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Precision alignment of an infrared imaging system

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ABSTRACT

The optical hardware design and methods of alignment for the GOES (Geostationary Operational Environmental Satellite) imaging instrument are discussed. The instrument is a multi-channel space-borne meteorological system. Included will be the results of a tolerance and sensitivity analysis for the optics and their adjustment mechanisms. A brief summary of the sequence of system alignment steps taken to achieve the final configuration of the instrument will conclude the discussion.

1.0 OPTICAL SYSTEM

The imaging instrument requiring alignment is part of a three axis stabilized geosynchronous platform. The earth viewing instrument will be operational by 1991 and is to be used by the National Oceanographic and Atmospheric Administration for weather forecasting. The host spacecraft, which is scheduled for launch in late 1990, is illustrated in Figure 1.1. The imaging instrument is completely independent of its companion spectrometer and is sensitive in visible wavelengths from .525 to .775 microns and infrared wavelengths from 3.775 to 12.5 microns.

The instrument is modular in nature with its major optical components consisting of a twelve-inch cassegrain telescope, a two-axis scan system, a visible optics assembly, a relay optics assembly, and a cooled optics assembly as shown in Figure 1.2. The visible optics includes the IR/VIS beamsplitter and the visible detector array. The relay optics further divide the IR energy into narrow channels. The location of the individual optical elements within these two assemblies are critical in achieving system alignment so most of the alignment effort is built into these subsystems. Figure 1.3 shows an exploded view of these elements and indicates which have been selected for adjustment.

