

# **Alignment and polarization sensitivity study for the Cassini - Composite InfraRed Spectrometer (CIRS) Far InfraRed (FIR) interferometer**

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## **ABSTRACT**

The Composite InfraRed Spectrometer (CIRS) instrument flying on the Cassini spacecraft to Saturn is a cryogenic spectrometer with far-infrared (FIR) and mid-infrared (MIR) channels. The CIRS FIR channel is a polarizing interferometer that contains three polarizing grid components. These components are an input polarizer, a polarizing beamsplitter, and an output polarizer/analyzer. They consist of a 1.5 micron ( $\mu\text{m}$ ) thick mylar substrate with 2  $\mu\text{m}$  wide copper wires, with 2  $\mu\text{m}$  spacing (4  $\mu\text{m}$  pitch) photolithographically deposited on the substrate. This paper details the polarization sensitivity studies performed on the output polarizer/analyzer, and the alignment sensitivity studies performed on the input polarizer and beamsplitter components in the FIR interferometer.

Key words: far infrared, interferometry, polarization, beamsplitters, alignment, sensitivity

## **1. INTRODUCTION**

The CIRS instrument is one of twelve instruments currently flying on the CASSINI spacecraft en route to Saturn on a TITAN Centaur rocket scheduled to arrive in 2004<sup>1</sup>. The CIRS instrument was built at the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC), however, it was an international project. Many of the CIRS components were fabricated outside of the U.S. The polarizing grids that this paper discusses were manufactured at Queen Mary Westfield College (QMWC) in London, U.K.<sup>2</sup>. The CIRS is a cryogenic instrument operating at 170 Kelvin (K), and consists of a 51 cm Cassegrain telescope which feeds two Fourier transform spectrometers: a mid infrared (MIR) Michelson interferometer covering the spectral range between 600  $\text{cm}^{-1}$  and 1100  $\text{cm}^{-1}$  and a FIR polarizing interferometer covering the spectral range between 10  $\text{cm}^{-1}$  and 600  $\text{cm}^{-1}$ . The optical design of the CIRS instrument has been previously detailed by Maymon et. al.<sup>3</sup>. An opto-mechanical drawing of the CIRS instrument is shown in Figure 1. An optical ray trace of the FIR interferometer is shown in Figure 2. Prior to the CIRS engineering and flight unit instruments, this particular polarizing interferometer design had never been modeled and tested. It was desired to model this polarizing interferometer design and characterize/quantify the various sensitivities of its optical components prior to building the engineering and flight units to learn and characterize as much as possible about this design. The backbone of this polarizing interferometer were three polarizing grid components described above. The polarization and alignment sensitivities of these crucial optical components had not been measured for this design. The alignment tolerancing done by optical analysis using Code V and Advanced Systems Analysis Programs (ASAP)<sup>4</sup> optical analysis codes needed to be verified.

## **2. FIR INTERFEROMETER BREADBOARD**

Two years prior to fabricating the FIR Engineering Model optics, the FIR interferometer was modeled and tested using high fidelity polarizing grid components (see section 3.2 of this paper) fabricated at QMWC and off-the-shelf optics and mounts. This FIR breadboard was used to develop and practice alignment techniques to be applied in the alignment of the engineering and flight unit FIR interferometers<sup>5</sup> and to test the alignment and polarization sensitivities of the FIR interferometer optical components to see if they agreed with the predicted sensitivities from the optical analyses.

