Technical Synopsis and Discussion of:

Optical Alignment of a Pupil Imaging Spectrometer by Stephen Horchem and Richard Kohrman Proc. of SPIE Vol. 1167, Precision Engineering and Optomechanics, ed. D. Vukobratovich (Nov 1989)

Abstract

This is a synopsis of the paper *Optical Alignment of a Pupil Imaging Spectrometer* (Horchem & Korman, 1989), which describes the optical alignment hardware and methods of the GOES (Geostationary Operational Environmental Satellite) Sounder optical system. This multispectral system includes visible, longwave infrared (IR), midwave IR, shortwave IR, and star sensing detector arrays. These detector arrays need to be co-registered both in terms of line-of-sight (LOS) and instantaneous field-of-view (IFOV). They also need to be focused independently for peak radiometric output. The compensation mechanisms to achieve this are described. A line-of-sight tolerance budget is given for various opto-mechanical and optical components. Some discussion of the pre-alignment and co-registration procedure is given.

1. Synopsis with discussion

1.1. Introduction

The GOES satellites collect atmospheric imaging and sounding data for weather forecasting. This particular paper regards the sounding module optics. The sounding module is a 19-channel discrete spectrometer with an additional channel for star sensing. There is much published information about the GOES satellites, see for example (NOAA, 2008) and (Space Systems LORAL, 2001).

1.2. Instrument optics and compensations

A schematic layout of the optical system is shown in Figure 1. Each of the IR and visible detector arrays consists of four detectors (radiometers). The corresponding detectors of the arrays need to be co-registered, i.e., they need to be pointing at the same area on the ground both in terms of centroid and area. Optically, they need to have the same LOS and IFOV.

This is a pupil imaging system, meaning that the detectors lie in the exit pupil plane. This is to maximize radiometric efficiency. The IFOV's of the detectors of each array are controlled by an array of four field stops. Field lens pairs improve the system throughput. Aplanatic pairs presumably allow for use of small detectors to improve signal to noise ratio.[1] The telescope is a Cassegrain reflector. The complex relay system is catadioptric. Because of the large number of optical relay elements with associated manufacturing and assembly tolerances, co-registration is nontrivial.

[1] Note that this synopsis contains much interpretation and speculation by its author in an attempt to better understand the original paper. In no way is this authoritative.