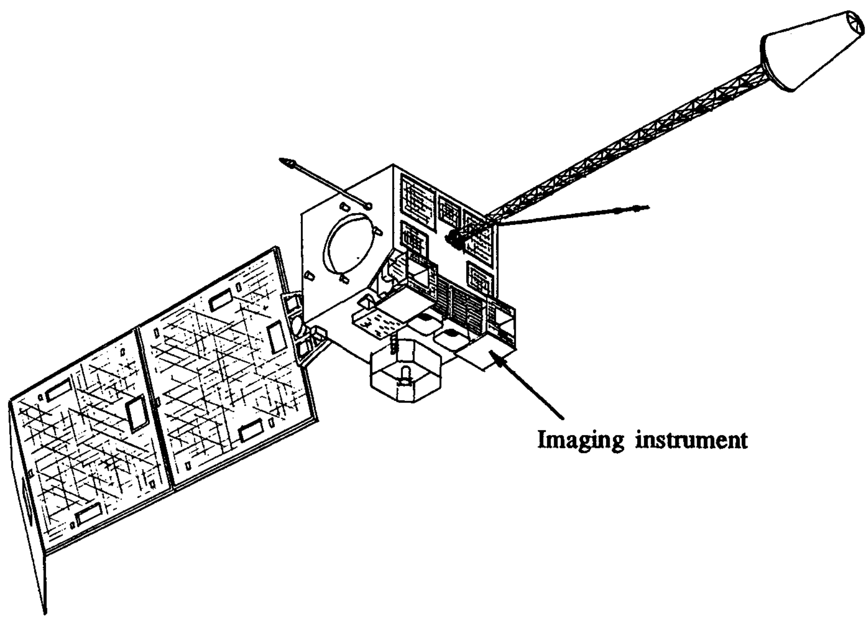


Figure 1.1 GOES weather satellite

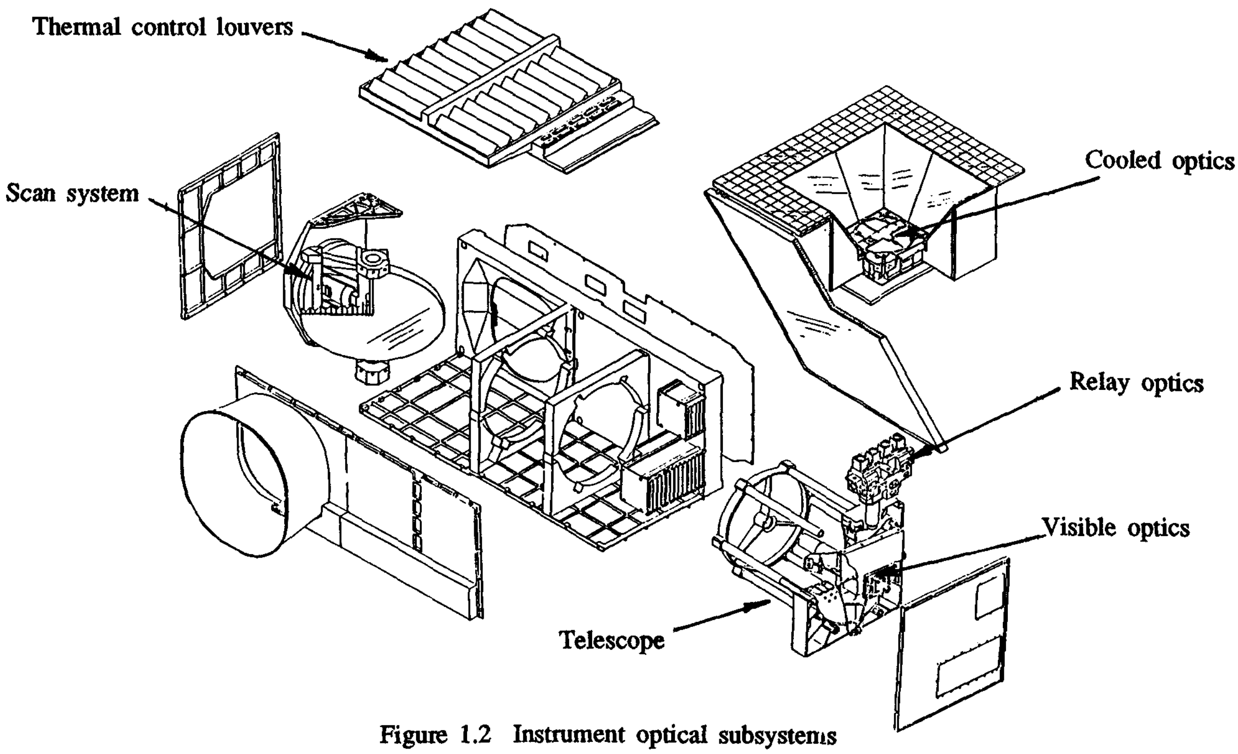
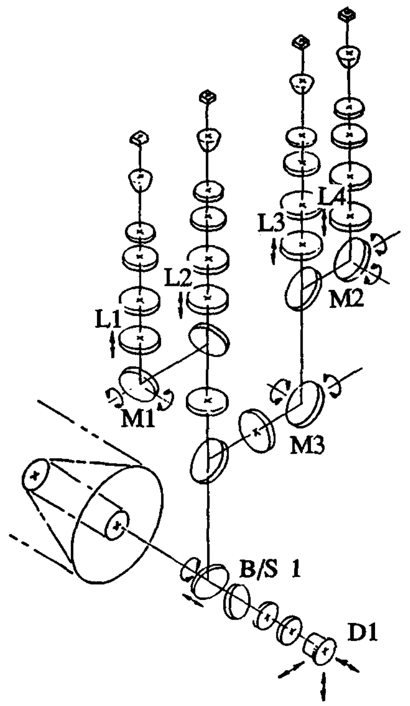


Figure 1.2 Instrument optical subsystems



LEGEND:

- D1 Visible detector
- B/S 1 IR/VIS Beamsplitter
- M1 11-micron folding mirror
- M2 4-micron folding mirror
- M3 7-micron folding mirror
- L1 11-micron focus lens
- L2 12-micron focus lens
- L3 7-micron focus lens
- L4 4-micron focus lens

Figure 1.3 Visible and infrared optical elements

2.0 ALIGNMENT CONSIDERATIONS

In general, the sequence for the total system alignment first begins with the positioning of the telescope to an optical reference attached to the base of the instrument. The scan system is then aligned to that reference, followed by the coregistration of the visible and infrared channels by alignment of the individual elements indicated in Figure 1.3.

Several factors required consideration in implementing the alignment techniques. As is always the case in space-borne equipment, weight and especially space limitations greatly restricted design alternatives and were the driving factors behind the mechanism designs. These was especially difficult in providing the means for real-time element adjustment during system testing. Within the visible and relay optics assemblies both the mechanisms and access to them had to be provided for in a limited region with the rest of the instrument in a fully assembled condition.

Another complication to the alignment scheme is that the IR detectors within the cooled optics must operate at temperatures near 100 K during the alignment. This presents obvious logistical problems. An elaborate cryogenically cooled vacuum cooler must be attached to the cooled optics structure while the adjustments are made.