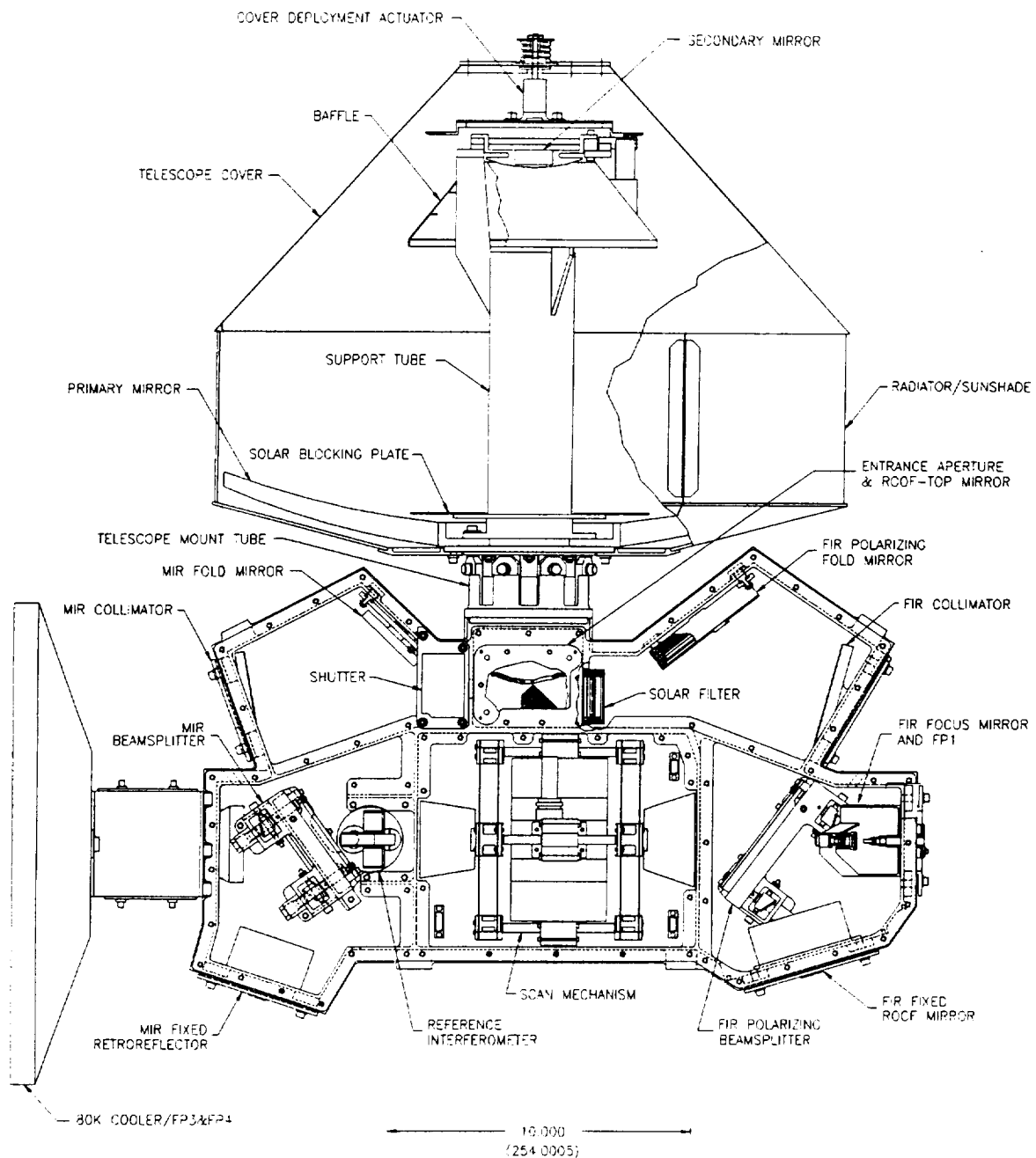


Figure 1: Composite Infrared Spectrometer

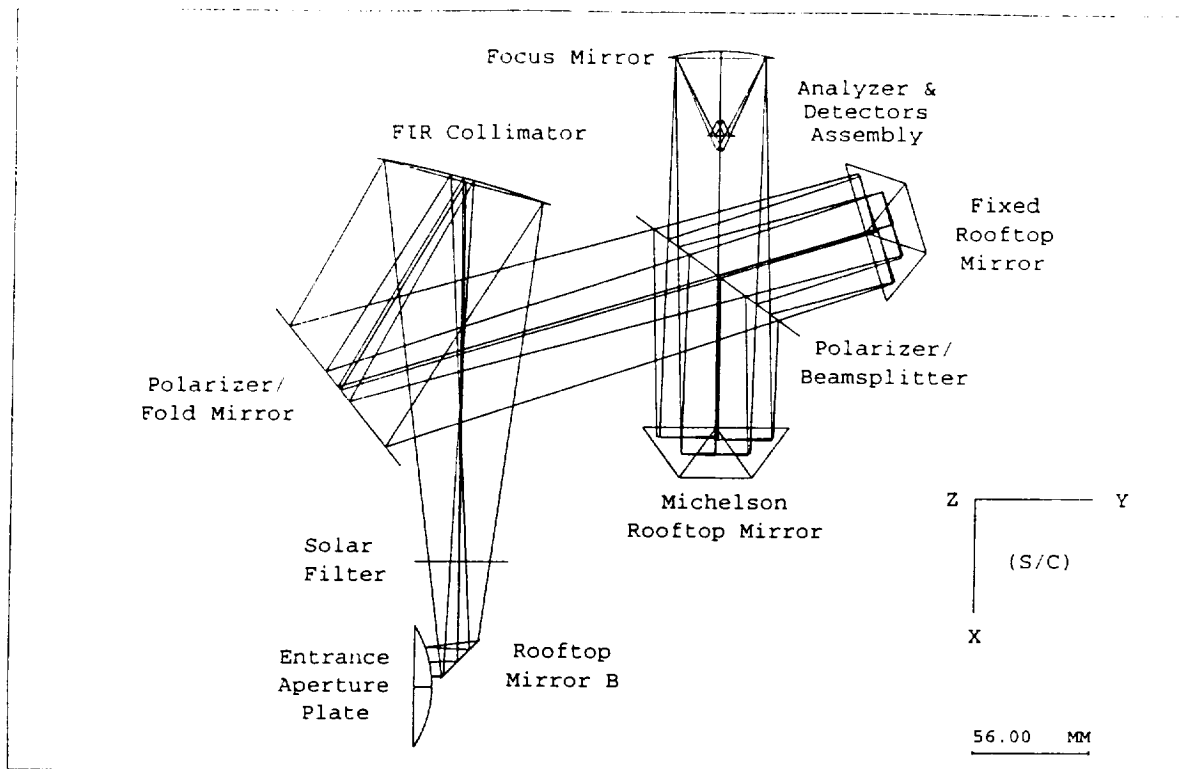


Figure 2: CIRS FIR interferometer optical ray trace

The three polarizing grids are the backbone of the FIR polarizing interferometer. They define the optical efficiency and throughput for the FIR interferometer. This is determined through the light path in the interferometer (see Martin and Puplett, 1969)<sup>6</sup>.