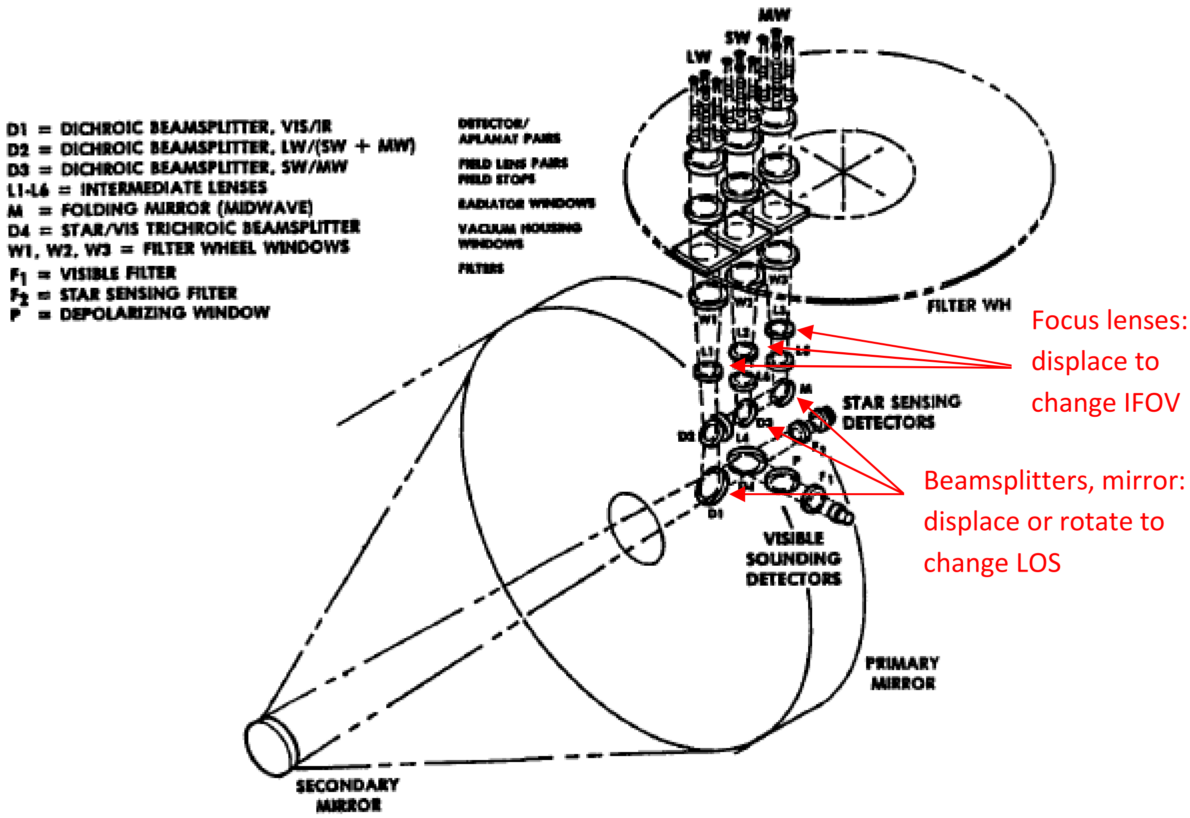

Figure 1: Schematic layout of optical system (Horchem & Korman, 1989)

Each IR detector array has three sets of adjustments. One set of adjustments is for co-registration of the field stops. The field stops do not move with respect to the main structure, so we can think of this as moving the pupil with respect to the field stops. This involves linear and angular displacements of beamsplitters D1 or D3, or of mirror M. Displacement of a beamsplitter/mirror along the longitudinal axis (parallel with the telescope boresight) moves the pupil in the same direction, rotating the field of view. Rotating a mirror about the longitudinal axis rotates the pupil in a similar direction. The sensitivities of these adjustments are discussed later.

The second set of adjustments is for changing the IFOV, to compensate for minor variations due to manufacturing and assembly imperfections. Changing the IFOV of each of the IR channels is achieved by displacing lens L1, L2 or L3 along the corresponding optical axis. Displacing a lens changes the system focal length, and thus IFOV.

The third set of adjustments is for maximizing radiometric output ("peaking" the detectors). This is achieved via three degree-of-freedom (DOF) adjustments of each detector array. This is so that the detector location can be matched three-dimensionally with the exit pupil.

1.3. Alignment rationale

Adjustment mechanisms in general are provided to satisfy system requirements. The x-y adjustment of the star sense detector is to satisfy the requirement that it be aligned to the visible detector. The z-axis adjustment is provided to maximize signal-to-noise ratio (SNR). The visible detector needs no x-y adjustment as it is the reference. Z-axis adjustment is provide is necessary to meet IFOV and sensitivity (SNR) requirements.

For the IR channels, the pupil registration adjustments are provided to satisfy the requirement that they be co-registered amongst themselves and with the visible detector. The x-y-z adjustments of the detectors are provided to meet sensitivity requirements.

The point of this is that the existence of each adjustment mechanism is justified from a system requirement. Adjustments are not provided simply because they are possible.

1.4. Alignment mechanism descriptions and sensitivities

The adjustments of the visible and star sense detectors are simple. Each detector can be adjusted by ±0.120" along the optical axis using shims in 0.005" increments. Lateral adjustments are achieved via two-DOF adjustment mechanisms, shown in Figure 2. There is little information about the optical prescription in the paper. We can infer the system focal length from the fact that a lateral adjustment of ±0.025" corresponds to a LOS change of ±172 μrad. This implies a system focal length of 3.7 m.

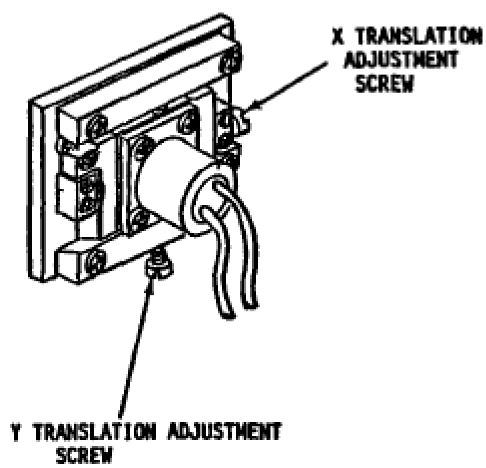

Figure 2: Visible and star sense detector adjustment mechanism (Horchem & Korman, 1989)

