Space Instrumentation: Cosmic Backgrounds

The cosmic microwave background (CMB) radiation contains approximately 99% of the electromagnetic radiation energy in the universe, and its photons outnumber the known massive particles by a factor of $\sim 10^8$. It is the primary observable indicator of conditions in the early universe and, according to COBE, it is remarkably featureless. Its spectrum is indistinguishable from a perfect blackbody spectrum with temperature 2.725 K. Other than the dipole variation, likely due to the motion of the solar system with respect to the CMB rest frame, its brightness is nearly isotropic with rms variations of only 30 μK on angular scales of 10 degrees. The cosmic infrared background (CIB) radiation recently detected by COBE is presumably due to the accumulated infrared emission from the first dusty galaxies to form in the universe. The observed properties of the infrared background will place strong constraints on the star formation history of the universe.

The COBE mission carried three instruments designed to probe these cosmic background radiations. The DIRBE was designed to make an absolute measurement of the spectrum and angular distribution of the diffuse infrared background. The FIRAS instrument was designed to study the spectrum of the CMB, and the DMR was a set of differential radiometers designed to measure the anisotropy of the CMB. A follow-up mission to COBE called MAP will carry a set of differential microwave radiometers that will remeasure the anisotropy of the CMB with much higher sensitivity and spatial resolution than did DMR. In the years leading up to the launch of MAP there have been a number of ground and balloon-based measurements of the CMB that have provided the first look at degree scale anisotropy. These measurements are covered in the general CMB article by WRIGHT. A follow-up mission to MAP, planned by ESA and called PLANCK, is to follow the MAP satellite and is supposed to provide the definitive measurement of the CMB anisotropy.

DIRBE

The DIRBE instrument was designed to make an absolute measurement of the spectrum and angular distribution of the diffuse infrared radiation. One of the most challenging aspects of this experiment is the need to understand and remove foreground emission from our own galaxy and solar system, which is known to substantially outshine the CIB. This drives the design of the instrument to include many well spaced frequency channels each of which requires very accurate absolute photometry.

The instrument is a cryogenically–cooled ten band absolute photometer that covers the wavelength range

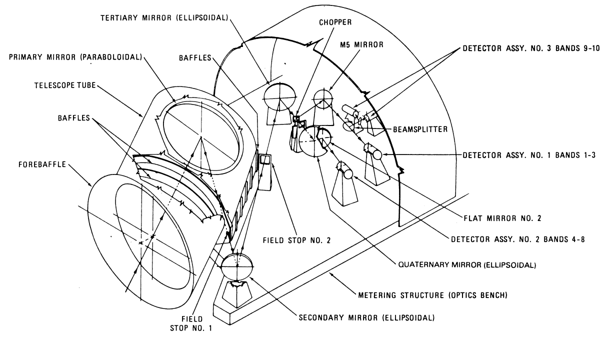

Figure 1: A schematic overview of the COBE-DIRBE 10 channel absolute photometer.

from 1.25 μm to 240 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}. The instrument also measures two perpendicular components of linear polarization in its short wavelength bands at 1.25, 2.2, and 3.5 μm. The polarization measurements were included to help distinguish the CIB from sunlight scattered by interplanetary dust. To further aid in separating interplanetary emission from more distant sources, the DIRBE optical axis is oriented 30° from the spin axis of the COBE spacecraft, so it views half the sky every day at solar elongation angles ranging from $\varepsilon = 64°$ to 124° with many redundant scans. Over the course of six months, every celestial direction is redundantly sampled at all possible solar elongation angles in this range.

