Design for the *COBE*[1] Far Infrared Absolute Spectrophotometer (FIRAS)

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Abstract

The Far InfraRed Absolute Spectrophotometer (FIRAS) was built to measure the spectrum of diffuse emission from 1 to 100 cm^{-1}, with particular attention to possible differences between the spectrum of the cosmic microwave background radiation (CMBR) and a blackbody spectrum as small as 0.1% of the peak of the CMBR spectrum. The FIRAS has differential inputs and outputs, a full beam external calibrator, a controllable reference blackbody, and a polarizing Michelson interferometer with bolometer detectors. It operated at a temperature of 1.5 K inside a liquid helium cryostat to suppress instrument emission and improve detector sensitivities. It has an intrinsic frequency resolution of the order of 0.7%, maximum path lengths of 1.2 and 5.9 cm, and a beamwidth of 7°, and achieved its goals for accuracy and rms sensitivity for νI_ν, which are better than 10^{-9} $\mathrm{W/cm^2sr}$ over the frequency range from 2 to 20 cm^{-1}.

1. Introduction

The cosmic microwave background radiation (CMBR) 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 indistinguishable from a perfect blackbody spectrum[1] with temperature $T = 2.726$ Kelvin (within 0.03% from 2 to 20 cm^{-1}). Other than a $\cos\theta$ variation, probably due to the motion of the solar system with respect to the CMBR rest frame[2,3], it is nearly isotropic[4] with rms variations of only 30 μK on angular scales of 10°. A blackbody spectrum is the equilibrium form and, as the photons outnumber the matter particles by such a large factor, even small deviations from the blackbody form require a massive energy release or conversion from other forms. Four characteristic forms of deviation can arise during different epochs of the expanding universe, as defined by the redshift z: a Bose-Einstein distribution with a chemical potential μ for $10^6 > z > 3\times10^4$; a Comptonized distribution characterized by y for $3\times10^4 > z > 10^3$; an optically thin Comptonization, possibly relativistic, by a hot intergalactic medium for $10^3 > z$; and thermal emission from dust. So far, the only deviations detected by FIRAS are consistent with thermal emission from dust, and that is consistent with all emission from dust within our Galaxy. Other microwave/radio observations have detected a diminution in the CMBR flux in the directions of certain clusters of galaxies (the Sunyaev-Zeldovich effect) which is an example of Comptonization effect from the same high temperature electrons that are directly observed in the X-ray observations of these same clusters.

The Far InfraRed Absolute Spectrophotometer (FIRAS) on the *COBE* satellite[5,6,7] is designed to measure small deviations (0.1%) of the CMBR from a blackbody spectrum. It improves upon previous measurements in reducing the potential contributions of the systematic errors by: 1) operating outside the atmosphere; 2) providing full aperture *in situ* calibration; 3) providing a continuous differential comparison with a reference blackbody adjusted to null the input signal; 4) operating the entire instrument, including the beam forming optics, in a shielded environment at cryogenic temperatures; and 5) using an improved horn antenna with a flared aperture to define the beam and reduce the contributions from objects outside the main beam.

The heart of the FIRAS is a polarizing Michelson Fourier spectrometer, operated with rapid scans inside a helium cryostat. It has two inputs (used differentially) and two outputs (each split into high and low frequencies by dichroic filters), and uses bolometer detectors. It has a movable external calibrator and an internal reference

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body, and optically matched quasi-optical horn antennas on the two inputs. Both calibrators and both antennas are temperature controlled by command over the range from 2 to 25 K. The differential nature of the instrument and the temperature controlled inputs are the keys to the accuracy of the instrument.

This paper describes the environment and interfaces for the FIRAS, its optical concept, mirror mechanism design, detectors and analog signal processing, digital signal processing, temperature controllers and monitors, and command capabilities. Detailed calibration algorithms, software design, calibrator design and test results, performance summaries, and scientific results have been presented elsewhere, including the current measurements of the CMBR spectrum[1] and its interpretation[8]; a measurement of the CMBR "dipole" spectrum[2]; a detailed discussion of the instrument calibration[9]; and a preliminary measurement of the galactic dust spectrum, and the detection of associated molecular and atomic lines from the galactic interstellar medium[10].

2. Optical Design

The FIRAS is a rapid-scan polarizing Michelson interferometer similar to earlier balloon and rocket instruments[11,12,13,14] with several improvements. The optical concept is given in Fig. 1. The optical layout has dual inputs and outputs. The two inputs are labeled as *Sky* and *ICAL*, where the Sky input is usually open to the sky via a 12.8 cm diameter non-imaging concentrator with 7° field of view (the *Sky Horn*), while the ICAL input is connected to an internal calibration source (ICAL) whose emission is within 5% of a blackbody via a similar concentrator (the *Reference Horn*). The two output ports are denoted as the *Left* and *Right* side outputs.