The adjustment mechanism used to move beamsplitters D1 and D2, and mirror M is shown in Figure 3. This controls registration of the field stops. Again we can make some inferences about the optical system from the LOS sensitivities. A lateral displacement of beamsplitter D1 by Δs = 0.010" results in a LOS change of Δθ = 67 μrad. The expected relation between these variables is (Burge, 2006)

$$\Delta\theta = \frac{\Delta s}{f}\frac{NA_{\mathrm{D1}}}{NA} \tag{1}$$

where f is the focal length, NA_{D1} is the numerical aperture at the beamsplitter and NA is the system, final numerical aperture. Assuming that most of the system power is in the Cassegrain telescope, it is reasonable to assume that $NA_{D1} \approx NA$. In this case we expect simply $\Delta\theta = \Delta s/f$. This turns out to be consistent with the previous estimate of the focal length of 3.7 m.

We are also told that a rotation of beamsplitter D1 about the longitudinal axis by $\Delta\theta_{D1}$ = 0.1 deg results in an LOS change of $\Delta\theta$ = 67 μrad. For this rotation about the incoming optical axis, the expected relation between these variables is (Burge, 2006)

$$\Delta\theta = \frac{D_{\text{D1}}}{D_{\text{EP}}}\Delta\theta_{\text{D1}} \quad (2)$$

where D_{D1} is the ray bundle diameter at the beamsplitter and D_{EP} is the entrance pupil diameter. Note that there is no factor of two for this particular rotation. From this we can estimate that the ray bundle diameter is about 2.3% of the entrance pupil diameter. While this seems small, it is not inconsistent with the schematic Figure 1.

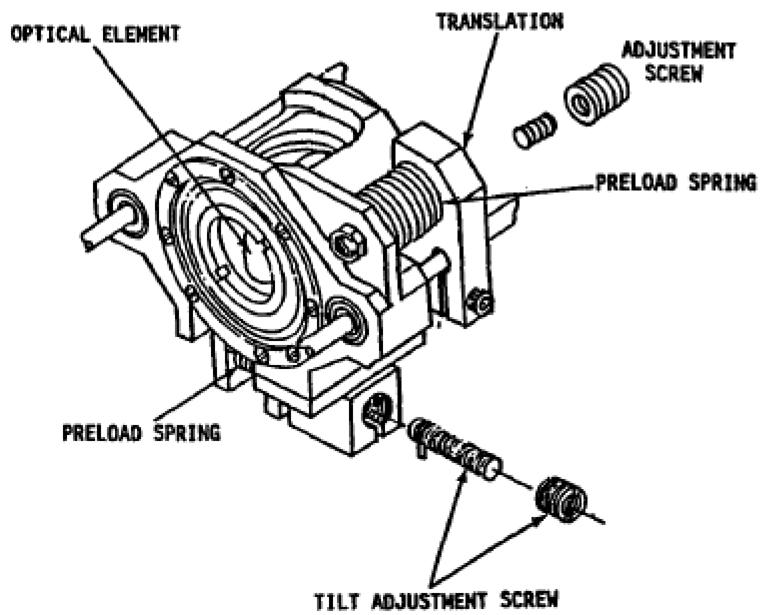

Figure 3: Visible Mirror / beamsplitter adjustment mechanism (Horchem & Korman, 1989)

The next important adjustment mechanism discussed in detail is the "dresser drawer" for the focus lenses, shown in Figure 4. These are clearly low power lenses given the large (3") range of adjustment provided. There doesn't seem to be enough information from the sensitivities given in the paper to infer the lens powers. Coarse displacement of a focus lenses is achieved by moving it from one slot to another. Fine displacement is achieved by shimming the lens within a given slot. Note the Lyot stop shown in the figure for stray light control. It is not stated whether the Lyot stop is placed in its nominal position, or whether it is adjusted to coincide with the actual pupil. It would seem to be difficult to determine the location of the actual pupil except perhaps by maximizing the detector output.

The final adjustment mechanisms discussed, though not depicted, are for adjusting the detector assemblies[2]. A range of ±0.015" is achieved in the lateral directions is provided. A range of +0.05" – 0.025" in the longitudinal, focus direction is provided. All three degrees of freedom are actuated by motorized micrometers, which are non-backdrivable and thus also provide a clamping function.