The DIRBE optics were carefully designed for strong stray light rejection (Figure 1). The configuration includes extensive internal baffling as well as a reflective forebaffle, and a complete light–tight enclosure within the COBE dewar to eliminate any optical cross–talk from the dewar or the FIRAS instrument. Additional protection from the Earth and Sun are provided by the shield surrounding the COBE dewar, which prevent any direct illumination of the dewar from these strong local sources. The front end of DIRBE utilizes an off–axis folded Gregorian telescope with a 19 cm diameter off–axis segment of a parabolic mirror as the primary. An off–axis segment of an elliptical secondary forms an image of the primary at a pupil stop (Lyot stop) which is smaller than the image of the primary, blocking radiation diffracted from the primary mirror. The secondary mirror also images the first field stop at a second field stop which is smaller than the first, blocking stray radiation scattered or diffracted at the first stop and setting the $0.^\circ7 \times 0.^\circ7$ instantaneous field of view. An ellipsoidal tertiary mirror images the pupil (Lyot stop) at a tuning fork chopper with mirrored blades. When the chopper is open, sky light reaches the elliptical quaternary mirror which images the pupil via a folding flat onto detector assembly 2. With the chopper closed, the aspheric mirror (M5) reimages the pupil onto detector assemblies 1 and 3.

In this arrangement, all detector assemblies are located at a pupil image and all of the spectral bands view the same instantaneous field of view. Each detector assembly received radiation chopped alternately between the sky and the cold beam stop. The cold beam stop is a black enclosure maintained below 3° K, producing no detectable signal at any DIRBE wavelength. DIRBE sky measurements were thus continuously referenced to zero flux – a crucial feature for reliable absolute photometry. Instrumental offsets were determined by blocking the sky with a cold shutter located at the prime focus. The shutter was demonstrated to attenuate saturation level sky signals to well below instrument noise levels at all DIRBE wavelengths. The back of the shutter has a mirror which allows light from an internal reference source (IRS), located out of the path of the sky beam, to reach the detectors via the secondary and subsequent mirrors when the shutter is closed. Measuring the instrument signal with the shutter closed and the IRS off permits determination of instrumental noise levels and electrical and radiative offsets. Turning on the IRS at fixed levels permits monitoring of system gain stability. The instrument readout with the shutter closed and the IRS turned off defined zero sky brightness for the DIRBE measurements.

FIRAS

The FIRAS instrument was designed to study spectrum of the CMB. As with the DIRBE instrument, this experiment requires very accurate absolute photometry and high gain stability. One of the key features of FIRAS is that it is differential: the instrument directly measures the difference between the sky signal (in a 7° beam) and that from a temperature controlled internal reference body (ICAL) whose emission is within 5% of a blackbody. The absolute calibration of FIRAS was accomplished in orbit by inserting an external blackbody calibrator (XCAL) periodically into the mouth of the sky horn. The XCAL is a precision temperature-controlled blackbody, with an emissivity greater than 0.999. Both the ICAL and XCAL are temperature controlled by command over the range from 2 to 25 K. This allows the sky signal to be approximately balanced and aids in distinguishing sky signals from instrument self emission. The differential nature of the instrument and the commandable temperature controlled inputs are the keys to the accuracy of FIRAS.

The heart of instrument is a four-port Michelson interferometer with two inputs (used differentially) and two outputs (Figure 2). The two input ports are fed by optically matched quasi-optical horn antennas. The interferometer uses polarizing grids as beam splitters

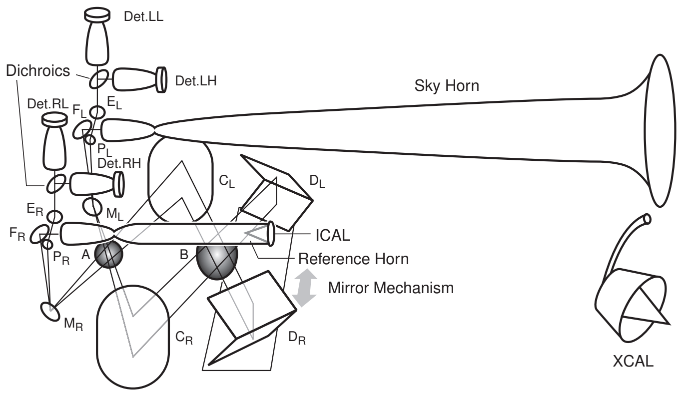

Figure 2: A schematic diagram of the Far Infrared Absolute Spectrophotometer (FIRAS).