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, or interferograms $I(x) \propto \int \; d\nu \; S(\nu) \cos(2\pi\nu x)$. The design symmetry and phase delays imposed by the beamsplitter and analyzer polarizers make FIRAS a differential instrument. The nearly blackbody ICAL signal is controlled by attached heaters. Adjusting the ICAL temperature to balance the sky input from the CMBR reduced the net signal by 99%. This differential approach is responsible for the ability of FIRAS to detect deviations of the CMBR from a perfect blackbody 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 (see Figure 4a). The XCAL signal is known because it is a blackbody to within 0.005%, both by construction and as shown by ground measurements, and 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 instrument design features that contribute to the FIRAS's success: a large étendue, 1.5 cm^2 sr for high sensitivity; two path length differences for the mirror mechanism of 1.2 and 5.9 cm allowing higher frequency resolution for the longer stroke length; and two scan speeds for the mirror mechanism to help distinguish instrument errors. The instrument operates over a frequency range from 1 to 100 cm^{-1}, with the upper limit determined by the high frequency performance of the beamsplitters. Each output beam is divided into a high frequency (> 20 cm^{-1}) and a low frequency channel using dichroic beam-splitters, for a total of four signal channels.

2.1 Calibrators

A significant advance over the previous instruments is the ability to replace the sky input with a high precision external blackbody with calculated effective emissivity >0.99995, based on measured material properties and the optical design. The calibrator is a folded cone with the shape of a trumpet mute (see Fig. 2a), made of Eccosorb CR-110 with a 25° included angle[15]. With this geometry, any ray received by the spectrometer from the calibrator undergoes at least 7 specular reflections from the Eccosorb, thus reducing the effective reflectance from the $\sim$ 11% of a single normal specular reflection to $\sim (0.11)^7 = 2 \times 10^{-7}$. The low net reflectance of the XCAL was confirmed at 1 and 3 cm^{-1} with ground based measurements.

The ICAL (see Fig. 2b) is smaller than the XCAL, and its measured emissivity is ~ 0.96. It is a cone pointed toward the detectors, so radiation from the detectors that is reflected from the ICAL will also reflect from the horn antenna before returning to the reference body for another chance to be absorbed. The point of the cone is cut off and replaced with two small "hot spots," small bodies which can be raised to high temperatures with little input power. These were used on the ground with short electrical pulses to stimulate the detectors and simulate cosmic ray impacts, but have not been useful in the photometric calibration. They are probably responsible for a ripple in the observed emissivity of the ICAL, having a peak to peak amplitude of 0.8% and a periodicity of $\sim$1.3 cm^{-1}(see

Fig. 4b). The periodicity arises from interference between waves reflected from the surfaces of the hot spots and the neighboring metallic supports. In general, these were not used in orbit. The calibration of FIRAS depends on both the calibrators being known, constant, uniform temperatures.

2.2 Antennas - The Sky Horn and Reference Horn

A ray, either from the sky or from the XCAL, must first pass through the Sky Horn, a non-imaging parabolic concentrator (Winston cone) which defines the accepted radiation from the sky, and establishes multiple images of the sky at the throat of the cone. The Sky Horn has a smoothly flared aperture to reduce diffractive sidelobes over a wide frequency range. The area of the throat (0.48 cm^2) and the effective beam pattern at the throat, π sr, establish the étendue of the instrument as $A\Omega = \pi^2 r^2_{\mathrm{throat}} = 1.5\ \mathrm{cm}^2\mathrm{sr}$. The effective beam size on the sky can be found by equating this to $\pi^2 r^2_{\mathrm{mouth}} \sin^2\theta_{\mathrm{max}}$, where $\theta_{\mathrm{max}} = 3.5°$ is the ideal half beamwidth on the sky. The étendue also establishes the long wavelength diffraction cutoff of the instrument, since the number of geometrical modes of the radiation field accepted is $A\Omega/\lambda^2$.

The detailed design of the horn antenna has been given previously[16], along with ground based measurements of the beam profile from $\lambda = 1$ cm to 0.5 μm. At long wavelengths, the beam is governed by diffraction of a few modes, while it is a top hat at short wavelengths, as required by geometrical optics. The orbit determination of the instrument beam profile (see Fig. 3), using the moon as a "point" source of illumination, shows an unexpected excess response from 20° to $\sim 60°$. The amplitude, though small, $\sim 3 \times 10^{-5}$ of the on axis response, is such that the moon is detectable in some high galactic latitude data out to 60°.

The central portion of the beam $< 3.5°$ is not flat topped, showing variations of as much as 30%. This is only important when making measurements of sky features with angular variations smaller than 3.5°. Even then, the effect is washed out by the rotation and orbital motion of the spacecraft during a single FIRAS integration, as well as by combining multiple measurements.

A ray originating in the internal reference body (ICAL) is concentrated by the Reference Horn, a parabolic concentrator similar to the Sky Horn with the same throat radius, but with a mouth radius of only 4 cm, extended with a cylinder to give the same effective length-to-throat ratio as the Sky Horn. The emissivity of the horn is approximately proportional to this ratio and, indeed, the measured Sky Horn and Reference Horn emissivities are approximately equal (see Fig. 4c), so that their contributions to the output interferograms cancel.

