WIDE-FIELD HIGH-PERFORMANCE GEOSYNCHRONOUS IMAGING

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Abstract

The NASA Earth Science Systems Program Office (ESSPO formerly Mission to Planet Earth) and the National Oceanic and Atmospheric Administration (NOAA) are sponsoring Advanced Geosynchronous Studies (AGS) to develop technologies and system concepts for Earth observation from geosynchronous orbit for the benefit of both ESSPO science and the NOAA Geostationary Operational Environmental Satellite (GOES) program. Within the AGS program, we have investigated two candidate concepts for near-term advanced geosynchronous imagers. One concept uses a scan mirror to direct the line of sight from a 3-axis stabilized platform. Another eliminates the need for a scan mirror by using an agile spacecraft bus to scan the entire instrument. The purpose of this paper is to discuss the optical design trades and system issues encountered in evaluating the two scanning approaches.

INTRODUCTION

To be of maximum value to both the operational and research communities, an advanced geosynchronous imager should carry out a dual role. It should meet or exceed the weather imaging needs foreseen by the U.S. National Weather Service and at the same time provide data that is valuable to ongoing scientific investigations into environmental processes being carried out by NASA's Earth Science Systems Program Office scientists. The imaging requirements that have emerged for the AGS study were derived from draft requirements for future GOES instruments and NASA Earth science needs. They call for 18 spectral bands spanning a wavelength range from the 0.45 visible region to 13.5 microns in the thermal infrared (IR). Table 1 shows the bandpasses and purposes of the bands. Discussion of the development of the imaging requirements is given in Chesters and Jenstrom (1996).

Table 1. Focal Plane Designation and Associated Spectral Bands

Focal Plane Designation	Bandpass (μm)	FOV (km)	Min. SNR @ref. level	Purpose
VIS (Visible)	0.45 - 0.50	0.5	250 @50% alb	dust
	0.53 - 0.67	0.5	250 @50% alb	cloud albedo
	0.75 - 0.85	0.5	200 @50% alb	vegetation
SWIR (short wave infrared)	1.36 - 1.39	1	150 @100% alb	cirrus clouds
	1.57 - 1.73	1	250 @100% alb	cloud water, snow
	2.10 - 2.35	1	200 @100% alb	cloud ice
MWIR (medium wave infrared)	3.40 - 3.80	2	0.1K @320K	low water vapor
	3.85 - 4.05	2	0.1K @320K	surface & cloud temp.
	4.10 - 4.20	2	0.2K @320K	low air temp.
	6.40 - 6.70	2	0.2K @320K	very high water vapor
	6.70 - 7.00	2	0.2K @250K	high water vapor
	7.00 - 7.30	2	0.2K @250K	mid water vapor
	7.30 - 7.60	2	0.1K @250K	low water vapor
LWIR (long wave infrared)	8.00 - 9.00	2	0.2K @320K	total water vapor
	9.60 - 9.80	2	1.0K @320K	ozone
	10.2 - 11.7	2	0.2K @320K	surface & cloud temp.
	11.9 - 12.9	2	0.3K @320K	total water vapor
	13.0 - 13.5	2	0.5K @320K	high cloud cover
Max. level = 100% albedo or 340K				

Imager design activities started with a look at first principles to evaluate what is the most efficient way to image the Earth in those numerous spectral bands of interest to ESSPO scientists and NOAA weather forecasters. Optical design trades included rotating filter wheels and dispersive grating instruments. The design converged on a bandpass filter instrument using four focal planes of parallel linear detector arrays in which the line-of-sight of the instrument is continuously swept in a raster fashion to construct Earth images. The optical design of the instrument was driven by the design parameters given in Table 2.