and creates an interferogram (Fourier transform of the source spectrum) by scanning a movable mirror platform. A dichroic filter at each output port further splits each beam into low and high frequency bands. The low frequency band, extending from 0.5 mm to 1 cm, was designed to measure the CMB spectrum. The high frequency band, from 0.12 to 0.5 mm, was designed to measure the emission from dust and gas in our galaxy and to allow the removal of this foreground from the low frequency CMB data. The objective was to attain a sensitivity of $\nu I_\nu \simeq 10^{-9}$ W m^{-2} sr^{-1} (0.1% of the peak brightness of a 2.7 K blackbody) in each 5% wide spectral element, in each 7° sky pixel. The FIRAS uses bolometric detectors in both frequency channels.

A movable mirror mechanism modulates the path difference, x, between the two optical paths resulting in a varying signal at the output ports proportional to the cosine transform of the input spectra $I(x) = \int d\nu S(\nu) \cos 2\pi\nu x$. The design symmetry and phase delays imposed by the beam splitter and analyzer polarizers make FIRAS a differential instrument. The nearly blackbody ICAL signal is controlled by attached heaters to nearly balance the sky input from the CMB. This reduces the net input signal by 99% and is responsible for the ability of FIRAS to detect deviations of the CMB from a perfect blackbody to less than 0.005% (rms) of the peak.

Absolute measurements of the sky flux require knowing the emission of the ICAL and other components of the instrument. This is done by examining the changes in the observed spectrum with variations in the component temperatures. For the ICAL and two horns, variation is produced by commands to attached heaters. The overall throughput of the instrument is measured by placing an external calibrator, or XCAL, in the sky horn aperture – replacing the sky signal with a known input. The XCAL signal is known because it is a blackbody to within 0.005% both by construction and as verified in ground measurements. Its temperature is controlled by an attached heater and measured by a set of thermometers. Errors in the thermometry of the XCAL are the limiting factor when comparing the absolute sky flux measurements of FIRAS to other instruments.

Other design features that contribute to the success of FIRAS include a large etendue (throughput) for high sensitivity; two path length differences for the mirror mechanism (1.2 and 5.9 cm) allowing for higher frequency resolution for the longer stroke length; and two scan speeds for the mirror mechanism to help distinguish instrument errors. The entire instrument is operated in a vacuum and cooled to 1.5 K by conduction to a superfluid liquid helium tank. A large external conical shield protects the cryostat and instruments from direct radiation from the Sun and the Earth.

DMR

The purpose of the Differential Microwave Radiometers (DMR) experiment is to measure large angular scale anisotropy of the CMB. Measuring the temperature of the microwave sky to an accuracy of one part in 10^5 requires careful attention to possible sources of systematic errors. Due to the extraordinary isotropy of the CMB, one of the primary concerns is instrument stability since any small perturbation to the instrument in the form stray radiation, electronic pick-up or thermal effects can easily produce a false signal that exceeds the anisotropy signal. One of the most important safeguards is to make the instrument differential. The DMR instrument consists of six differential microwave radiometers, two nearly independent channels (labeled A and B) at each of three frequencies: 31.5, 53, and 90 GHz. Each radiometer measures the difference in power, expressed as a differential antenna temperature, between two regions of the sky separated by 60°. The combined motions of spacecraft spin (73 s period), orbit (103 m period) and orbital precession ($\sim 1°$/day) allow each sky position to be compared to all others through a highly redundant set of all possible difference measurements spaced 60° apart. The DMR has three separate receiver boxes, one for each frequency, that are mounted 120° apart on the outside of the COBE cryostat containing the FIRAS and DIRBE. A shield surrounding the aperture plane protects all three instruments from solar and terrestrial emission. The 31 GHz system operates at room temperature while the 53 and 90 GHz systems are passively cooled to 140 K.