## 2.1 FIR interferometer breadboard configuration

The FIR breadboard configuration is shown in Figure 3 and is described below. A blackbody infrared (IR) source with a 0.2 inch diameter aperture radiating at 1000° C was placed and aligned at the focus of a two inch diameter f/9 on-axis parabola. A fold flat was placed between the pinhole blackbody source and the parabola. The angles that the beam traversed were kept as small as possible to minimize aberrations caused by using an on-axis parabola off axis. This provided a two inch diameter collimated IR beam which proceeded towards the input polarizer. The input polarizer, which had its polarization axis optically at 45° counter-clockwise from vertical, reflected 50% of the collimated beam becoming linearly polarized at 45° counter-clockwise with respect to vertical, and proceeded towards the polarizing beamsplitter. The other 50% of the beam incident on the input polarizer was transmitted and not utilized. The beamsplitter's polarization axis was vertical at 0°. The beamsplitter transmitted and reflected 50% respectively of the orthogonal horizontal and vertical polarization components, each leg containing 25% of the original beam. The transmitted portion became horizontally, linearly polarized, and reflected off a fixed dihedral with its roofline was at +45° clockwise from vertical so its polarization axis was rotated by 90° to vertical linear polarization. All of this polarized light was reflected by the beamsplitter towards the output polarizer/analyzer and detector. Likewise, the original reflected portion by the beamsplitter was reflected off a scanning dihedral with its roofline at -45° from vertical. This light's polarization axis also was flipped 90° and became horizontally, linearly polarized. All of this beam was then transmitted through the beamsplitter towards the output polarizer and detector. The reflected and transmitted portions contained two orthogonal, linear polarization states which recombined and proceeded towards the output polarizer/analyzer.

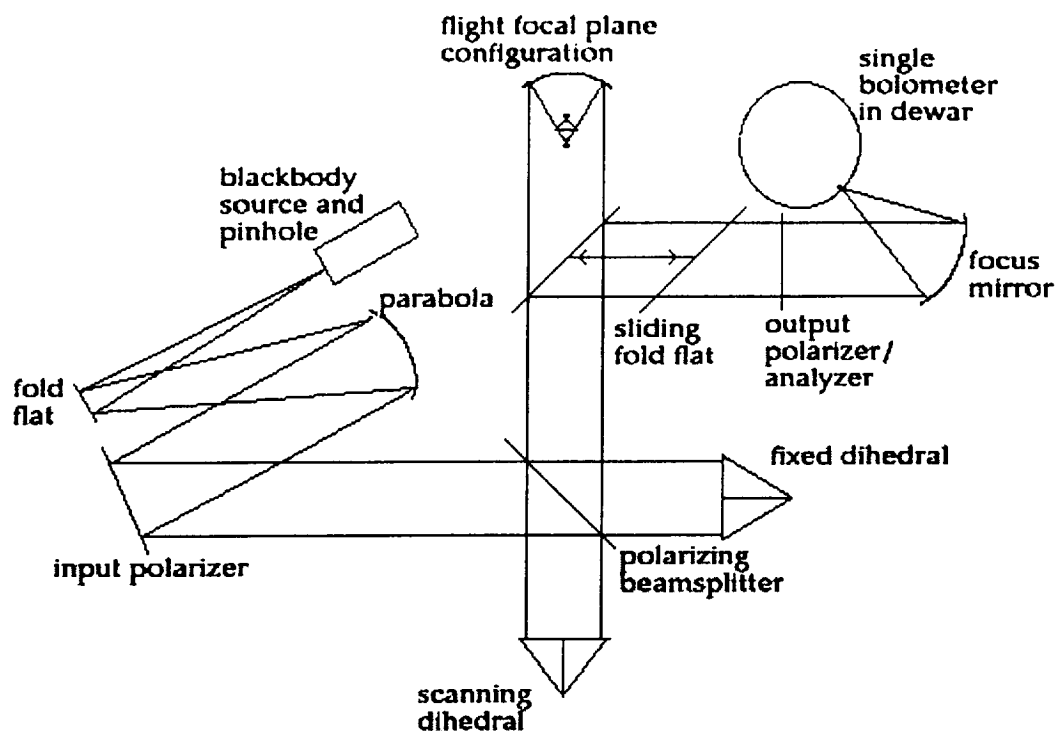


Figure 3: FIR interferometer breadboard configuration

The difference in path length between the two arms of the interferometer created a polarization state in the combined output beam which changed as the moving dihedral was scanned. The output polarizer/analyzer transmitted one of the two orthogonal polarization states to a focus mirror which focussed the beam through a dewar window port onto a single bolometer detector cryocooled to liquid helium temperature of 4 K. Note that 50% of the total throughput is thrown away at the input polarizer. The 50% loss is not due to the customary amplitude Michelson interferometer design where the 50% gets thrown away at the beamsplitter and sent back towards the source.