2.3 Interferometer and Focusing Elements

In order to obtain good beamsplitter efficiency over a wide frequency range, a polarizing or Martin-Puplett form of the interferometer was constructed. The limited volume within the *COBE* dewar required that the optical path be folded. To keep the beam from expanding beyond the size of the optics it was refocused 5 times. By convention, the left side refers to the elements on the same side as the Sky Horn, and right side for the ICAL.

After the throat of each input horn, the ray is recollimated by an elliptical concentrator with an aperture of radius 2 cm, directed onto a folding flat F_L (for the sky) or F_R (for the ICAL), and then imaged on the collimator mirrors M_L, M_R. The elliptical concentrators place scrambled images of their throats on the collimators, 25 cm distant. The collimator mirrors are off-axis paraboloids with their foci near the apertures of the concentrators, but not centered on them.

The ray next encounters a wire grid polarizer, labeled A for Input/Output Analyzer. The wires are gold-coated tungsten, stretched to half the yield stress as they are wound, and then glued with epoxy to an Invar frame. The wires are spaced 53 μm apart and are 20 μm in diameter. Ideally, the polarizer separates two perpendicular polarizations, one transmitted and one reflected. The symmetry of design ensures that the reflected sky signal, which remains on the left side, is added to the transmitted ICAL signal, with the perpendicular polarization, and similarly the transmitted sky signal, on the right side, is combined with the reflected ICAL signal.

The polarized ray now encounters another off-axis parabolic collimator mirror, C_L or C_R. Each C has a focal point at the center of the corresponding D and is 40 cm away from it, making an image of the sky at infinity and an image of the pupil on the dihedral mirrors D 40 cm farther ahead. Before reaching the dihedral mirrors, the beam encounters a second polarizer, labeled B for Beamsplitter, whose wires are oriented 45° from the wires on the previous polarizer, as seen by the beam. It therefore splits coherently into two new beams which go to the dihedral mirrors D_L and D_R.

The dihedral mirrors shift the beam position and change the polarization, while reflecting each beam back to the beamsplitter. The polarization rotation means that the fraction which had been reflected is now transmitted, and *vice versa.* The beams therefore recombine coherently, but with an elliptical polarization state which depends on x, the difference in the path length from the beamsplitter to the dihedrals. After the recombination, the beams return, but shifted in position because of the dihedral mirror shift: off the collimator mirrors C; to the analyzer polarizer

A which analyzes the polarization state and makes two output beams. The net result of all the combinations of polarizations, for a monochromatic source of frequency ν measured in wave numbers, is that the whole interferometer has the transmission functions $(1 \pm \cos 2\pi\nu x)/2$, with the sign depending on whether the output beam is on the same side or opposite the source.

Moving the dihedral mirrors to scan, or stroke, through a range of path differences produces an interferogram, $I(x)$. If we label the various sources, sky, ICAL, Sky Horn, Reference Horn, etc., by a source index, i, and ignore the constant unmodulated power term,

$$I(x)_{(L,R)} = \int_0^\infty d\nu \, \cos(2\pi\nu x) \sum_i \epsilon_{i\,(L,R)}(\nu) S_i(\nu)$$

where $S_i(\nu)$ is the emitted spectrum of the ith source, and $\epsilon_{i\,(L,R)}$ is the efficiency of the instrument for the ith object as observed in the Left or Right output. ϵ is positive for the sky side inputs on the left side, or for the ICAL side inputs on the right side, and *vice versa*.

At high frequencies, the polarizer grids are not ideal, their efficiency drops, and the symmetry between inputs and outputs is no longer guaranteed by design. In addition, there is a complex interaction between the two polarizers, as they form a fixed-tuned two-beam interferometer themselves. The result is that the interferometer efficiency drops to essentially zero at certain frequencies. We tilted the input/output polarizer away from the ideal position to recover the nulled frequencies. This detuning of the interferometer may be responsible for an additional observed non-ideal effect. The antenna beam profile near the on-axis position as measured using the Moon is not flat, as expected from the performance of the Sky Horn. Also, the position of the zero path difference point depends on the location of the Moon in the beam. However, none of these problems affect the determination of surface brightness for extended sources.

A fundamental limitation of the performance of the interferometer is the divergence of the optical path. The beam divergence at the dihedral mirrors is 14° full width which modifies the path difference relative to the principal ray by the factor $\cos\psi$, where ψ is the angle from the principal ray. For an ideal instrument, this effect can be calculated by integrating this factor over a circular beam. The variation in the path difference effectively modulates the input interferogram by an "instrument apodization function," which is equivalent to an effective spectral window function of full width $\Delta\nu/\nu = 1 - \cos\psi_{\max} = 0.007$, and also shifts the mean apparent frequency downward by half this amount. This ideal resolution is complicated by the fact, as measured by the analysis of the Moon data described above, that the true instrument angular response is not uniform. The general effect can be directly observed in the interferogram for monochromatic sources. In fact, nature provides two narrow emission lines from ionized carbon and nitrogen in the interstellar medium which are bright enough to provide a direct measure of the FIRAS resolution at two frequencies, 48.72 and 63.395 cm^{-1}. However, the measured instrument FWHM resolution derived from these lines, of $\Delta\nu/\nu \approx 0.0035$, is substantially better than the expected value estimated above.

