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Optical Alignment of a Pupil Imaging Spectrometer

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ABSTRACT

The optical alignment hardware and methods now in use for the GOES (Geostationary Operational Enviromental Satellite) Sounder optics are described. The alignment mechanisms and their mechanical and optical sensitivities are included. The alignment methods discussion includes a description of the prealignment testing and the optical measurements used for final instrument coregistration.

1. INTRODUCTION

The GOES Sounder is a nineteen channel discrete filter spectrometer with an additional channel for star sensing. This instrument is used with an imaging instrument on a three axis stabilized geosynchronous satellite by the National Oceanographic and Atmospheric Administration for weather forecasting. The Sounder consists of a sensor module, an electronics module, and a power supply. The sensor module contains all of the instrument optics.

2. INSTRUMENT OPTICS AND COMPENSATIONS

An exploded view of the Sounder sensor module is shown in Figure 1. The subassemblies which include optical components are the scan assembly, telescope (approximately 12 inch aperture), relay optics, filter wheel assembly, and cooler assembly. The Sounder optical schematic, minus the scan mirror, is shown in Figure 2. Referring to Figure 2, the relay optics contain all of the optics after the telescope primary up to the filter wheel windows. The filter wheel optics consist of the filter wheel windows and filters and the remainder of the optics are part of the cooler assembly. The visible and star sense detectors shown in Figure 2 are at the telescope prime focus. In the infrared bands the telescope prime focus is located between D2 and L4 and between D2 and L1. This energy is split into the longwave (LW),

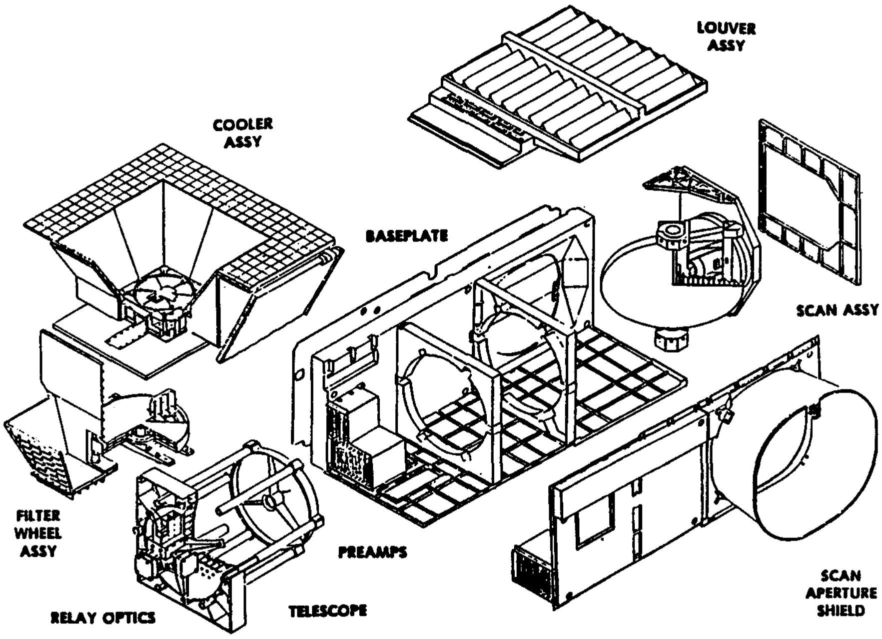

Figure 1. Exploded view of the GOES Sounder sensor module.