Table 2. Key Imager Baseline Optical Design Parameters
(for a 30cm telescope)

Focal Plane	Bandpass (μm)	SNR (min)	Pixel Size (μm)	FOV/Pixel (km)	EFL (m)	F/#	OPTICAL MTF REQUIREMENT**
VIS	0.45 - 0.85	250	12.0	0.33	1.29	4.3	0.63
SWIR	1.36 - 2.35	200	38.5	0.67	2.08	6.9	0.62
MWIR	3.40 - 7.6	0.1K*	38.5	1.33	1.03	3.4	0.43
LWIR	8.0 - 13.5	0.2K*	38.5	1.33	1.03	3.4	0.43

*** equivalent noise temperature to achieve required signal to noise**
**** at Nyquist frequency**

SNR = Signal to Noise Ratio; EFL = Effective Focal Length; MTF = Modulation Transfer Function; FOV = Field Of View

Design studies considered two different approaches to point the instrument line of sight, one using a scan mirror from a 3-axis stabilized platform, and another that eliminates the need for a scan mirror by using an agile spacecraft bus to scan the entire instrument. This paper discusses the optical design trades and system issues encountered in evaluating the two scanning approaches.

THE SCANNING SPACECRAFT STUDY

The first imager design we studied uses a small agile spacecraft to raster the imager field of view (FOV) back and forth over the Earth to eliminate the need for a scan mirror. The lack of a scan mirror simplifies the imager instrument and also eliminates the problem of image rotation inherent in 2-axis gimbaled mirror systems. The price paid for doing away with the scan mirror is significant energy and time required to reverse the spacecraft slew motions at the end of each scan line.

The desire to minimize the number of turn-arounds drove the telescope design to a 1.6 degree FOV orthogonal to the scan direction to provide full Earth disk coverage in only 12 E-W swaths. Various off-axis telescope designs were investigated to accommodate this FOV and accompanying image quality requirements. Figure 1 shows the best design achieved in this wide-field scanning spacecraft study, an afocal three-element off-axis anastigmat.

Telescope magnification, plate scale and pupil diameter at the beamsplitters were important trade parameters in the optical design. The beamsplitters were made to be as small as possible for reduced mass and manufacturability. The plate scale was set by the production detectors to be used and the required pixel size on the ground at nadir. The telescope aperture (30 cm) was set by the spatial resolution requirements and the radiometric requirements of the LWIR channel, the most photon-starved channel of the four. The telescope magnification was optimized to the smallest pupil diameter possible. Relay optics to image smaller pupils on the beamsplitters were traded away to save mass.

The large FOV and diffraction-limited performance drove the design to a tertiary mirror nearly as large as the primary mirror. In addition, the optical design drove the large tertiary to a relatively large separation from the secondary. To minimize the instrument package size, fold mirrors (not shown) were placed between the secondary and tertiary, and between the tertiary and first beam splitter to allow for the longest legs of this design to be bent 90 degrees.

During the spring and autumn seasons, when the sun is near equinox, geosynchronous Earth-viewing instruments experience sunlight shining into the aperture as the sun passes behind the Earth. To keep the sunlight from reaching the focal planes, a heat-tolerant field stop was positioned near the first focus between the secondary and tertiary mirrors. However, sunlight can still shine on the primary and secondary, and the concentrating effect of the primary

