.25% of the peak brightness.

The dipole anisotropy of the CMB can be seen clearly in both the FIRAS and DMR data, and is consistent with previous results (Cheng et al. 1990). The FIRAS data show for the first time that the difference in spectra between the poles of the dipole is that expected from two Doppler-shifted blackbody curves. This result also indicates that the stability of the FIRAS instrument is better than one part in 5000 over long time scales. Wright et al. (1990) have used the FIRAS and DMR data to show that the ratio of the Galactic emission to that of the CMB reaches a minimum between 60 and 90 GHz.

FIRAS results also include the first all-sky far-infrared spectral-line survey, as well as maps of the Galactic dust distribution at wavelengths greater than 120 μm. Lines from interstellar [C I], [C II], [N II], and CO have been detected, and the lines of [C II] at 158 μm and [N II] at 205.3 μm were sufficiently strong to be mapped (Wright et al. 1991). This is the first time the 205.3 μm line has been observed. The total far-infrared luminosity of the Galaxy is inferred to be $(1.8 \pm 0.6) \times 10^{10} L_{\odot}$.

In ten months of cryogenic operation the FIRAS obtained over two million interferograms. This complete data set is now undergoing careful analysis, and data processing software developed in response to the anomalous operation of the mirror mechanisms is nearly completed.

The DMR has obtained the most precise all-sky maps to date of the microwave background. Results using the first several months of DMR data with their cosmological implications were first reported by Smoot et al. (1991a). The all-sky maps in all six channels reveal the promminent features of the dipole anisotropy and Galactic emission. In these early data, using conservative systematic error estimates, the 95% CL upper limit to the rms quadrupole amplitude corresponds to $\Delta T/T < 3 \times 10^{-5}$, and anisotropies on all angular scales larger than 7° are smaller than 4×10^{-5} (Smoot et al. 1991b).

The DIRBE data provide the most extensive infrared absolute sky brightness measurements and maps to date, providing new views of the Milky Way and permitting the first systematic search for the cumulative radiation from the earliest luminous objects in the universe. Preliminary results from the DIRBE have been given by Hauser et al. (1991). A spectrum determined from data in one of the darkest directions in the sky, the south ecliptic pole, shows that the faintest levels of emissions from our galaxy and solar system occur at wavelengths in the vicinity of 3.4 μm and near or longward of 240 μm. A comparison of DIRBE data with those of *IRAS* reveal significant differences at 60 and 100 μm, indicating errors in the zero point determinations and in the low-frequency gain for diffuse sources used in *IRAS*. Quantitative characterization of these differences is in progress. Three bright comets were observed with the DIRBE during the first year of operation. Preliminary presentations of these data have been given by Lisse et al. (1991).

Numerous papers giving overviews, implications, and additional detailed information about *COBE* have been presented by Mather et al. (1990b), Mather et al. (1991), Mather (1991), Janssen & Gulkis (1991), Wright (1990), Wright (1991), Hauser (1991a), Hauser (1991b), Smoot et al. (1991c), Smoot (1991), Bennett (1991), and Boggess (1991). It should be emphasized that all of those presentations are based upon preliminary reduction and analysis of small samples of the *COBE* data. Far more precise and accurate measurements will emerge in the coming years following careful photometric data reduction, assessment of systematic errors, modeling, and acquisition of additional data.

6.2. *Data Products and Plans*

Extensive data products from the *COBE* mission consisting of calibrated maps and spectra with associated documentation will be made publicly available. The *COBE* data bases have been described by White & Mather (1991). The design of the *COBE* software system has been described by Cheng (1991).

All *COBE* data processing and software development for analysis take place at the Cosmology Data Analysis Center (CDAC) in Greenbelt, MD, a facility developed by the *COBE* project for that purpose. This facility, and the software tools developed there, will become available to the scientific community when the data products become public.

The initial data products are planned for release in mid-1993 and will be calibrated and corrected for almost all known instrumental and spacecraft effects. The initial maps will include all 10 DIRBE bands and the high-frequency FIRAS band for the Galactic plane, including the nuclear bulge. The DMR data will be all-sky maps from all six radiometers.

Full sky maps from all three *COBE* instruments, spanning four decades of wavelength, are planned for release in mid-1994. After proper characterization, calibration and the removal of sources of systematic error have been accomplished, the data gathered by *COBE*'s three instruments will constitute a comprehensive data set unprecedented in scope and sensitivity for studies of cosmology, Galactic astronomy, and solar system science.

In addition to the authors of this paper, many people have made essential contributions to the success of *COBE* in all its stages, from conception and approval through hardware and software development, launch, and flight operations. To all these people, in government agencies, universities, and industry, the authors extend their thanks and gratitude. In particular, we thank the large number of people at the GSFC who brought this challenging in-house project to fruition.

APPENDIX

The *COBE* Science Working Group, listed in Table 3, has provided scientific guidance throughout *COBE*'s design, development, test, and data analysis phases. 11 members are co-investigators on all three instruments and are responsible for the scientific integrity of the data and their initial interpretation.

TABLE 3

COBE Science Working Group (SWG)

Name	Affiliation	Project Function
Bennett, C. L.	NASA-GSFC	DMR Deputy Principal Investigator
Boggess, N. W.	NASA-GSFC	*COBE* Deputy Project Scientist
Cheng, E. S.	NASA-GSFC	*COBE* Deputy Project Scientist
Dwek, E.	NASA-GSFC	...
Gulkis, S.	NASA-JPL	...
Hauser, M. G.	NASA-GSFC	DIRBE Principal Investigator
Janssen, M.	NASA-JPL	...
Kelsall, T.	NASA-GSFC	DIRBE Deputy Principal Investigator
Lubin, P. M.	UCSB	...
Mather, J. C.	NASA-GSFC	FIRAS Principal Investigator and *COBE* Project Scientist
Meyer, S. S.	MIT	...
Moseley, S. H.	NASA-GSFC	...
Murdock, T. L.	General Research Corp.	...
Shafer, R. A.	NASA-GSFC	FIRAS Deputy Principal Investigator
Silverberg, R. F.	NASA-GSFC	...
Smoot, G. F.	U C Berkeley	DMR Principal Investigator
Weiss, R.	MIT	*COBE* SWG Chairman
Wilkinson, D. T.	Princeton	...
Wright, E. L.	UCLA	...

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