Finally, the entire system must withstand exposure to qualification sine and random vibration and daily on-orbit temperature cycling with component temperatures varying from 10°C to 50°C. The instrument must maintain its coregistration and produce a repeatable pointing profile which is then corrected by electronic processing of the image data.

3.0 TOLERANCE AND SENSITIVITY ANALYSIS

Because of the large number of optical elements involved in the imaging system, especially in the IR channels, the definition of the performance requirements for the adjustment mechanisms was not trivial. A detailed tolerance analysis of two of the four IR channels was performed. Those selected were the 12-micron channel which involves the fewest optical elements and the 4-micron channel which includes the most. These were chosen to bound the problem and to define the range of performance required for each mechanism.

The results of the tolerance analysis are shown in Tables 3.1 and 3.2. Notice that only the non-zero contributors to the stack-up are listed. In all, the parameters considered for each element included curvature tolerance for each surface, the associated surface irregularities, element thickness, axial positioning, centration, decenter, refractive index, wedge, and tilt. The adjustable elements included positioning errors as well. After completion of this analysis the total range requirements of the mechanisms were determined, and provisions were made within their mechanical designs to ensure that these requirements were achieved.

The sensitivities of each mechanism are driven by the coregistration requirements between channels. The mechanisms must position each optical element with enough control and repeatability to stop the adjustment of each channel within the desired region without overshoot. Experience and subsystem testing has shown that rotation of the actuation screw for each mechanism about 20 degrees is the minimum reasonably achieved adjustment increment. The mechanisms were therefore designed such that the 20 degrees actuation resulted in a position shift of less than 50% of the specified coregistration range.

Optical Element	Tolerance		Line of sight shift (microradians)
IR/VIS Beamsplitter (Adjustable)			
Tilt	0.100 deg		45.0
Adjustment Error	0.100 deg		22.5
Axial Position	0.010 in		67.0
LW/MW2 Beamsplitter			
Wedge	0.033 deg		31.0
Tilt	0.100 deg		1.0
Collimating Lens			
Centration	0.002 in		9.0
Decenter	0.010 in		65.0
LW/MW1 Beamsplitter			
Wedge	0.033 deg		36.7
Focus Lens			
Centration	0.002 in		31.0
Decenter	0.010 in		65.0
Tilt	0.500 deg		5.0
Vacuum Window			
Wedge	0.033 deg		17.7
Tilt	0.440 deg		4.4
Radiator Window			
Wedge	0.033 deg		13.0
Tilt	0.440 deg		4.4
Filter			
Wedge	0.033 deg		23.0
Tilt	0.100 deg		1.0
Aplanat Lens			
Centration	0.0005 in		72.0
Decenter	0.0020 in		72.0
Tilt	0.1000 deg		0.0
		Total:	585.7
		RSS:	174.0

Table 3.1 12 Micron Channel Tolerance Analysis

Optical Element	Tolerance	Line of sight shift (microradians)
LW/MW2 Beamsplitter		
Axial position	0.010 in	95.0
Tilt	0.100 deg	83.0
IR/VIS Beamsplitter (Adjustable)		
Axial position	0.010 in	67.0
Tilt	0.100 deg	44.0
Adjustment tilt	0.100 deg	22.0
Collimating Lens		
Centration	0.002 in	9.0
Decenter	0.010 in	65.0
MW2 Folding Mirror (Adjustable)		
Axial position	0.015 in	1.5
Miner axis rotation	0.100 deg	101.0
Axial rotation	0.100 deg	50.5
MW2/SW Beamsplitter		
Tilt	0.100 deg	101.0
SW Folding Mirror (Adjustable)		
Minor Axis Rotation	0.100 deg	101.0
Axial Rotation	0.100 deg	50.5
Focus Lens		
Centration	0.002 in	58.0
Decenter	0.010 in	125.0
Tilt	0.100 deg	1.0
Vacuum Window		
Wedge	0.033 deg	9.3
Tilt	0.440 deg	4.4
Radiator Window		
Wedge	0.033 deg	4.7
Tilt	0.440 deg	4.4
Filter		
Wedge	0.033 deg	17.3
Tilt	0.100 deg	1.0
Aplanat Lens		
Centration	0.0005 in	73.0
Decenter	0.0005 in	18.0
	Total:	1106.6
	RSS:	296.6

Table 3.2 4 Micron Channel Tolerance Analysis

4.0 ALIGNMENT MECHANISMS

Each of the adjustable elements indicated in section 2.0 has a specialized mechanism which provides sufficient access, range, and sensitivity to position the optical element while all of the instrument subsystems are installed. Each of the mechanisms is described below and is illustrated in its respective figure.