## 2.2 FIR interferometer breadboard configuration differences from the engineering and flight unit configuration

There were differences between the breadboard FIR interferometer optical layout and the engineering and flight unit FIR interferometers that are important to note, which were not critical in the characterization of the interferometer, nor the development and evaluation of the alignment techniques and alignment and polarization sensitivity studies.

1. In the engineering and flight unit FIR interferometers, an off-axis parabola collimated the light from a telescope. In the breadboard, a slow, on-axis parabola and a blackbody source provided the collimated beam. The effect of this was minimal, causing small aberrations in the form of astigmatism and coma.
2. In the engineering and flight unit FIR interferometers, a black, aluminum, honeycomb structure was located behind the input polarizer which absorbed the light that was transmitted through the input polarizer to prevent scattered light from being reflected back into the interferometer towards the detectors. This absorber was the reference port for the FIR interferometer. The FIR breadboard interferometer did not have an absorber behind the input polarizer.

3. The engineering and flight unit FIR focal planes<sup>7</sup> consisted of a focus mirror, an output polarizer/analyzer, two detectors, and a subassembly spider mount structure that held the two detectors and the output polarizer/analyzer in their proper positions. This spider mount was structurally attached to the focus mirror's integral flange. The output polarizer/analyzer was located near the focus of the beam which split the beam towards the two detectors which were directly opposite each other such that each detector received one of the two orthogonal polarization states. One polarization state was the transmitted component going to one detector, and the orthogonal polarization state was the reflected component going to the other detector. In the breadboard, a large polarizing grid was used in collimated space placed in front of a focus mirror which then focussed the beam onto a single bolometer detector inside a helium dewar. This configuration of having the output polarizer/analyzer transmit only one of the orthogonal polarization states in collimated space vs. powered space has no impact on the data. All of the spectral information is contained in both of the orthogonal, reflected and transmitted, polarization states. The only purpose for having two detectors instead of one detector was to double the signal level.

### **3. FIR POLARIZING GRID COMPONENTS**

As mentioned above, the FIR breadboard interferometer used the large polarizers for all three grid components. These grid components allowed the FIR interferometer to work well in the shorter wavelengths. These unique components were the first ever space flight qualified 1.5 micron mylar substrate with copper photolithographed grids used in an interferometer. This new technology replaced the free standing wire grids used on Far Infrared Absolute Spectrometer (FIRAS) for the Cosmic Background Explorer (COBE) where the state of the art was pushed to using 20 micron wide wires spaced 20 microns apart. Theoretically, the wire thickness and pitch of free standing wire grids could be made smaller.

#### **3.1 FIR polarizing grid component description**

The input polarizer and beamsplitter's physical dimensions are identical, and therefore, are interchangeable. The only difference between the two was their cryogenic flatness performance requirement which was more stringent for the beamsplitter than the input polarizer, because the beamsplitter affects the modulation efficiency which affects the interferometric performance. All three grid components consist of a 1.5 micron thick mylar substrate with 2 micron wide copper wires, 4 micron pitch, photolithographically deposited on the substrate. The substrate is stretched and sandwiched between two stainless steel rings. The developmental model, engineering and flight unit input polarizer and beamsplitter rings have an outer diameter of 100 mm and an inner diameter of 85 mm. The engineering and flight unit output polarizer/analyzers have an outer diameter of 15.2 mm and an inner diameter of 10.6 mm. The thickness of the two rings and substrate assembled is 13 mm. There is a notch on one of the two rings of each grid component that indicates the polarization grid axis orientation and the side that the copper wires are located on the substrate.

#### **3.2 High fidelity FIR breadboard/developmental model polarizing grid components**

The witness sample grids and breadboard/developmental model grids were high fidelity components. All witness samples, breadboard/developmental model, engineering and flight model polarizing grid components were manufactured at QMWC from the same lot of mylar material and were all fabricated using identical manufacturing processes. This was a manufacturing requirement placed on QMWC, because the grid components had to go through environmental survivability and performance flight qualification testing<sup>8</sup>. This requirement validated the results of the tests performed on the breadboard and witness sample components.

### **4. FIR BREADBOARD CALIBRATIONS AND ALIGNMENT**

All optical FIR breadboard components were optically aligned to their nominal flight orientations with respect to the other components. The nominal alignment of the components was achieved using

theodolites, plummets, and other optical metrology equipment. To characterize the interferometer and perform sensitivity studies, the mounts of the components needed to be characterized and calibrated.