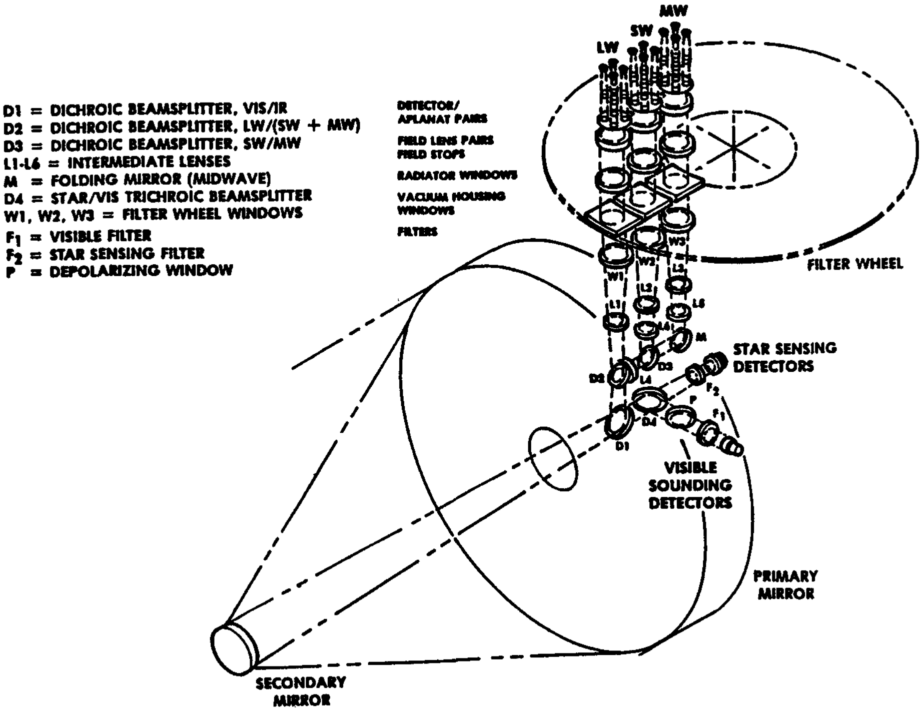

Figure 2. Sounder optical schematic.

shortwave (SW), and midwave (MW) bands (and are further subdivided into 18 spectral channels by the filter wheel) and reimaged onto the field stops. The field stop apertures (4 per channel), field lenses (2 per field stop aperture), and detectors (1 per field stop aperture) in the infrared bands are offset from the main optical axis. The infrared detectors are nominally at the image of the system aperture stop, or in other words, at the system exit pupil. For the purpose of this section we will define a local (to each optical element) Cartesian coordinate system where the z axis is the incident optical axis and the x-y plane is the plane of the optical element or detector except for beamsplitters and fold mirrors which are tilted from the x-y plane by 45°. In general, adjustment is provided in each channel in the x, y, and z directions by detector motion or optical element motion. In the infrared channels there are two sets of x, y, and z adjustments, one set for coregistration of the field stops and the other set for maximizing energy output at the detector.

The visible and star sense detectors are mounted in their separate mechanisms which provide x and y adjustment. These mechanisms are mounted to the relay optics housing using shims so that the addition or deletion of shims allows adjustment along the z axis.

The x-y type adjustment used for coregistration of the field stops are located at optical elements D1, D3, and M shown in Figure 2. These elements are mounted in mechanisms which translate the corresponding beamsplitter or mirror along the incoming optical axis and also rotate about this axis. These two motions provide x-y adjustment at the field stops. This x-y type adjustment and manufacturing tolerances such as element decenter, surface irregularity, etc. change the IFOV size which may be compensated for by moving the lenses labeled L1 through L3 along the optical axis. L1 through L3 are mounted in a housing which allows the lenses to be translated along the optical axis. For maximizing energy output at the detectors, x, y, and z adjustments are provided in the detector mechanisms.

3. ALIGNMENT RATIONALE

The star sense detector is required to be aligned to the visible detector and this specification determines the need for x-y adjustment at the star sense detector. The z axis adjustment at the star sense detector is necessary for signal to noise optimization. The x-y adjustment in the visible channel is required in order to meet coregistration (sounding channels) specifications. The z axis adjustment at the visible detector is necessary in order to meet instantaneous field of view (IFOV) and sensitivity requirements.