The antennas are wavelength-scaled corrugated horns that were chosen for their low sidelobe response, low insertion loss, and compactness. The main beam response is approximately Gaussian with a 7° FWHM. Each pair of antennas (labeled 1 and 2) feed a Dicke-switched radiometer. The output of the ferrite Dicke switch alternates the signal from the two input antennas at a rate of 100 Hz. This is an essential step in the process of reducing systematic effects by reducing the impact of low-frequency gain fluctuations and $1/f$ noise in the radiometer amplifiers. The output of the Dicke switch is sent through ferrite isolation to a mixer-preamplifier. A local oscillator signal obtained from a Gunn diode oscillator is used to mix the signal down to intermediate frequencies. It is then sent to a lock-in amplifier where the signal is square-law detected, converted to a proportional voltage and amplified with a lock-in that is synchronous to the Dicke switch. The lock-in amplifier includes a circuit which integrates this switch-modulated signal for 0.5 s producing a voltage that is proportional to the brightness difference between the two input signals. The signal is calibrated to antenna temperature by periodically injecting broad-band power of a known amplitude from a noise diode into the throat of each antenna.

MAP

The MAP mission is a follow-up to the COBE mission that is scheduled to launch in the Spring of 2001. MAP will remeasure the anisotropy of the CMB with higher sensitivity and angular resolution than COBE-DMR. The MAP instrument consists of a set of passively cooled microwave radiometers with 1.4×1.6 meter diameter primary reflectors to provide the desired angular resolution of less than $0.^{\circ}3$. The need to suppress systematic measurement errors led to the following instrument features: 1) MAP is a differential experiment based on pseudo-correlation microwave radiometers. The instrument measures temperature differences between two points $\sim 141°$ apart on the sky. 2) MAP will orbit about the Sun-Earth L_2 libration point which provides for a very stable thermal environment and near 100% observing efficiency since the Sun, Earth, and Moon are always behind the instrument's field of view. 3) MAP will rapidly scan the sky to compare many pixels pairs on many different time scales.

The reflector design incorporates two back-to-back off-axis Gregorian telescopes with 1.4×1.6 m primary reflectors and 0.52 m secondary reflectors. Each primary is a shaped elliptical section of a paraboloid, while the secondaries are nearly elliptical. This arrangement produces two slightly convex focal surfaces on opposite sides of the spacecraft spin (and symmetry) axis with plate scales of $15'$/cm. In order to limit diffracted signals to less than 0.5 μK, diffraction shields are employed above, below, and to the sides of each secondary. In addition, the deployable solar panels and multi–layer insulation guarantee that the secondaries remain in shadow during observing.

The feed design calls for as small an aperture as possible consistent with a primary edge taper require-

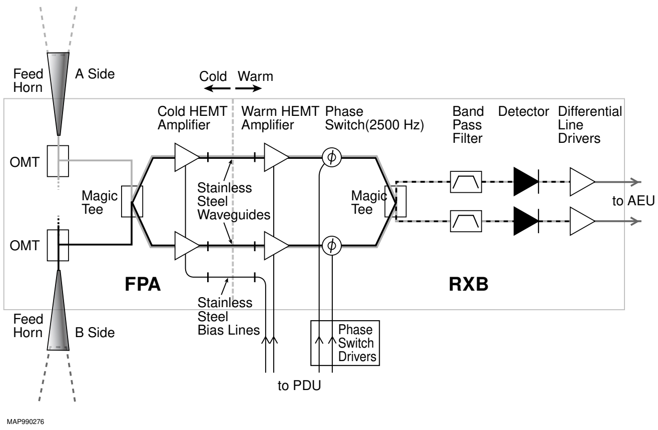

Figure 3: A schematic diagram of a single MAP pseudo-correlation radiometer including the cold Focal Plane Assembly (FPA) and the warm Receiver Box (RXB).

ment of -20 dB, and a length that places the throat of each differential feed pair in close proximity to the other. The feed aperture diameters scale inversely with frequency, while the primary is equally illuminated at each frequency, leading to a frequency dependent beam size. The feeds are corrugated to produce beams with high symmetry, low loss, and minimal sidelobes. The phase center of each feed is kept as close as possible to its aperture, resulting in a frequency-independent beam for each feed.