#### **4.1 FIR polarizing grid component bi-axial tilt mount calibration**

Prior to installing and aligning the polarizing grid components in the FIR breadboard, they were placed in mounts with bi-axial tilt azimuth and elevation adjustment micrometers. These adjustment mounts provided the quantitative tilt capability to perform the alignment sensitivity study on the polarizing grid components. It was necessary to calibrate the micrometers prior to installation. The micrometers were calibrated by measuring the actual tilt amount corresponding to known micrometer increments. The tilts of the grids were measured using a theodolite autocollimating off of an alignment flat epoxied to the mount. The grid substrate normal was measured with respect to the alignment flat normal on the mount. The substitution of using the alignment flat instead of the grid substrate was done for all of the calibration measurements, because the autocollimating return from the alignment flat was clearer, brighter, and sharper which made the calibration measurements more accurate. A total of 54 micrometer to tilt calibration measurements were averaged. The calibration measured that each micrometer increment of 0.01 inch tilted the beamsplitter by  $13.5 \pm 1.3$  arc seconds in both azimuth and elevation.

#### **4.2 FIR polarizing grid component and mount polarization sensitivity calibrations**

The grid axis orientation was verified to be aligned to the notch located on the grid rings of each grid component using a HeNe laser that diffracted upon hitting the polarizing grids. The diffraction pattern was a straight line of laser spots that were perpendicular to the grid axis orientation.

The bi-axial tilt mounts had nominal and test orientation degree markings for all three grid components. A protractor was used to mark the polarizing grid mounts indicating the nominal angle increments that the grid notch should be aligned to. On the output analyzer, one degree marks about the nominal grid axis orientation were made as well as marks that were in  $45^\circ$  increments from nominal. The nominal grid axis orientation was achieved by aligning the grid notch to these degree marks on the bi-axial tilt mounts.

#### **4.3 Dihedral scan mechanism calibration**

The scanning dihedral was mounted and aligned parallel to the scan axis of a Klinger motorized single axis translation stage with 1 inch of travel. First, the scan axis of the motorized stage was optically characterized. The dihedral optical axis with the roofline at  $45^\circ$  was then mounted and aligned to the stage's travel axis. The scan mechanism was programmed so that it could perform various scan lengths and velocities in addition to the nominal flight velocity and scan length. Shorter and faster scans were needed during the fine tune interferometric alignment of the beamsplitter. The scan velocity and scan distance were set back to the nominal flight specifications to perform the Fast Fourier Transform (FFT) scans.

### **5. FIR BREADBOARD ELECTRONICS AND DATA COLLECTION SYSTEM**

#### **5.1 FIR breadboard electronics**

The detector used in the FIR breadboard was a single bolometer that operated at liquid helium temperature. The signal from the bolometer went through a pre-amplifier, an electronic filter, and an amplifier.

#### **5.2 FIR breadboard data collection system**

The data collection system was a Macintosh IIfx computer with a GW Instruments 12 bit AD board with custom Superscope software<sup>9</sup> written to collect, store, and average power spectra instead of interferograms so that the timing wasn't critical. The end result was a power spectrum covering the FIR spectral range between  $10 \text{ cm}^{-1}$  and  $600 \text{ cm}^{-1}$ .

The Superscope custom software also controlled the scanning dihedral. The scanning was controlled through an IEEE interface to the Klinger controller. The total Klinger scan length was 2.54 cm. The nominal flight scan length was 1 cm and the nominal flight scan velocity was .0282 cm/second. Before collecting power spectra, the alignment of the beamsplitter was peaked using a chopper and a Nicolet oscilloscope.

## **6. FIR BREADBOARD ENVIRONMENT**

The breadboard table was enclosed in a plexiglass container so the interferometer could be purged with nitrogen to eliminate the water lines in the spectra. Glove and mechanical feedthroughs were fabricated into the purge box to allow micrometer adjustments for the alignment sensitivity measurements without breaking the purge. Extensions with micrometers on the ends were attached to the micrometer adjustments on the mounts. The glove feedthrough into the plexiglass container permitted the tilt adjustments of the grid components using the micrometer extensions.

## **7. POLARIZATION SENSITIVITY TESTS AND RESULTS**

The polarization sensitivity tests determined how sensitive the interferometer's performance was to an individual component's misalignment of the grid axis orientation. The output polarizer/analyzer was the only component tested.

### **7.1 Output polarizer/analyzer polarization sensitivity tests**

The output polarizer/analyzer was tested for its polarization sensitivity around its nominal polarization orientation and at 45° increments from nominal.

FFT scans were taken with the output polarizer/analyzer at 1° clocking increments over a range of  $\pm 5^\circ$  about the nominal grid axis orientation. The 1° increments proved not to be sensitive. Over a 5° range, the signal between 400 and 600  $\text{cm}^{-1}$  did not change. Between 10 and 400  $\text{cm}^{-1}$  at 4° and 5° from nominal, the signal dropped by only a few percent. Between 1° and 3°, the drop in signal between 10 and 400  $\text{cm}^{-1}$  was less than the signal noise and repeatability from scan to scan.

FFT scans were taken at 45° increments between 0° (vertical) and 270°. The 45° increments proved to be the most interesting and sensitive. At all other 45° increment orientations the signal dropped significantly as seen in Figure 4. This showed that when the grid axes were crossed, little signal got through as expected. Only the nominal grid axis orientation of 45° counter clockwise with respect to vertical (0°) produced a clean, large throughput power spectrum. Note that 45° clockwise with respect to vertical (0°) was the lowest signal level for the transmitted beam. With the flight configuration focal plane which uses two detectors, one each receives the transmitted and reflected beams respectively, the reflected beam would have the highest throughput while the transmitted beam would have the lowest throughput with the output analyzer clocked with its grid axis at 45° clockwise with respect to vertical (0°) and vice versa.