The beam divergence has another consequence called baseline curvature. The stroke length is not small compared to the depth of focus of the interferometer, and ray traces show that the amount of background power, unmodulated by the interferometer, that reaches the detectors varies by $\sim 0.5\%$ over the stroke. This produces a very low frequency modulation of the interferogram that masks true infrared signals at those same frequencies. This signal is proportional to the total power coming through both input ports (and not their difference). We remove this by subtracting a quartic polynomial before Fourier transforming the incident spectrum. This also renders unusable the lowest frequency points of the discrete Fourier transform spectrum.

Finally, after the rays leave the analyzer polarizer, they are reflected off the flat $F_{L,R}$ and then separated from the input rays by a small pickoff mirror $P_{L,R}$, and focused again by an elliptical mirror $E_{L,R}$, on their way to a set of dichroic filters (see the following) and the apertures of the detector concentrator cones. Ray traces predict that approximately 20% of the light is lost because of aberrations at the off-axis mirrors, and that there is not much improvement possible from the use of other shapes.

2.4 Optical Filters and Detector Optics

Each of the two output beams is further split by a dichroic filter into a reflected high frequency beam and a transmitted low frequency beam, for a total of four output beams. These four outputs are labeled "Left Low," "Left High," etc. The dichroic filters are multilayer capacitive grid filters, with aluminum squares photoetched on polyethylene sheets. The nominal separation frequency is 20 cm^{-1} but the high frequency detector also gets reflections from the front and back surfaces of the polyethylene giving rise to a characteristic interference pattern. In addition, each detector has a low pass capacitive grid filter across the large aperture of its concentrator cone. In the case of the low frequency detectors, the low pass filters are identical to the dichroic filters, but for the high frequency detectors the cutoff frequency is 100 cm^{-1}. The concentrators are elliptical concentrators matched to those on the input antennas, and have the same throat size and étendue.

3. Detectors

The four detectors are composite bolometers[17] with electrical NEP of $\sim 4 \times 10^{-15}\mathrm{W}/\sqrt{\mathrm{Hz}}$. The operating temperature of the bolometers is 1.58 K during normal observations, but rises as high as 1.73 K during calibrations with high temperature sources. Each bolometer is a diamond octagon 0.78 cm across the corners and 25 μm thick. The size is chosen to match the étendue of the antennas and cones, and the diamond is blackened with a chrome-gold film. Each has a silicon thermometer glued to a corner and thermally anchored with 0.3 mil brass lead wires. The diamond is supported by a crossed pair of taut Kevlar fibers from an Invar frame (since Kevlar expands on cooling). The low frequency bolometers are made with a smaller thermal conductance and longer time constant than the high frequency bolometers.

The electrical and thermal properties are interrelated, and we have modeled this behavior according to the equations of Mather[18,19,20]. There is no sign of multiple time constants: the responsivity is well described by a simple one-pole formula: $S = S_o/(1 + j\omega\tau)$, but the dependence of S_o and τ on the operating conditions is not simple. In particular, the infrared power absorbed by the detector changes its temperature and responsivity, and for some conditions the signal is large enough to produce dynamic nonlinearities as well. The size of the non-linear correction is of order the fractional change in the bolometer voltage, $\sim \Delta V/V_{\mathrm{bias}}$. This is negligible for any of the sky data taken, but becomes more important for the very large signals observed during portions of the calibrations.

Each bolometer is mounted in a housing with a short aluminum tube between the concentrator throat and the detector, to reduce the view factor for cosmic rays. Machined tantalum shields capable of stopping protons of 50 to 100 MeV (depending on direction) surround the rest of the detector for the same reason. The natural Galactic cosmic ray rate is of the order of 4 per square centimeter per second, depending on the effectiveness of the Earth's magnetic field in shielding them, and most of these are at very high energy (GeV and higher). In addition, trapped particles in the Earth's field are much more abundant than the cosmic rays in certain portions of the orbit, particularly in the South Atlantic Anomaly. Penetrating protons in this region are so intense that no useful data can be obtained. In the remainder of the orbit, particles produce abrupt signals in the bolometers which decay with the characteristic detector time constant. These signals, dubbed glitches, when bright enough can be modeled and removed by software. The lower amplitude (and more numerous) glitches are not individually detectable, but are responsible for a significant fraction, $\sim$ 80%, of the total in orbit "detector" noise. Even after the "deglitching" is done the in orbit noise is twice as high as the noise in the ground data (see Figure 5).

The two sides of the interferometer have nearly identical detectors and filters, but the optical responses of the two sides are dramatically different. There are two possible causes: degradation of the detector absorbing film, and defective filters, but the latter seems unlikely because the spectral responses are similar. On one side, the low frequency detector is good and the high frequency detector is poor, while the opposite is true on the other side. The ratio between the good and poor detector responses is of the order of 5.