4.1 Visible Detector Mechanism

As shown in Figure 1.3, the visible detector is adjustable which provides the alignment for the visible channel in all three directions. The optical axis adjustment is accomplished by shimming between the detector mechanism and the visible optics housing with the minimum shim size being 0.005 inches. The detector mechanism is separated from the visible optics housing by a total of 0.120 inches of shim material. In the opposite direction, 0.120 inches of shim material can be added so the total range is ±0.120 inches. The detector is mounted in a translation stage which provides the other two axes of adjustment. These are accomplished by mounting the detector in a housing which can slide in two orthogonal directions. The housing has guides which limit the motion exclusively to these directions. In each direction there is an adjustment screw which drives each stage against a preloaded spring on the opposite side. The screws are captivated and have their threaded end screwed directly into the stages. As each screw is turned, its stage, and therefore the detector, is forced to move along the axis of the screw. The detector mechanism allows a total of ±0.100 inches (in each direction) which corresponds to ±667 microradians of total range. The adjustment screw pitch was selected to allow 0.0179 inches/turn which corresponds to a 119 microradians/turn sensitivity. An illustration of the mechanism mounted to the visible optics is shown in Figure 4.1.

Adjustment	Range	Sensitivity
Translation	±667 microradians	6.6 microradians
Focus	±.120 inches	0.005 inches

Sensitivities based on 20 degree rotation of adjustment screw

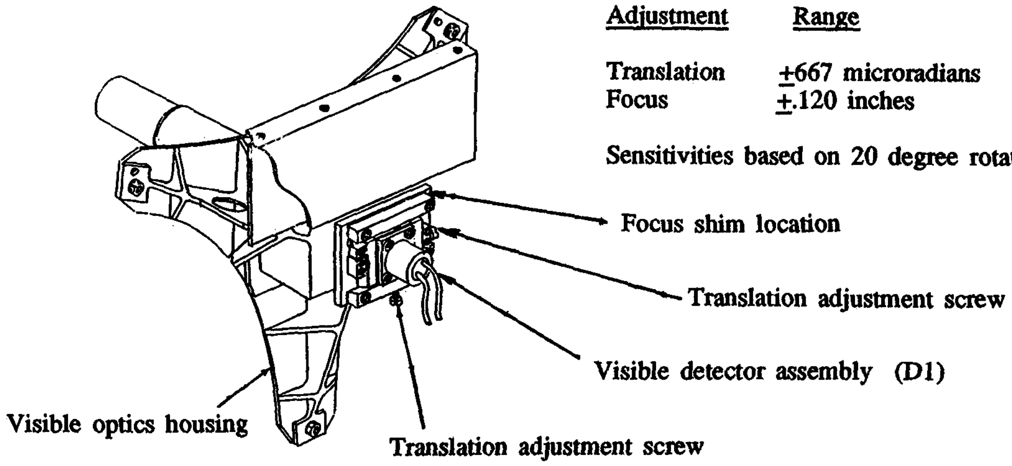
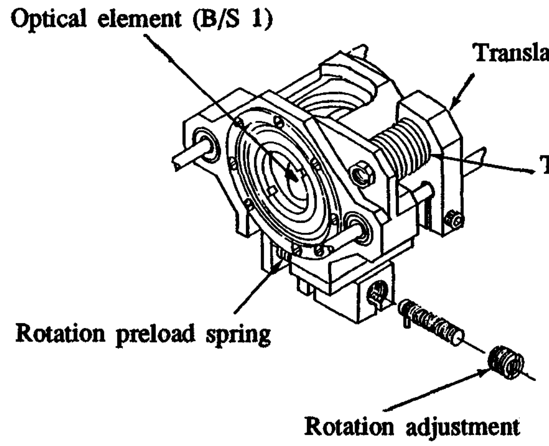