The microwave system consists of 10 4-channel "differencing assemblies", one for each pair of feeds (Figure 3). One assembly operates at 22 GHz, one at 30 GHz, two at 40 GHz, two at 60 GHz, and four at 90 GHz. This gives the spectral coverage required to separate galactic foreground emission from the CMB and provides roughly equal sensitivity at each frequency. Each feed is attached to a low-loss orthomode transducer which separates the sky signal into two orthogonal polarizations. The A side signal of one polarization is differenced against the orthogonal polarization, B′, from the corresponding B-side feed, and vice-versa. The differencing is accomplished by first combining the two signals A and B′ in a hybrid tee to form $(A+B')/\sqrt{2}$ and $(A-B')/\sqrt{2}$, then amplifying each in two cold High Electron Mobility Transistor (HEMT) amplifiers and sending the phase-matched outputs to the warm receiver box (RXB) via waveguide. In the RXB the two signals are amplified in two warm HEMT amplifiers, phase switched between 0 degrees and +90 or -90 degrees, respectively, at 2.5 kHz, then split back into A and B′ in a second hybrid tee. At this point, the two signals are square-law detected, amplified by two line drivers, and sent to the Analog Electronics Unit for synchronous demodulation and digitization. The other pair of signals, A′ and B, are differenced in the same manner giving a total of four detector channels per differencing assembly. The output in each channel is proportional to the temperature difference between the A and B side pixels. The signal is calibrated by fitting the data to the strong dipole signal that was accurately measured by COBE.

The splitting, phase switching, and subsequent combining of the signals enhances the instrument's performance in two ways. 1) Since both signals to be differenced are amplified by both amplifier chains, gain fluctuations in either amplifier chain act identically on both signals and thus cancel upon differencing. 2) The phase switches introduce a 180 degree relative phase change between the two signal paths, thereby interchanging which signal is fed to which square law detector. Thus, low frequency noise from the detector diodes is common mode and also cancels, further reducing susceptibility to systematic effects.

PLANCK

PLANCK is the third Medium-Sized Mission (M3) of ESA's Horizon 2000 Scientific Programme. It is designed to image the anisotropy of the CMB over the whole sky, with unprecedented sensitivity and angular resolution. It is now planned to launch in the first quarter of 2007 together with the FIRST satellite, in a configuration often referred to as the "Carrier" (because FIRST is "carried" by PLANCK in the launcher). After launch, PLANCK and FIRST will separate and will be placed in different orbits around the second Lagrangian point of the Earth-Sun System. PLANCK will carry two main instruments: the Low Frequency Instrument (LFI) which covers the frequency range 30-100 GHz, and the High Frequency Instrument (HFI) which will cover the frequency range 100-850 GHz. This very wide frequency coverage should provide a wealth of information on both the CMB anisotropy and on a number of interesting foreground sources such as the Sunyaev-Zeldovich effect and emission from our own Galaxy. Further information on the PLANCK mission may be found on the PLANCK web site at http://astro.estec.esa.nl/Planck/.

Bibliography

For more information on the COBE mission see Boggess et al. 1992 The COBE Mission: Its Design and Performance Two Years After Launch *Astrophys. J.* **397** 420. See also the COBE web site at http://space.gsfc.nasa.gov/astro/cobe/. A very complete description of the COBE-DIRBE instrument is given in the DIRBE explanatory supplement located on the COBE web site.

A very complete description of the COBE-FIRAS instrument is given by Mather, J C, Fixsen, D J, and Shafer, R A 1992 in Proc. SPIE, 2019, 168 (SPIE:

Bellingham, WA). This is also available in Postscript form from the COBE web site.

The design of the COBE-DMR experiment is given by Smoot et al. 1990 COBE Differential Microwave Radiometers: Instrument Design and Implementation *Astrophys. J.* **360** 685.

Further information on the MAP mission may be found on the MAP web site at http://map.gsfc.nasa.gov/.

Further information on the PLANCK mission may be found on the PLANCK web site at http://astro.estec.esa.nl/Planck/.

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