2. Instrument Description

The Far Infrared Absolute Spectrophotometer (*FIRAS*) has been described in detail by Mather, Fixsen, and Shafer (1993), which is included in this document as Appendix B. Briefly, the *FIRAS* is a scanning, four-port (two input, two output) Michelson interferometer that uses polarizing grids as beamsplitters and creates an interferogram (*i.e.*, the Fourier transform of the source spectrum) by scanning a movable mirror platform (the "Mirror Transport Mechanism", or MTM). A dichroic filter at each output port (arbitrarily labeled "Left" and "Right") further splits each beam into low ($1-21$ cm^{-1}) and high ($20-97$ cm^{-1}) frequency bands. The four detectors are thus referred to as LH, LL, RH, and RL, for "Left High", etc.

The sky input antenna, or sky horn, of the *FIRAS* provides a 7° field of view with low side lobes. The beam pattern of the sky horn pattern is designed to be circularly symmetrical and unpolarized. The spacecraft rotates at 0.8 rpm throughout the mission, making more than 1/2 revolution while taking a single telemetered group of interferograms. This spin eliminates most of the beam asymmetry and polarization sensitivity that may appear in the data. The beam asymmetry and polarization sensitivity are further reduced by the averaging of data taken in random orientations of the instrument.

The MTM can be scanned at either of two speeds: "slow", at about 0.8 cm/s, or "fast", at about 1.2 cm/s of path difference. The interferograms ("IFG"s) are sampled at the detectors at the same clock rate in both cases (681.43 Hz), but the raw onboard samples are binned in different amounts depending on MTM scan speed so that the infrared Nyquist frequency of the telemetered data is the same. The sampling is controlled by the motion of the mirror. Data collected in the different scan speeds have been averaged ("coadded") and calibrated separately.

The MTM sweep can also be set to one of two scan lengths, "short" or "long", which limit the spectral resolution. Long scans have four times the maximum optical path difference compared to short scans. In the low frequency channels, the long scan mode thus yields four times the spectral resolution of the short. However, in the high frequency channel there is insufficient telemetry bandwidth to take advantage of the longer sweep, and only the first quarter of it is used. All high frequency data therefore have the same spectral resolution. Thus, the data can be divided into low resolution (LRES): low frequency short scan length, high frequency short scan length, and high frequency long scan length; and high resolution (HRES): low frequency long scan length. As with scan speeds, data taken in the two scan lengths have been processed separately. Table 2.1 shows the maximum optical path difference, spectral resolution, and other parameters of the high and low resolution scan modes and channels.

Table 2.1: Channel- and Scan Mode- Dependent Properties

		LRES	HRES
Maximum path difference	(cm)	1.22	5.85
Total scan length	(cm)	1.76	7.07
MTM sampling rate	Hz	681.43	681.43
Nyquist frequency	(cm^{-1})	145.21	36.30
Nyquist frequency	(GHz)	4353.3	1088.3
Unapodized resolution	(cm^{-1})	0.57	0.14
Unapodized resolution	(GHz)	17	4.2
Bin resolution	(cm^{-1})	0.45	0.11
Bin resolution	(GHz)	13.6	3.4
Apodized resolution	(cm^{-1})	0.82	0.23
Apodized resolution	(GHz)	24.6	6.9

The four possible MTM scan speed and length combinations are referred to as SS, SF, LS, and LF, for "Short Slow", etc. There are thus in principle sixteen possible detector/scan mode combinations for data processing: LLSS, for example, is "Left Low Short Slow".

Telemetered groups of interferograms take an average of about 40 seconds to collect; the range is from $\sim$32 to $\sim$46 seconds, depending on scan mode. The collection time varies with scan mode because multiple passes ("sweeps") of the MTM are averaged on board before telemetering the IFG. Either 16 or four sweeps (for short or long scans, respectively) are averaged, and the onboard sampling is set such that each telemetered IFG is 512 samples long. By design, the collection time for an IFG is about equal to the time that the instrument boresight scans across a single sky pixel.

The unapodized resolution of the calibrated spectra quoted in Table 2.1 is the reciprocal of the total scan length and is applicable if no assumption of symmetry of the interferograms is made. The bin resolution is smaller because in processing the data, we pad the 512 point IFG to 640 points with zeros. The apodized resolution of the spectra is the full width at half maximum of the absolute value of the Fourier transform of the apodization function.

One of the most important features of the *FIRAS* is that it is a differential device, wherein the measured signal is determined by the difference between the spectra at the two input ports. One of the two inputs (the sky horn) is usually open to the sky, while the other (the reference horn) is filled by an internal near-blackbody reference source called the ICAL. For the low frequency channels, the dominant celestial signal is the cosmic microwave background radiation (CMBR), which is well described by a blackbody spectrum at a temperature of 2.728 K. By adjusting the ICAL temperature to a point near that of the CMBR, a near null interferogram is produced and the derived spectrum is insensitive to errors in the instrument gain.

In order to determine the instrument gains and offsets and the deviation of the ICAL from a blackbody, the *FIRAS* is calibrated by placing a full-beam external calibrator (the XCAL) into the sky aperture. The XCAL is a highly accurate blackbody and is controlled over a range of temperatures that includes the CMBR temperature, thereby acting as a direct substitution for the sky. This provides a substantially accurate calibration for small deviations of the CMBR from a Planck spectrum. Gain uncertainties of 1% translate into uncertainties in the calibrated measurement of the CMBR to less than 0.01% of its peak intensity.

At higher frequencies the sky spectrum includes a noticeable contribution from interstellar dust emission. This is in excess of the CMBR and, having a much higher brightness temperature, is not balanced by the ICAL. For these signals, errors in the absolute instrument gain translate directly into photometric errors in the calibrated sky spectra. The calibration procedures included heating the XCAL and ICAL to a wide range of temperatures up to 22 K in order to determine the high frequency gain. (For comparison, the infrared color temperature of interstellar dust is $\sim$18 K.)