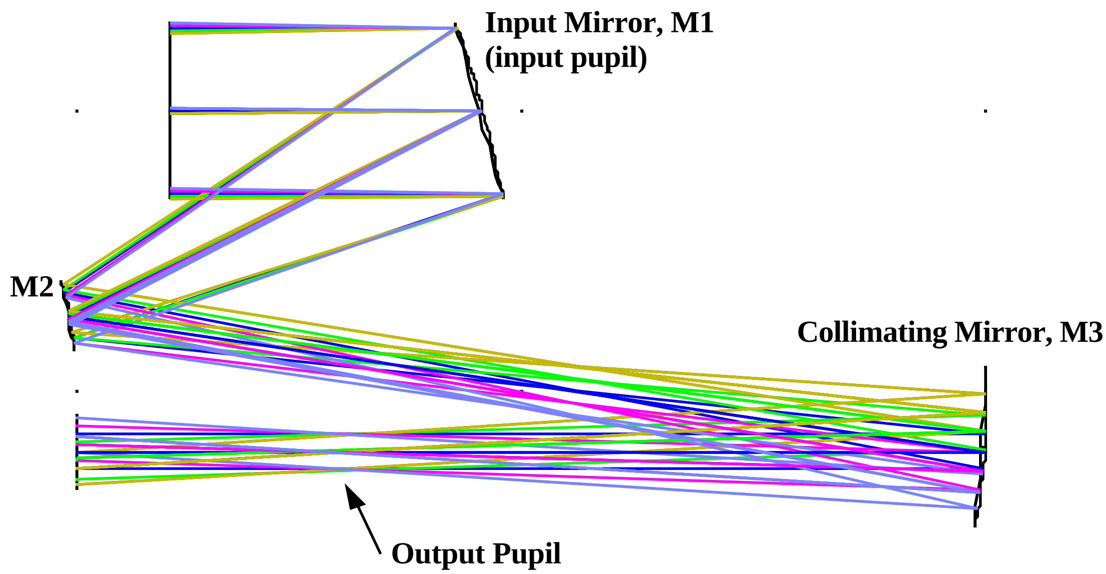

Figure 1. Wide - Field 1.8 degree FOV 4.48X Afocal Anastigmat. M1 is 30cm diameter.
courtesy Gary Baldwin

mirror means that the secondary will receive a considerable heat load. This heating due to solar intrusion produced concern for the optical performance of the telescope and for the overall instrument and led to a choice of telescope optics made of silicon carbide for its combined thermal and mechanical properties. Calculations show deformations of the secondary mirror due to the concentrated midnight sun should be very small, on the order of 1/250 wave. Resulting temperature fluctuations should be less than one degree during normal imaging activities. Thus the telescope should work well throughout the year with effectively no solar restrictions.

The beamsplitters are large: ellipses of 13.7 by 9.7 cm clear aperture. They constitute a major component in the instrument mass budget. We are looking into the substitution of dichroic pellicles to help save mass.

The four refractive objectives have 6, 3, 8 and 4 lens components each and some of the surfaces are aspheric. The largest lenses are 8.6 cm diameter. Some of the lenses are made of germanium which has interesting thermal properties and must be used with special care in the instrument overall design.

This design meets virtually all of the optical requirements and a preliminary tolerance analysis indicates alignment sensitivities are within an acceptable range. In spite of considerable effort to optimize the refractive objectives, the Modulation Transfer Function (MTF) response of some of the MWIR channels caused a trade-off that compromised the original requirements at the extreme ends of the MWIR spectral range in order to achieve manufacturability. All other channels easily meet MTF requirements.

The resulting instrument design has a mass conservatively estimated at 156 kg and dimensions of 1.25 x 1.2 x 0.9m. These parameters impose significant but manageable demands on reaction wheel control and power from a spacecraft specially designed and dedicated to pointing this instrument. The design was shown to be achievable with existing technology. An interesting consequence of having considered the scanning spacecraft implementation first is that it provided a departure from current geosynchronous imaging practices and a “clean sheet approach” that gave a fresh technology basis for considering a scanning mirror implementation.

Scanning spacecraft version calibration

Calibration of the VIS and SWIR channels in orbit is accomplished using a perforated plate covering the telescope as the instrument views the sun (Bremer and Si, 1997). The attenuation of the plate is on the order of a factor of

50,000 so that the flux level will be near that of 100% albedo Earth. In the scanning spacecraft, the calibration plate is swung over the aperture in a guillotine fashion. It has the advantage of providing a repeatable reference dependent only on geometry of the perforations and not materials properties, as in a reflecting reference, which can more readily change over the course of a mission. Calibration stability is very important to climatological studies and for synergism with instruments on other platforms. In the thermal channels, the calibration is performed using a full-aperture blackbody source on the back of the perforated plate.

THE SCAN MIRROR STUDY

In the second high-level trade study, the AGS imager team looked at incorporating a scan mirror so that the satellite can be three-axis stabilized. An important advantage of the scan mirror approach is that, unlike the scanning spacecraft, the scan mirror can turn around very quickly at the end of each scan line. Thus, more time can be spent imaging the Earth rather than looking at space while the spacecraft turns around. This higher imaging duty cycle allows the FOV to be reduced without sacrificing total scan time for each full image. Reducing the FOV of the afocal telescope to 0.8°, or half that of the scanning spacecraft, allows for somewhat smaller and simpler telescope and objective optics assemblies with improved performance.