The mechanisms at D1, D3, M, and L1 through L3 provide the adjustments necessary for coregistration of the field stops and correction of IFOV size in the infrared bands. The x, y, and z adjustments at the infrared detectors allow for peaking of the signal at the detector, and thereby improve system sensitivity.

4. ALIGNMENT MECHANISM DESCRIPTIONS AND SENSITIVITIES

The x, y, and z adjustments in the visible and star sense channels are provided at the detectors. Figure 3 shows a diagram of the mechanism used for visible and star sense detector adjustment. The z axis adjustment is accomplished by shimming between the detector mechanisms and the relay optics housing with the minimum shim size being .005". The detector mechanisms are separated from the relay optics housing by a total of .120" of shim material. In the opposite z direction at least .120" of shim material can be added so the range in the z direction is ± .120". The detectors are mounted in nearly identical mechanisms which provide x-y adjustment. The adjustment is accomplished by mounting a detector in a housing which can slide in two orthogonal directions. The housing has guides which limit the motion to these orthogonal directions. In each direction there is an adjustment screw loading one side of the housing or housing slide plate and a spring load on the other side. The screws are captivated and have their threaded end screwed into either the housing or housing slide plate. As the screw is turned, the housing, and therefore the detector, is forced to move along the axis of the screw. The detector mechanism allows a total of ±.060" (in each direction) which corresponds to ± 412 microradians (urad, field angle) total range. The adjustment screws allow .025"/turn which corresponds to a 172 urad/turn sensitivity.

The x-y coregistration type adjustment for the LW band is provided by the mechanism that holds D1. As may be surmised from Figure 2, this adjustment will have an equivalent effect in the other infrared bands, however, the other infrared bands also have unique x-y coregistration adjustment at D3 and M. The mechanisms at these three elements allow translation along and rotation about the incident z axis. A diagram of these mechanisms is shown in Figure 4. The mechanisms are mounted on two shafts, via linear bearings, and the shafts are supported by the relay optics housing. For each mechanism, a bracket is fixed to one shaft with a set screw and this bracket is set off from the mechanism main housing with a differential screw pair and a spring load. Turning the differential screw pair translates the mechanism main housing, and therefore the beamsplitter or mirror, along the shafts. The range of these adjustments (in ray motion at the field stops) for the LW, SW, and MW bands are ± 145, ± 120, and ± 120 urad respectively with sensitivities of 29, 24, and 24 urad/turn of the adjustment screw. Within these mechanisms, the optical element (beamsplitter or mirror) is mounted in a cell which rotates on

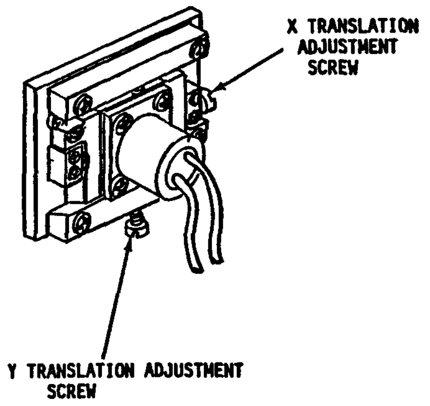

Figure 3. Visible and star sense adjustment mechanism.

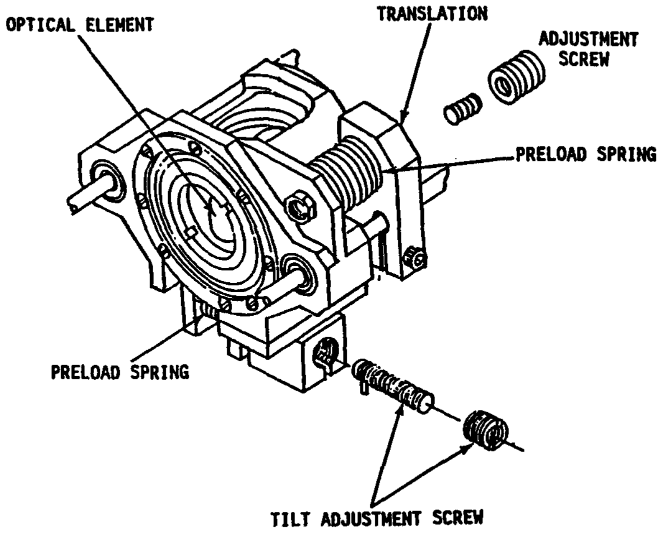

Figure 4. Mirror/beamsplitter adjustment mechanism.