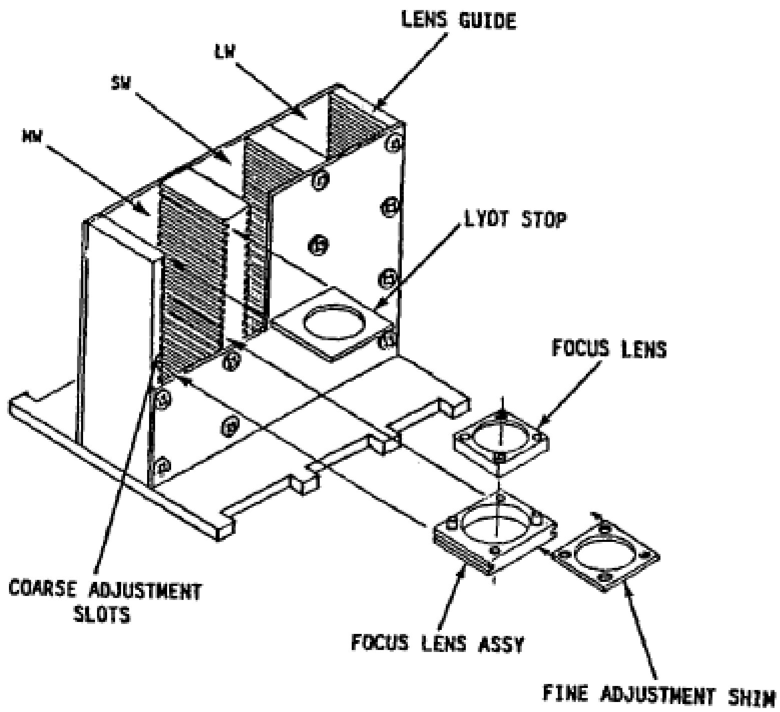

Figure 4: Focus lens adjustment mechanism (Horchem & Korman, 1989)

1.5. Line of sight tolerance analysis

The paper then presents a line-of-sight tolerance analysis of the IR channels. This consists in no small part of three relatively lengthy tables of sensitivities, one for each channel. There is no doubt information to be gleaned from the analysis of those sensitivities. This was already done to estimate the ray bundle diameter at beamsplitter D1. The parameters included in this analysis were axial position, decenter, tilts, wedge, and thickness of the beamsplitters and mirrors. For the focus lenses, decenter, centration and tilt was considered. For the windows, tilt and wedge were considered. Thus all of the parameters considered were optomechanical and not optical (e.g., sag and surface quality). The sensitivities given serve as a useful reference for designers of similar systems.

1.6. Pre-alignment and instrument co-registration

Finally, a short discussion of the pre-alignment and instrumentation co-registration procedure is given. This is discussed in much more detail elsewhere (Zurmehly & Hookman, 1989), see also (Yoder, 2006). A modified 14" commercial telescope is used as both a collimator and autocollimator. It is aligned to the GOES baseplate acting as an autocollimator, where a point source is reflected off a reference mirror on the baseplate. Once aligned it acts as a collimator for target generation.

[2] Presumably a detector assembly consists of a detector and its aplanatic lens pair.

The relay optics are pre-aligned as a subsystem via gage plates, reference mirrors and a HeNe laser. Details are not given in this paper, again see (Zurmehly & Hookman, 1989). After the filter wheel and other components are installed, the IR detectors are "peaked" (adjusted for maximum output). This is done by flooding the FOV and thus filling the pupil with the collimator, and then adjusting the detector assemblies for maximum output. Although not stated in the paper, this is probably done automatically given the motorized micrometer actuation system.

The next step is to co-register the field stops of the various spectral channels. This is done by scanning a slit target. LOS is adjusted using the beamsplitter/mirror adjustments of Figure 3. IFOV is adjusted using the focus lens adjustments of Figure 4. The process of scanning and adjusting is iterated until completion.

2. Concluding comments

I did learn quite a bit from this paper. The concept of pupil imaging (place detector at exit pupil and control the IFOV with a field stop) was new, which required some background work to understand. There is so much technical information available on the GOES satellites; it's a shame the prescription of the whole design isn't published. I particularly wish I knew more about the focusing lenses, the field lens pairs, the aplanatic pairs, and the detectors themselves. This would improve understanding of the system in general and of the adjustment mechanisms in particular.

3. Bibliography

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