These results verified that the grid axis orientations of the grid components needed to be placed at their nominal orientations of  $\pm 1^\circ$ .

## **8. ALIGNMENT SENSITIVITY TESTS**

The alignment sensitivity tests determined how sensitive the interferometer's performance was to an individual component's misalignment from the nominal alignment. The actual sensitivities were then compared with the predicted sensitivities from the optical analysis.

The alignment sensitivities of the input polarizer and beamsplitter determined and drove the alignment stability requirements to be placed on the input polarizer and beamsplitter mounts that would need to endure

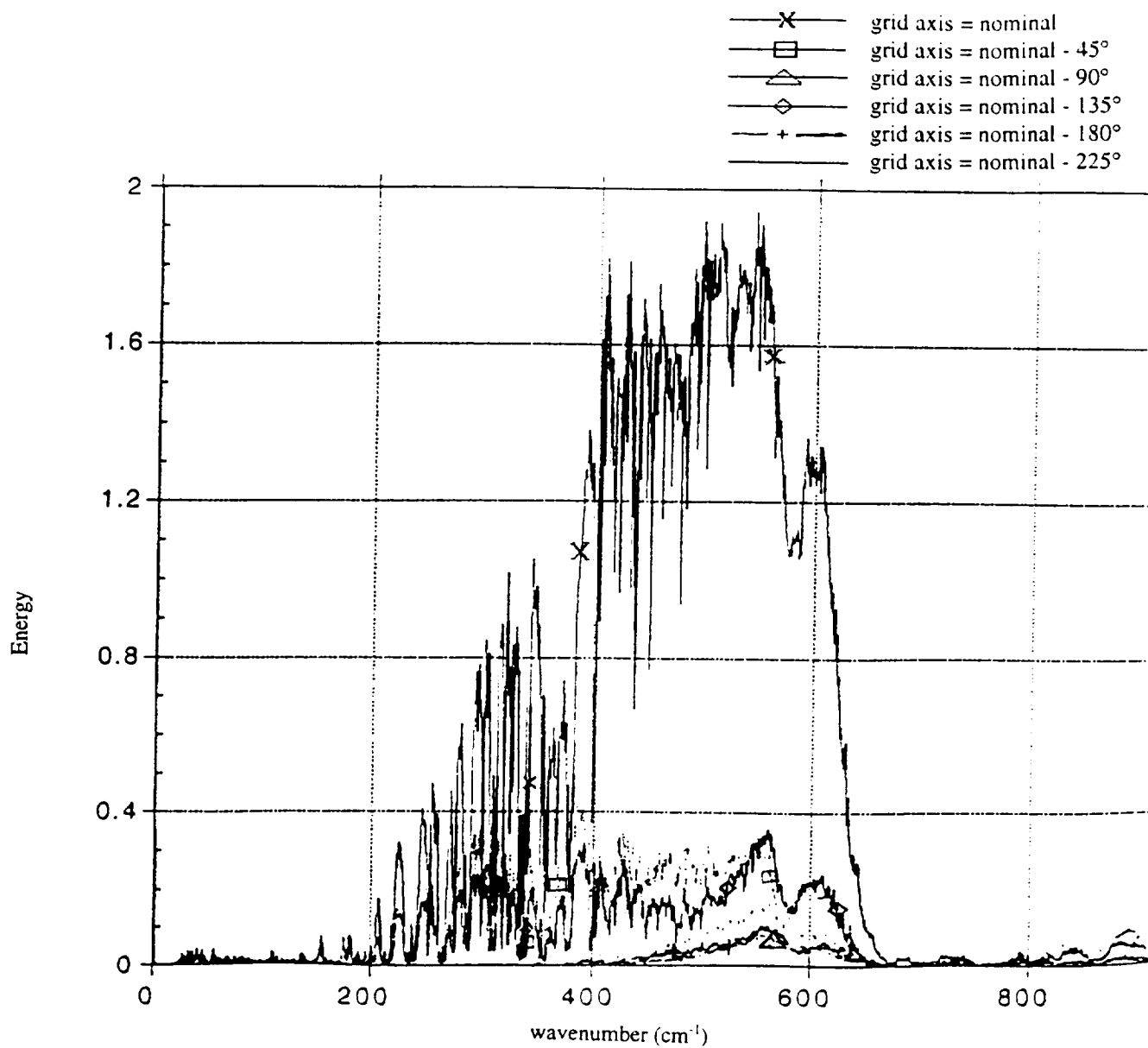


Figure 4: Output polarizer / analyzer nominal polarization grid axis orientation power spectrum vs. 45° increments from nominal



through lock down of the mount, thermal cycling, instrument handling on the ground, launch vibration, seven years of travel to Saturn and four years of mission operation<sup>10</sup>.