bearings inside the mechanism main housing. A tab is attached to the cell and a differential screw pair moves the tab against a spring load to effect a rotation of the beamsplitter. The range of these adjustments (in ray motion at the field stops) for the LW, SW, and MW bands are ± 145, ± 135, and ± 135 urad respectively with sensitivities of 29, 27, and 27 urad/turn.

The lenses L1 through L3 which are used for IFOV magnification compensation in the infrared bands are mounted in a dresser drawer arrangement where a lens is adjusted along the optical axis by pulling it out of one slot and sliding it into another in .060" increments. In addition to this coarse adjustment the lens can be shimmed in its mount in .001" increments. The total range of this adjustment is approximately 1" in the direction moving towards the telescope axis and approximately 2" in the direction toward the filter wheel for all three bands. A diagram of the focus adjustment mechanism is shown in Figure 5. The sensitivity of these adjustments at the field stop is a nonlinear function of the lens position along the optical axis and is also a function of the errors for which the adjustment is compensating. For one simulated set of conditions, analysis has shown that the sensitivities (in ray motion at the field stop per motion of the lens along the optical axis) are 141, 265, and 18.7 urad/inch for the LW, SW, and MW bands respectively.

The infrared detectors are mounted in mechanisms which allow each detector assembly (4 per band, or in other words 12 total) to move along bearing surfaces in the x and y directions. In the focus direction there is a captivated screw which threads into the housing that holds the detector. The housing is not allowed to rotate, therefore, when the screw is turned the detector moves in the z direction. The mechanisms are actuated with motorized micrometers which are not part of the instrument. In addition to the x, y, and z actuation the motorized micrometers provide a clamp function that hold the detectors in place after they have been peaked. Each detector has ± .015" total range in both the x and y directions and + .050" -.025" in the z direction. The mechanisms are essentially infinitely adjustable, however, the sensitivity of the adjustment is limited by the method of actuation and is approximately .0002".

5. LINE OF SIGHT TOLERANCE ANALYSIS

A ray trace analysis using ACCOS was performed to determine the line of sight sensitivities of the Sounder IR optics including components after the telescope and up to the field stops. The visible and star sense channels were not analyzed because of the small number of components involved and relatively large range of the adjustment mechanisms in these channels. In the IR bands, each optical component was adjusted according to the allowed manufacturing and/or assembly tolerances, the line of sight sensitivities were calculated by tracing a single central

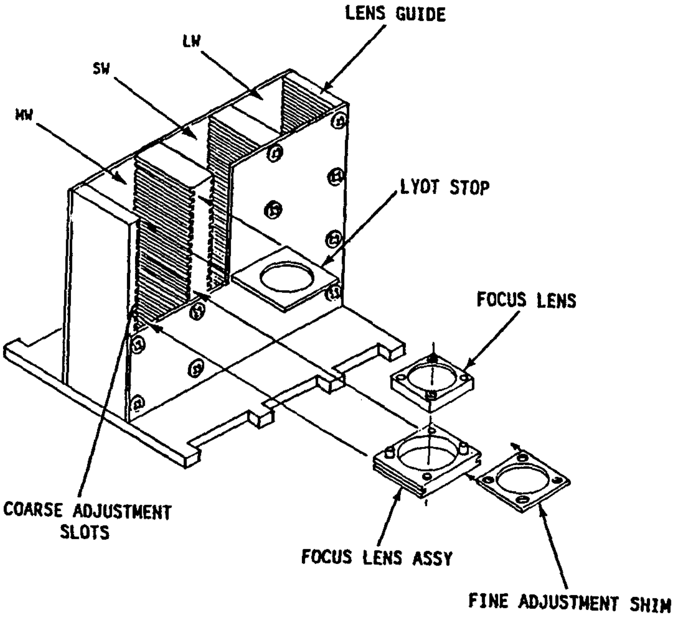

Figure 5. Focus lens adjustment mechanism.