Each detector is biased through a load resistor of 40 MΩ by a low noise DC voltage supply, adjustable from 0 to 10 volts. The detector voltage is measured through a JFET source follower amplifier (gain $\sim$ 0.995) mounted near the detector but thermally isolated from it. The amplifier uses dual JFETs connected in parallel, and suspended by Kevlar threads inside a copper can, so that the JFET bias power can heat it to an operating temperature of $\sim$ 70 K, similar to that used for the *IRAS* detectors. Each amplifier has its own copper cooling strap directly attached to the instrument mounting flange. Wires into the bolometer housing are filtered against radio and microwave energy by being cast into an iron-loaded epoxy disk. Nevertheless, the detectors were sensitive to radio frequency emitted by the microprocessor clocks ($\sim$ 4 MHz), and beat frequency signals between different clocks were seen as excess noise levels at those frequencies despite efforts to provide additional external decoupling. Fortunately, these beat frequencies were not in the frequency range of interest for the infrared signals.

4. Mirror Mechanism

The moving dihedral mirror mechanism, responsible for varying the path difference in the interferometer, was the most difficult part of the instrument to design, build, and test. Although the wavelengths involved are long compared to optical light and tolerances are increased accordingly, the cryogenic operation and spatial constraints made this a challenge. A parallelogram linkage with leaf springs at the corners was chosen because it requires no lubrication, provides a smooth motion, and has little friction. Standard design half inch Bendix flex pivots containing perpendicular sets of leaves in cylindrical mounts are used, but the high vibration levels of launch required the use of A718 alloy springs instead of the usual steel. For maximum path difference for a given mechanical stroke, both of the dihedral mirrors move on a single platform, in a direction perpendicular to the beamsplitter plane and 30° from the optical axes. This means that as the mirrors move, there is a lateral movement of mirrors across the beams, but this has no effect on the path difference. The maximum physical stroke length is 4 cm.

The position of the mirrors in their stroke is measured by counting fringes on a reference ruler on a glass scale, with a fringe spacing of 20 μm at room temperature. The scale is illuminated by an optical fiber from an external light emitting diode (LED), and a segment of a spherical mirror creates an image of the scale back on itself to create an optical lever. Light is transmitted through the scale twice and is returned to a detector outside the cryostat by another fiber. Because of the angle between the optical axes and the direction of stroke, the change in the optical path difference is $40 \cos 30°$ μm per fringe. A single slit in the scale is also imaged back on itself to serve as a reference marker for the beginning of the stroke. This method of measurement and control has the advantage of avoiding cryogenic complexity and power dissipation, but the joints in the fiber optic system produce 60 dB attenuation. As a result, signal levels are not far above the Johnson noise of the room temperature detectors, and occasional cosmic rays penetrating the detectors produce spurious signals in the beginning of stroke marker circuit. The accuracy of translation of this mechanism was measured with a laser interferometer, and the orientations of the flex pivots were adjusted slightly to minimize tilts and rotations during the stroke.

The mechanism is driven by a linear motor, with fixed coils attached to the baseplate, and a moving permanent magnet and iron circuit. The flex pivots have very low thermal conductance and we wish to minimize the heat dissipated in the moving portion. Clearances in the motor are tight because the platform moves in an arc. The motion is sensed by two analog methods as well as the glass scale: a magnet moving in a coil measures the velocity, and a linear variable differential transformer (LVDT) measures the position. When energized, the LVDT coils dissipate a significant amount of power so that the LVDT was usually used only when the mirror mechanism was commanded to hold a particular position in its stroke. This caused an increase in the dihedral temperature, to 7 K, and an increase in the detector temperatures, up to 1.6 K.

The motor is driven by a current source (to account for changes in coil resistance with temperature) controlled by a linear servo amplifier. The servo is a simple velocity servo, with the commanded velocity toggled at each end of the stroke by the control logic. Two forward stroke velocities, labeled "fast" and "slow," are provided, as a way of optimizing the sensitivity and recognizing potential coherent interference effects from the spacecraft. These scan velocities give path difference rates of 0.783 and 1.175 cm/s, in the ratio of 2 to 3. In the forward direction, a counter is set by the signal from the reference marker, and then fringes are counted until the desired stroke length has been achieved and the logic reverses the stroke direction. Two stroke lengths are provided: a "short" stroke of 512 fringes; and a "long" stroke of 2048 fringes. The long stroke has a potential fourfold improvement in the frequency resolution of the instrument. The zero path difference location is at the 355th fringe, thus its location is not symmetric in either scan length. In the reverse direction, the scan speed is 1.46cm/s (=5 cm/s path difference). The reverse motion continues until the reference mark has been passed, at which point the commanded velocity returns to its forward value.