Figure 4.1 Visible detector adjustment mechanism

4.2 IR/VIS Beamsplitter Mechanism

The translation adjustments normal to the optical axis for the 12-micron infrared channel is provided by the mechanism that holds B/S-1. As may be surmised from Figure 1.3, this adjustment will also have an equivalent effect in the other infrared channels. However, the other infrared channels also have unique translation adjustments which can be made to offset this effect. The B/S-1 mechanism allows translation along and rotation about the incoming optical axis. The mechanism is mounted on two shafts, via linear bearings with the shafts supported by the visible optics housing. A bracket is clamped to one shaft and interfaces with the mechanism main housing with a differential screw pair and a preload spring. Turning the differential screw translates the mechanism main housing, and therefore the beamsplitter, along the shafts. The range (in image motion at the detector plane) of this adjustment is ±145 microradians with a sensitivity of 29 microradians/turn of the adjustment screw. The adjustment in the other axis is also provided by actuating a differential screw. The beamsplitter is mounted in a cell which rotates on bearings within the mechanism main housing. A tab is attached to the cell and the differential screw moves the tab against a spring load to effect a rotation of the beamsplitter. The reflected beam changes its direction with the surface normal which results in the other translation adjustment. The range of this adjustment is ±295 microradians with a sensitivity of 59 microradians/turn.



Adjustment	Range	Sensitivity
Translation	±145 microradians	1.6 microradians
Rotation	±295 microradians	3.3 microradians

Sensitivities are line of sight shifts at the detector based upon a 20 degree rotation of the adjustment screw

Figure 4.2 IR/VIS beamsplitter adjustment mechanism

4.3 IR Folding Mirror Mechanism

In the 4, 7, and 11 micron channels, the translation adjustments are slightly different. Since the incoming beam is collimated for these elements, the translation along the optical axis is ineffective in moving the reflected beam. Therefore translations are provided by rotations at the fold mirrors. (See Figure 1.3.) As with the IR beamsplitter, mirrors rotate about the incoming optical axis. The other rotation is about an axis which is orthogonal to the incoming optical axis and also lies in the plane of the mirror (the minor axis of the elliptical mirror). The first rotation uses the same method as was described above for the 12 micron channel beamsplitter adjustment. The second rotation is similar except that the tab is an integral part of the mechanism main housing so that the entire mechanism rotates within the relay optics assembly. The optical axis rotation range for the 4, 7, and 11 micron channels is ±390 microradians and the sensitivity is 78 microradians/turn. The 4, 7, and 11 microns channels are ±490 microradians, ±330 microradians, and ±490 microradians respectively with sensitivities of 98, 66, and 98 microradians/turn respectively.

Adjustment	Range	Sensitivity
Optical axis (M1,M2)	±490 microradians	5.4 microradians
Optical axis (M3)	±330 microradians	3.6 microradians
Minor axis (M1,M2,M3)	±390 microradians	4.3 microradians

Sensitivities are line of sight shifts at the detector based upon a 20 degree rotation of the adjustment screw

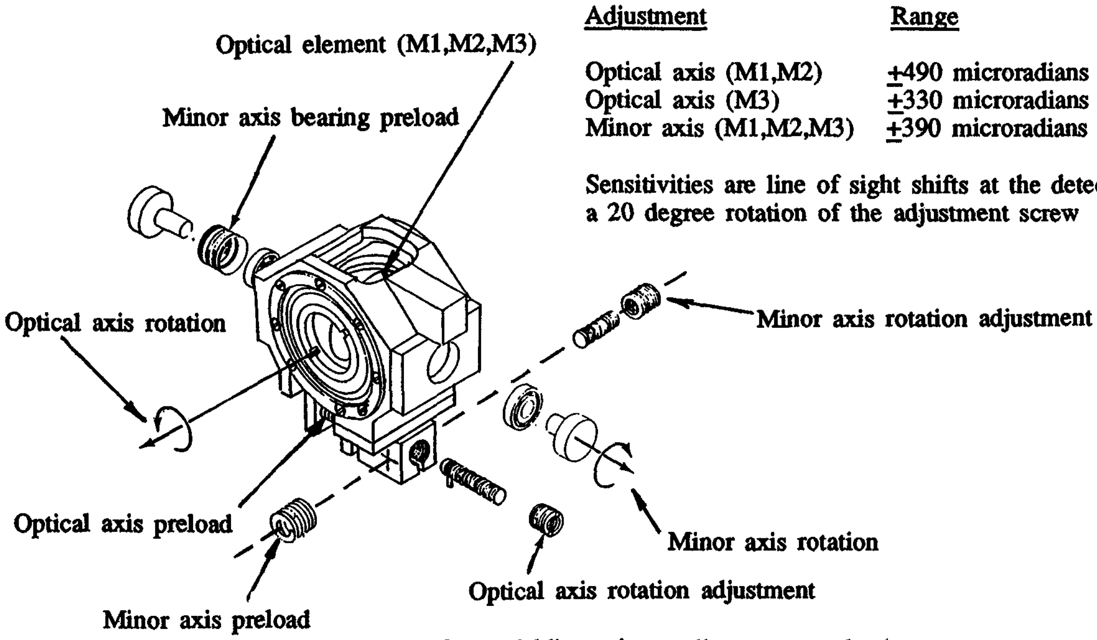
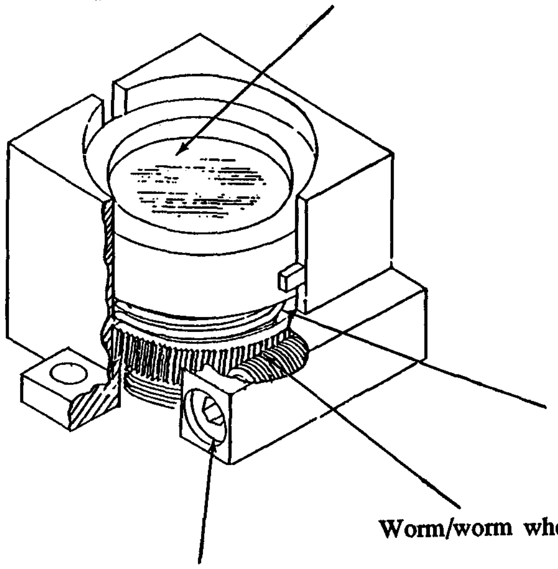