ray (0 field angle, on axis object point) through the component channel and the ray height at the field stop was calculated. The parameters affecting line of sight are axial position and thickness (for beamsplitters and fold mirrors only), decenter, tilt, wedge, and centration. The modeling techniques are given below.

Axial position - the optic was moved along the optical axis.
Thickness - the thickness of the optic was changed.
Decenter - the center of the optic was shifted off the optical axis.
Tilt - the optic was tilted beyond the nominal position.
Wedge - a tilt was added to the second surface of the optic.
Centration - the optic was decentered by an amount that simulates the maximum edge thickness variation (ETV) specified for the part.

Tables 1, 2, and 3 list the data for the LW, SW, and MW bands respectively. The absolute worst case and root-sum-square (RSS) performance expectations were calculated for the three channels, and are listed in the data tables in two places. The first, a subtotal, indicates the expected performance of the relay optics up to and including the focus lenses. The second is the final total, taking all of the optics into account.

The RSS totals for the SW and MW bands given in Tables 2 and 3 respectively exceed the range of adjustment for these bands described in section 4. When the RSS subtotals and totals from Tables 1-3 are compared, it is obvious that the major contributor to line of sight shift in all three IR bands is the relay optics. Within the bands, the major contributors include the elements which are mounted in adjustment mechanisms. Specifically, these are the IR/VIS beamsplitter D1, the SW beamsplitter D3, and the fold mirror M. From this analysis, it was concluded that a method of prealignment for the relay optics must be devised that would null the errors in the relay optics without using any available adjustment range and thereby allow the instrument to be coregistered within system specifications.

Table 1: LW Channel Sensitivities

Parameter	Change From Nominal	Line of Sight Shift (microradians)
IR/VIS B/S D1		
Axial Position	.01"	67
Decenter	.01"	67
Tilt (z axis)	.1°	20
Tilt (x axis)	.1°	40
Wedge	.0167°	6.8
Thickness	.001"	9.5
LW B/S D2		
Tilt (z axis)	.1°	.36

Wedge	.0167°	1.0
Thickness	.002"	6.8
Focus Lens L1		
Decenter	.01"	86
Centration	.0002" ETV	7.1
Tilt	.1°	.04
Subtotal		
Worst Case		312
RSS		136
Filter Window W1		
Tilt	.55°	1.2
Wedge	.0167°	3.4
Filter		
Tilt	.67°	1.7
Wedge	.0042°	1.2
Vacuum Window		
Tilt	.44°	1.2
Wedge	.0167°	.41
Radiator Window		
Tilt	.44°	1.2
Wedge	.0167°	.15
Total		
Worst Case		322
RSS		136

Table 2: SW Channel Sensitivities

Parameter	Change From Nominal	Line of Sight Shift (microradians)
IR/VIS B/S D1		
Axial Position	.01"	68
Decenter	.01"	68
Tilt (z axis)	.1°	21
Tilt (x axis)	.1°	42
Wedge	.0167°	7.0
Thickness	.001"	9.6
LW B/S D2		
Axial Position	.01"	68
Decenter	.01"	68
Tilt (z axis)	.1°	2.8
Tilt (x axis)	.1°	5.6
Wedge	.0167°	.94
Thickness	.002"	19
Beam Ext Lens L4		
Decenter	.01"	12
Centration	.0005" ETV	1.4
Tilt	.1°	.04
SW B/S D3		
Axial Position	.01"	57