One drawback to using a 2-axis scan mirror is the resultant rotation of the image on the focal plane. Various methods exist to mitigate this problem, each with its own set of drawbacks. One was chosen for this study that minimizes the impact to the instrument but complicates ground processing (significant discussion of image rotation is beyond the scope of this paper).

Three optical designs were considered for the afocal telescope: confocal parabolas, an aspheric anastigmat and a Cassegrain afocal.

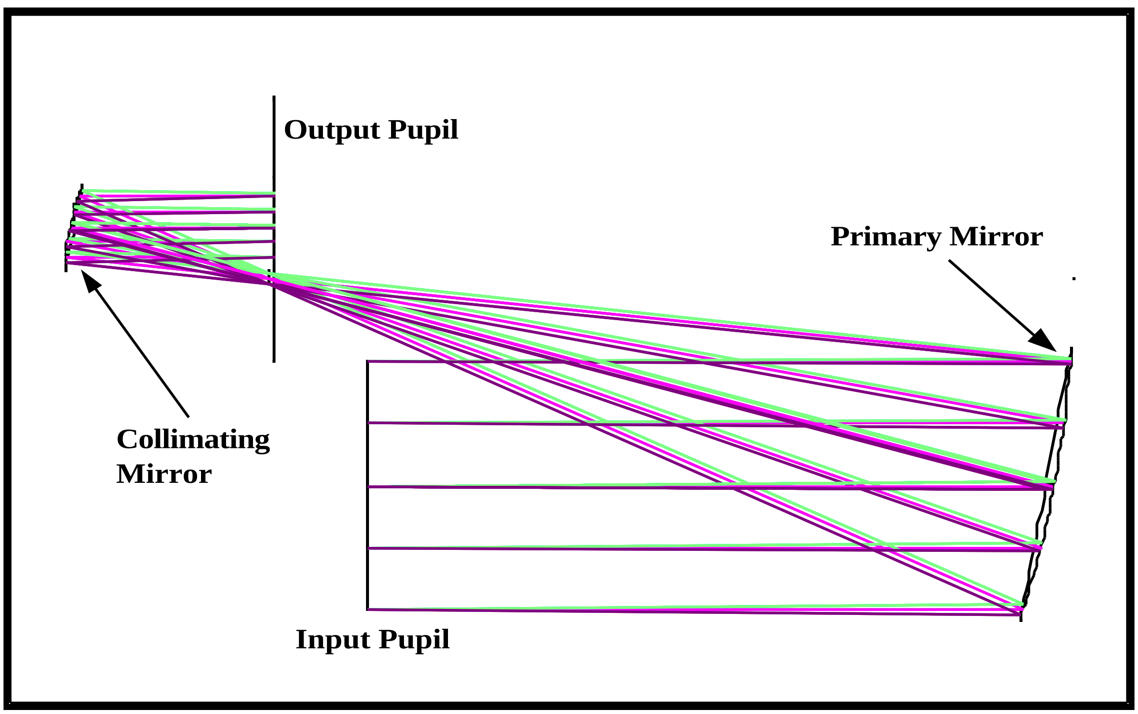

FIGURE 2. The AGS Confocal Parabola 30cm Telescope. Curvature of field dominates ***courtesy Gary Baldwin***

Figure 2 shows the confocal parabola design. The volume is small, being 38% the volume of the scanning spacecraft telescope shown in Figure 1. The major objection to the confocal parabola design is the strong Petzval curvature (field curvature). This would require field-flattener optical elements in the refractive objectives, which are already complex and crowded designs. In addition, we would lose the ability to test the refractive objectives independent of the telescope. We would have to build an aberrated beam simulator to produce the telescope's Petzval curvature for laboratory testing of the refractive objectives.