Figure 4.3 IR folding mirror adjustment mechanism

4.4 Focus Lens Mechanism

The adjustment in the direction along the optical axis for the imager infrared channels is provided by direct translation of the focus lenses as shown in Figure 1.3. Each focus lens is mounted within a separate adjustment mechanism. An adjustment screw turns a worm gear which in turn translates the focus lens along the optical axis. These mechanisms have a total range of $\pm$.100 inches with a sensitivity of 0.00047 inches/turn of the adjustment screw. The optical sensitivities of the focus lenses are such that the percent change in channel effective focal length per .001 in translation of the lens for the 4, 7, 11 and 12 micron channels is approximately the same and equal to .069%/.001 in.



Adjustment	Range	Sensitivity
Translation	$\pm$0.100 inches	0.000026 inches

Sensitivity based on 20 degree rotation of adjustment screw

Figure 4.4 IR focus lens adjustment mechanism

In all of the above mechanisms, the preload spring is an integral part of the design. It provides the necessary preload against the differential screws to remove the thread backlash in both thread pairs. In addition it provides the necessary push/pull feature of each adjustment to permit repeated translations in both directions.

5.0 System Test Sequence

As previously indicated in section 2.0, the first step in the instrument alignment is positioning the telescope with respect to an optical reference on the instrument base followed by a similar alignment of the scan system. While the telescope and scanner are being built and installed, the optical elements and mechanisms are installed into the visible and relay optics housing. It is impossible to correctly position the elements in the housings until the entire system is assembled. There is a significant advantage, however in positioning the elements in a nominal position. This greatly enhances the likelihood that the desired final position of the element is within the range of the mechanism.

A separate test has been designed and is used to perform a subsystem level pre-alignment of the visible and relay optics assemblies. When these aligned subsystems are integrated into the instrument, the registration of the channels begins. Because of the adjustment of one channel in some cases affects the others, it is necessary to iterate the adjustments to achieve and acceptable final alignment configuration.

During and after the alignment procedure, the coregistration of the channels is measured and verified by an instantaneous field of view measurement obtained by scanning a slit source across the aperture in both translational axes. The 50% energy points for each direction are recorded for each channel and the position of each detector within the field of view is determined.

After alignment is completed for all channels the mechanisms are epoxied in place to preclude later motion of the optical elements during environmental testing and during mission life. This step is performed just prior to environment qualification testing so that adjustments are possible throughout the pre-environmental testing.

At this writing, a functioning prototype instrument has been completed. The adjustment mechanisms exceeded expectations as the alignment of the visible and infrared channels was performed within a two-week period. While test results after environmental testing are not yet available to determine environmental response, the mechanisms and alignment sequence has thus far proven to be a successful effort.

6.0 Acknowledgments

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