Decenter	.01"	57
Tilt (z axis)	.1°	8.7
Tilt (x axis)	.1°	17
Wedge	.0167°	2.9
Thickness	.001"	8.1
Relay Lens L6		
Decenter	.01"	31
Centration	.0002" ETV	12
Tilt	.1°	.32
Focus Lens L2		
Decenter	.01"	45
Centration	.0002" ETV	53
Tilt	.1°	2.0
Subtotal		
Worst Case		687
RSS		185
Filter Window W2		
Tilt	.55°	1.4
Wedge	.0167°	6.4
Filter		
Tilt	.67°	1.7
Wedge	.0042°	1.2
Vacuum Window		
Tilt	.44°	.79
Wedge	.0167°	.18
Radiator Window		
Tilt	.44°	.79
Wedge	.0167°	.06
Total		
Worst Case		700
RSS		186

Table 3: MW Channel Sensitivities

Parameter	Change From Nominal	Line of Sight Shift (microradians)
IR/VIS B/S D1		
Axial Position	.01"	69
Decenter	.01"	69
Tilt (z axis)	.1°	21
Tilt (x axis)	.1°	42
Wedge	.0167°	7.0
Thickness	.001"	9.8
LW B/S D2		
Axial Position	.01"	69
Decenter	.01"	69
Tilt (z axis)	.1°	2.9
Tilt (x axis)	.1°	5.8
Wedge	.0167°	.92

Thickness	.002"	20
Beam Ext Lens L4		
Decenter	.01"	12
Centration	.0005" ETV	1.4
Tilt	.1°	.03
SW B/S D3		
Tilt (z axis)	.1°	.58
Wedge	.0167°	6.9
Thickness	.001"	3.3
Fold Mirror M		
Axial Position	.01"	57
Decenter	.01"	57
Tilt (z axis)	.1°	19
Tilt (x axis)	.1°	38
Wedge	.091°	35
Thickness	.001"	8.1
Relay Lens L5		
Decenter	.01"	81
Centration	.0002" ETV	18
Tilt	.1°	.5
Focus Lens L3		
Decenter	.01"	4.5
Centration	.0002" ETV	2.3
Tilt	.1°	1.6
Subtotal		
Worst Case		732
RSS		196
Filter Window W3		
Tilt	.55°	1.4
Wedge	.0167°	6.4
Filter		
Tilt	.67°	1.7
Wedge	.0042°	1.2
Vacuum Window		
Tilt	.44°	1.1
Wedge	.0167°	.32
Radiator Window		
Tilt	.44°	1.1
Wedge	.0167°	.11
Total		
Worst Case		745
RSS		196

6. PREALIGNMENT AND INSTRUMENT COREGISTRATION

As part of subsystem integration, the scan mirror and telescope are referenced to a precision mirror on the baseplate using a 14" aperture collimator with a target on motorized stages and a combined IR/visible glower source. The relay optics are prealigned at the subsystem level using a system of custom gage plates, reference mirrors, and a HeNe laser and then mounted on the back of the telescope. After the filter wheel and radiant cooler have been installed, the first step of system alignment can begin which is the peaking of the IR detectors. The peaking of the IR detectors is accomplished by flooding the field of view of the instrument with the aforementioned collimator and then moving the detectors in their mechanisms with motorized micrometers to the position of peak signal. With the completion of the IR detector peaking, coregistration begins with the scanning of a slit target using the collimator and its motorized stages and glower to determine the relative position of the detector elements in object space. An appropriate sequence of adjustments are made, interspersed with slit scans, until the sounding channels are coincident in object space.

Due to schedule and cost considerations the prototype GOES Sounder has only seven IR detectors. As of this writing five of the seven have been peaked. The coregistration effort is waiting until the remaining two IR detectors are peaked, however, preliminary measurements have indicated that the line of sight errors in the IR channels are small enough to be compensated for with the mirror/beamsplitter adjustment mechanisms. This preliminary result lends confidence to the prealignment philosophy.

7. ACKNOWLEDGMENTS

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