### **8.1 Input polarizer alignment sensitivity tests**

The input polarizer was tilted separately in azimuth and elevation using the micrometer extensions. The input polarizer was sensitive to misalignments in the tens of arc minutes range. The input polarizer's alignment sensitivity survey is shown in Figure 5. Predicted alignment sensitivities of the input polarizer agreed with the observed experimental test results that showed that an adjustable mount for the input polarizer was unnecessary.

### **8.2 Beamsplitter alignment sensitivity tests**

The beamsplitter was tilted away from the nominal alignment at known increments separately in azimuth and elevation using the micrometer extensions while under purge. These measurements showed that the beamsplitter was sensitive to misalignments in the arc second range. A change of 13 arc seconds dropped the power spectrum signal level by 10-15%. The beamsplitter was equally sensitive in azimuth and elevation. Figure 6 shows the nominal vs. incrementally degraded power spectrum from elevation misalignments of the beamsplitter. The azimuthal misalignment degradation looked very similar. A combination of elevation and azimuthal misalignments was twice as sensitive optically perpendicular to the roofline of the dihedrals. These measurements supported the predicted sensitivities that lead to the requirement for a real-time bi-axial tilt adjustable beamsplitter mount that would remain stable and in alignment to within less than 10 arc seconds over its entire life.

## **9. SUMMARY**

This FIR polarizing interferometer design had never been modeled before. During the testing of the FIR breadboard interferometer, the alignment tolerancing and sensitivity analyses were being performed. A major reason to breadboard this design was to verify the sensitivities that came out of the analyses, characterize the interferometer, and test its component sensitivities, and develop alignment techniques to be used on the engineering and flight units. The polarization sensitivities proved not to be sensitive and the grid axis orientations had a polarization axis alignment tolerance of  $\pm 1^\circ$  for all three components. The verification that the beamsplitter was extremely sensitive to tilt misalignments led to a number of future tasks. The polarizing beamsplitter sensitivity testing emphasized the need for bi-axially adjustable flight mounts<sup>10</sup> that were stable to 5 and 10 arc seconds, and a 1 wave peak-to-valley wavefront error measured at 632.8 nm. over its design lifetime.

## **10. ACKNOWLEDGEMENTS**

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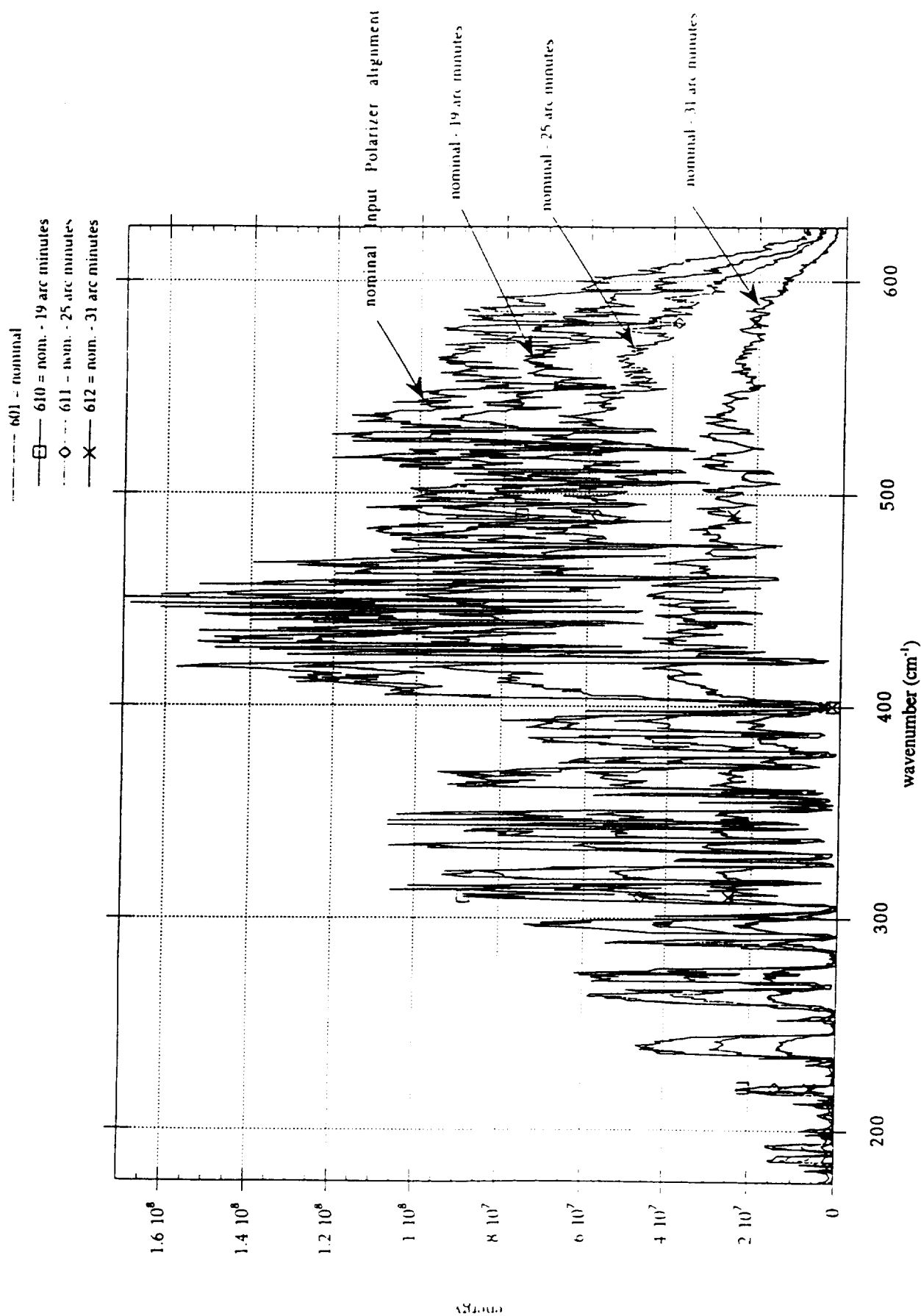