As mentioned above, particles in the detector could generate spurious reference mark pulses. During the forward stroke, this resets the fringe counter used to determine the end of the stroke. Particularly for long stroke modes, this could result in the mirror mechanism being driven all the way to its stop, whereupon the drive circuitry would put a significant current into the mechanism. Though the drive coils were protected by current limiting components, a significant amount of heat is generated. Because similar behavior was observed before launch (though in that case the spurious signals were due to electrical pick up rather than particles), a special "watch dog" circuit was added. The watch dog would explicitly command a reverse stroke if 15 seconds had elapsed without one. This limited, but did not eliminate, the amount of heat generated by each end of travel event. In orbit, the end of travel events were strongly correlated with the density of particles as measured by the detector glitch rates, and were much less prevalent when the mirror mechanism was performing short strokes, which by the above model would have required at least four separate spurious reference mark pulses in order to generate an end of travel event.

The velocity signal is low pass filtered to reduce the forces applied during the velocity reversals, and minimize excitation of spacecraft and cryostat vibration modes, but there is measurable evidence of these. The mechanical resonant frequency of the desired parallelogram mode of the mirror system is approximately 0.5 Hz, and the next important mode is at 57 Hz with $Q \sim 500$. This appears to be a torsional mode, excited because the force vector of the motor does not pass through the center of mass. It is the primary limitation on the servo bandwidth, so a notch filter tuned to this frequency is inserted in the feedback loop. There is also an ~ 8 Hz vibration, the exact frequency depending on the mirror speed, which is probably the combination of a low Q mechanical resonance and the limited band width of the mirror mechanism servo loop.

The fringes on the reference scale are the source of the pulses used to sample the interferograms at the correct locations. More frequent pulses are needed, so the marks from the scale are subdivided in time by 2 or 3, depending on whether the mirror velocity mode is fast or slow, respectively, using a phase locked loop with a frequency divider (counter) in its feedback circuit. The bandwidth of this loop is not wide enough to respond to the 57 Hz vibrations, nor to completely track the 8 Hz vibrations excited by the mechanism. The timing of the sample pulses gives information about the vibrations and enables the accuracy of the sampling to be estimated. A spectrum of the vibrations, obtained by Fourier transforming the number sequence representing the sample intervals, is shown in Fig. 6. By comparing the coherent power density spectrum of many strokes, with the incoherent average of the power density of individual strokes, it can be seen that at least two of the vibrations are synchronous with the stroke and, hence, are principally being excited by the mirror mechanism drive forward, reverse, and turn around cycle.

5. Signal Processing

The signals from the detectors are amplified, sampled, digitized, and digitally filtered on board the spacecraft prior to telemetry. Each analog amplifier chain has three commandable gain stages, with nominal gains of 1 or 3, 1 or 10, and 1 or 101, and in addition has a fixed gain of 100. The resulting gains range from 100 to 303,000. Each chain includes 6 poles of high pass filters between the amplifier stages. There is also a 5 pole low pass Bessel filter with a −3dB frequency of 100 Hz. Finally, there is a compensating network that provides a $1 + j\omega\tau$ factor to match the similar factor in the denominator of the detector transfer function. This speeds up the effective response time of the detector to reduce the transient recovery time after a particle hit.

Prior to sampling and digitization, an adjustable DC offset voltage is added to the output of the AC amplifier. This "dither" voltage is to exercise different parts of the analog-to-digital converter and average out its differential nonlinearities. This is important for high amplitude calibration data, where the low gain required reduces the detector noise to less than one bit in the 12 bit successive approximation digitizer. The DC voltage is changed according to a pseudo-random sequence after each group of scans is collected, and exercises 1/4 of the full scale range of the digitizer.

The detector signals are sampled at equal intervals of path difference as indicated by the output of the mirror mechanism phase lock loop, slaved to the mirror position fringes. The sample rate is $\sim$ 681.43 Hz, which is enough to avoid significant aliasing of high frequency noise into the infrared signal bandwidth (1 to 100 Hz). They are then processed in an SBP 9989 16 bit microprocessor, one for each detector output. Under normal operations, it applies a digital low pass filter to the incoming data, and between 2 and 12 samples (depending on the mirror scan mode) are averaged together to produce an interferogram 512 points long, regardless of the scan mode, and adds together a set of either 4 long scans or 16 short ones to form a group for telemetry to the ground. Double buffering is used as the data transmission is asynchronous with the digitization. The microprocessor also runs a pulse finder algorithm on the original (unaveraged) samples to identify glitches from cosmic rays, and flags all points where a glitch has been located in any one of the set of scans.

While taking long stroke data for the high frequency detector channels, the microprocessors only sample the initial quarter of the stroke, producing an interferogram almost identical to the short stroke data, though 1/4 of the duty cycle. If an entire long stroke is accumulated with a 512 point interferogram, the Nyquist frequency would be at 36 cm^{-1}, midway through the high frequency channels' band pass.

Many of the details of the operation of the microprocessors were determined by values contained in a table which could be varied by command: *e.g.*, the number of samples to average, the number of sweeps to take, the sample number to start accumulations at, etc.; as well as a choice of basic program modes that enabled or disabled the digital filter, the glitch location, and the glitch removal software. Diagnostic modes were also provided, in which the raw, unfiltered data could be examined, the intervals between samples could be measured to a 10 microsecond resolution, and the microprocessor memory could be checked or reprogrammed. No evidence was seen of microprocessor errors in orbit caused by cosmic rays.