Figure 5: Input polarizer alignment sensitivity showing nominal alignment vs. incremental misalignment degradation of the power spectrum

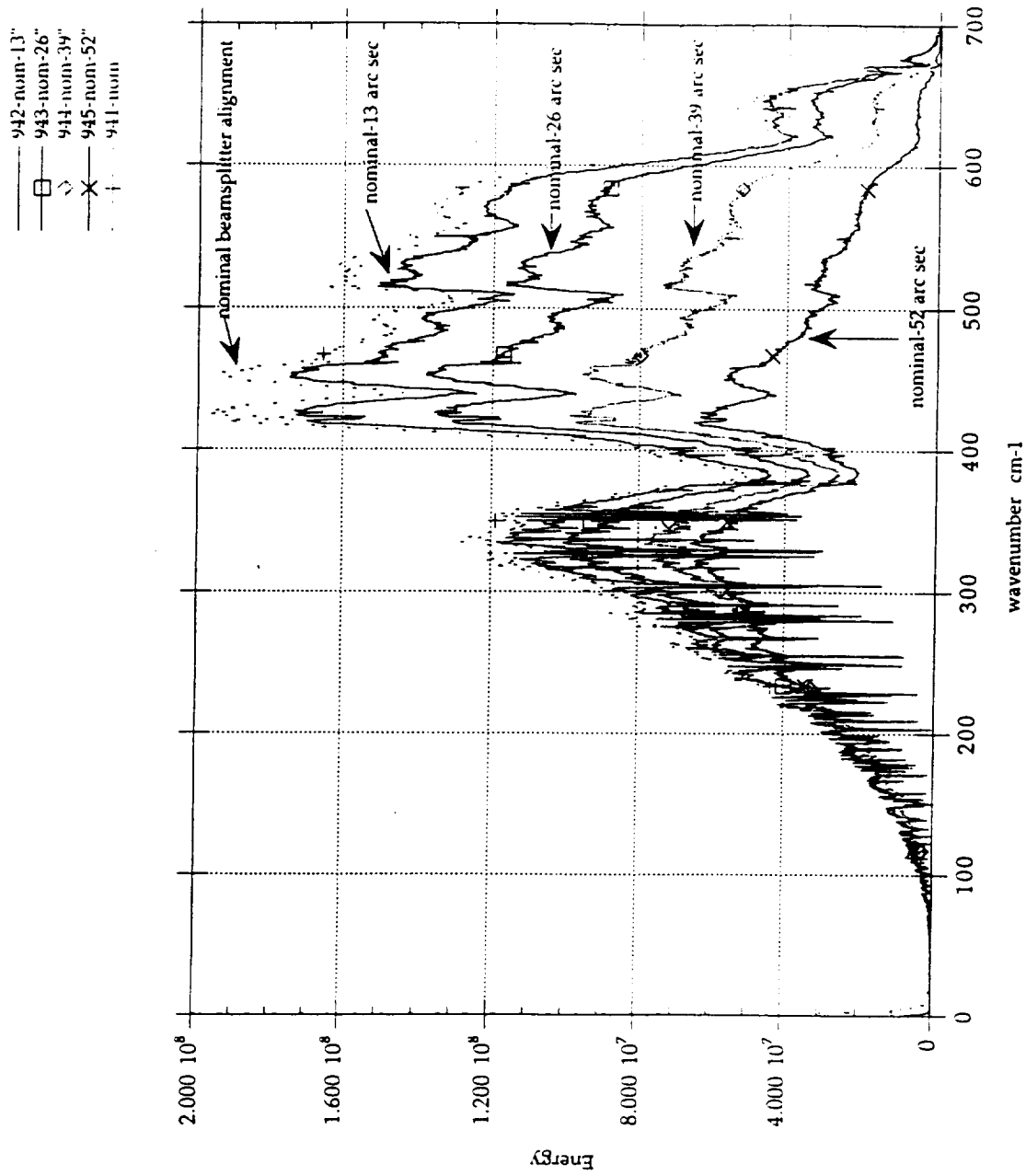


Figure 6: Polarizing beamsplitter alignment sensitivity showing nominal alignment vs. incremental misalignment degradation of the power spectrum

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