6. Mechanical Design

Except for the Sky Horn and the XCAL, the optical components, moving mirrors, and detectors are all built into a box roughly 50 cm on a side, constructed on a baseplate, which is in turn attached to the dewar interface flange. This box is surrounded by a cylindrical Instrument Interface Structure (IIS), which supports the Sky Horn and XCAL, and the DIRBE instrument, and is joined to the baseplate at a flange. The lower portion of the IIS is closed off with a cover to protect the interferometer from stray infrared inputs. This cover has two holes, one for each horn antenna, with labyrinth seals of aluminum and infrared absorber to allow air to escape while blocking infrared radiation.

The entire mechanical structure and all the mirrors and cones are built from 6061-T6 aluminum alloy, so that cooling to liquid helium temperatures introduces no differential contractions. The cooling process produces thermal gradients which could produce strain or slip at bolted joints, so the cooling rate was limited and the cool down to 4 K took two days. Bolt threads were coated with Solithane to prevent loosening under vibration. Belleville washers are used throughout to take up the differential contraction of the steel bolts and the aluminum structures. Where needed, thermal insulators of G-10 epoxy fiberglass are used, and relative motions of the parts are minimized by compensating lengths of fiberglass elsewhere.

In one case, the polarizing beamsplitters, it is not possible to use aluminum, because the aluminum would contract more than the tungsten wires and relax their tension. Therefore, the polarizer frames are Invar, and a kinematic mount is provided with spring-loaded slip joints and adjusting screws. This area caused alignment problems, since the vibration levels during test were sufficient to cause erosion of the kinematic mounts. However, the alignment was well preserved, as determined by comparison of the high frequency instrument responsivity before and after launch.

The Sky Horn antenna is supported primarily at the top end, where it is mounted on a platform inside the IIS, with a G-10 thermal insulator. Its lower end is mounted in a loose slip joint near the input to the spectrometer, with minimal contact area and pressure to reduce heat flow along the horn. This was successful in that the thermal gradient along the horn was negligible. The XCAL mechanism is attached to the same platform on the IIS. It includes a stepper motor with redundant coils, an 8:1 gearbox, and ball bearings.

Stepper motor controllers are provided for three motors: one to move the XCAL and two to latch the calibrator and the mirror mechanism. For each motor there is a prime and a redundant controller, with its own windings on the motor, and a command to slave the redundant to the prime if both are powered on simultaneously.

7. Temperature Control and Measurement

All of the principal input sources for the FIRAS are temperature controlled: the XCAL and ICAL, as well as both horn antennas. Redundant controllers were placed on each item. The controller consisted of a resistive heater, a nearby germanium resistance thermometer (GRT), and associated electronics. The controller circuitry included proportional and integral gains, commandable from 1 to 128 by factors of 2, and the integrator can be turned on or off (the latter discharging the stored integrator signal). The set point voltage is controlled by a 12 bit digital-to-analog converter. In addition, the current used to stimulate the GRT could be commanded to one of four different values, 1, 4, 16, and 64 μA, allowing the controller to be able to control at temperatures from 2 to 25 K. The performance of the controller and, in particular, the choice of optimal proportional and integral gains was strongly dependent on the heat capacity and internal thermal conductivity of the object to be controlled. At the highest temperatures used during the calibrations ($>$ 15 Kelvin), the calibrators equilibration times were tens of minutes, and the time to cool down to the lower temperatures used for sky observations $\sim$ 1 hour. At the lower temperatures, the control loop time constants and the thermal time constants were very short, a few seconds, and in general the temperature stability, when not subject to abrupt environmental inputs, was better than 0.2 mK.

The temperature controllers' GRTs' measured voltages were not directly available in the FIRAS telemetry and, hence, could not be used for the temperature measurement. There were 22 separate GRTs used for temperature measurement, both for the controllable items and scattered throughout the rest of the instrument: viz. pairs on each of the four detector housings, the dihedral mirrors, and other elements of the instrument structure. In general, there were two GRTs used in each location. The GRTs were calibrated to 1 mK accuracy against a transfer standard GRT from the NIST (NBS) using switched polarity DC excitation. The flight electronics provided AC excitation at $\sim$ 45 Hz for improved immunity to thermoelectric effects and low frequency electronic noises. The DC and AC results were consistent. The AC measurement was made using a stabilized oscillator driving an AC current source to excite the thermometer. All the thermometers were used in a 4-lead configuration to eliminate sensitivity to the cryostat lead resistances, which were $\sim 64\Omega$ each way. The voltage developed across each GRT was amplified by a wide band differential amplifier and synchronously demodulated before DC amplification. The analog to digital converter provided 14 bits of resolution, equivalent to 0.05 mK per bit at 2.7 K. Each GRT was read out by one of two digitizers through MOSFET multiplexers, which cycled through the GRTs and four standard resistors to provide frequent calibration. The current levels used were 0.4 and 6.4 μA, where only the low current readings were used below $\sim$ 2.5 K and, except for the thermometers on the detector housings, both current ranges were measured in every major telemetry frame (32 sec). The stability of the calibration resistors was good enough that averages of their values taken over a day could be used in calibrating the measurements. There was no evidence of thermometer self heating at these currents and accuracy levels.

Heat from the instrument is conducted to the cryostat through the interface flange. To minimize gradients within the instrument, high purity annealed copper straps connect each detector housing, each JFET preamplifier for the detectors, and the mirror mechanism directly to the flange. Heat from the horns and calibrators flows through their thermal insulating supports into the IIS and then into the flange on its way to the helium. In addition, a separate strap is provided from the movable XCAL directly to the top of the liquid helium tank. The thermal conductances of the horn and calibrator supports are similar, and the power flow from each is approximately proportional to the difference in the squares of the temperatures at the two ends of the supports.

Temperature gradients within the external and internal calibrators and horns are minimized by heating each one only at its single point of mechanical support. The ICAL temperature is measured by two germanium resistance thermometers (GRTs) and controlled by a third. The XCAL temperature is measured by three GRTs and controlled by a fourth. The scatter among the readings of these GRTs is 9 mK for the internal calibrator and 3 mK for the external calibrator, when these bodies are set at 2.7 K. Each horn has two thermometers, which agree much better than the calibrator thermometers. Tests, using flight spare models of the calibrators and spare GRTs placed at additional locations, are in progress to resolve this question.

8. Instrument Calibration

The important calibration data were taken in 16 calibration periods. Nine of these periods were at the third quarter of the moon when part of the data would have been contaminated by the moon. In these calibration periods, data were collected with the XCAL in the horn and at ~ 2.2 K, which is close to the minimum temperature achievable by the controller. Then, the XCAL was raised to 2.7, 3.5, 6, 8, 10, and 15 K. Interspersed with these measurements, the ICAL was raised to 6 K and then, in steps, to 15K. Also the horn temperatures were raised to 6K. While the XCAL was only raised in temperature, the ICAL and horns were both raised and lowered so that a wide variety of combinations were available. In the last 40 days, it was realized that the lack of calibration data would be the limit on the ultimate sensitivity, so seven additional periods of calibration data were added with the XCAL, the ICAL, and the horns near 2.7 K.

9. Lessons Learned

Many lessons can be learned from the process of developing an instrument of this complexity. Here, we mention only a few relating to design concepts.

Mechanical assembly was difficult for this instrument, due to the interlocking of the parts and difficult access to bolt holes, made more difficult by high standards of cleanliness. A kinematic design with fewer interfaces and possibilities for alignment troubles would have been a valuable simplification. A less ambitious instrument might have had a reduced size and more clearance, at the expense of some signal strength.

The unwanted servo resonance of the mirror mechanism nearly spoiled the performance of the instrument, and flight calibration data still show effects of it. This resonance might have been avoided by an earlier analysis of the resonances of the mechanical structure and the ways in which they are excited by a servo. Design concepts exist to avoid them, primarily stiffening key portions of a mechanism and rigidly coupling the velocity sensor and motor. Our device has the motor force vector applied at a location where it produces a torque around the center of mass, and can thereby excite torsional modes. A more symmetrical design would avoid this kind of trouble.

We used a phase lock loop to subdivide the sample pulses because we did not think we could risk a finer grating spacing in the ruling. The phase lock loop works, but causes time delays and phase shifts in responding to the original sample pulses, and has a bandwidth limited to a value much less than the carrier frequency. Our version of the phase lock loop was also unnecessarily sensitive to noise impulses on the input, and great effort was required to keep the input clean.

We used fiber optics to read out the position of the mirror mechanism. These work but have certain difficulties. First, the fibers are susceptible to damage by alcohol solvents, which enter the space between the core and jacket of the fiber. Second, the large number of connectors we used caused excessive attenuation, which could only be partially overcome by use of brighter light sources and better detectors and amplifiers. As a result, the signals coming from the photodetectors were small, and susceptible to interference from electrical signals and from cosmic rays hitting the photodiodes.

The temperature controllers, although effective in controlling the calibrators and horns once an equilibrium condition was reached, were difficult to command to new temperatures in an efficient manner and could have unacceptable behavior in response to strong transient inputs. A programmable control circuit would have had better flexibility to make the transitions.

The performance of the GRTs for the instrument thermometry, and depending on only two or three measurements for the calibrators in particular, has produced a probably irreducible error of at least several milliKelvin when making comparisons between the FIRAS results and other measurements of the CMBR. The use of superconducting transition thermometers was considered, but rejected as an unneeded complication, with an insufficient level of experience in their use and stability. The disagreement between the tip and plate GRT measurements in the calibrators showed early on that there were measurement discrepancies to be dealt with, but this may have masked a real gradient within the ICAL, the magnitude of which is still to be determined.

We also were reminded that calibration time is important and, in this case (as in many cases), as much as half of the time should have been devoted to calibration.

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