Another design that was considered (not shown) is a three-mirror anastigmat with aspheric elements of extreme compactness. It has a volume of 14% that of the Figure 1 telescope, and gives diffraction-limited performance and a flat focal plane. However, it was ruled out because of extreme sensitivity to optical alignment of the component mirrors. Compared to the Cassegrain afocal described below, it is ten times more sensitive to M1 - M2 separation and twice as sensitive to each of M2 tilt and M2 decentration.

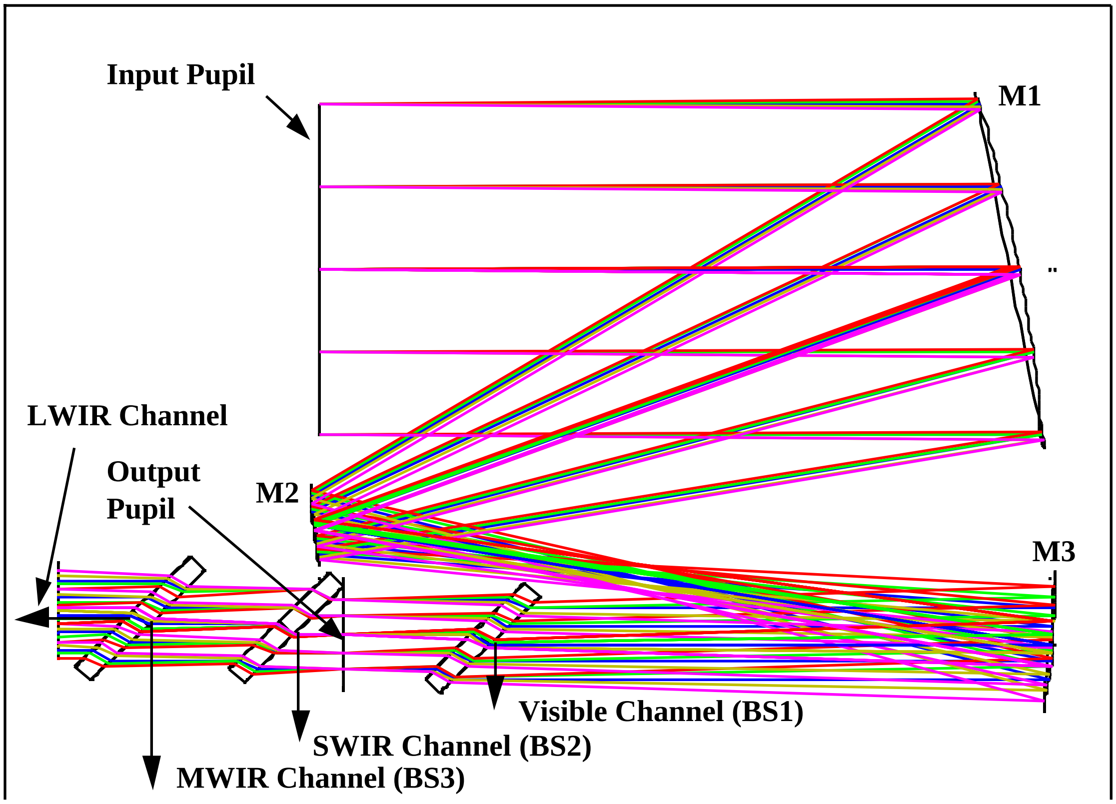

FIGURE 3. Cassegrain Afocal Telescope Feeding Four Focal Plane Assemblies
courtesy Gary Baldwin

The design selected for the scan mirror configuration is the Cassegrain afocal shown in Figure 3. M1 is a parabola, M2 a hyperbola and M3 a parabolic "eyepiece" mirror to render the light parallel. The light for the LWIR channel strikes a 45 degree fold flat to make it lay parallel to the other three channels. Selection of the new 18-channel telescope design for the scan mirror implementation was based on optical performance, a tolerance analysis for manufacturability and system integration complexity. This telescope is very compact, occupying only 24% of the volume of the telescope shown in Figure 1. The scan-mirror instrument concept based on this telescope is shown in Figure 4 .

The four refractive objective assemblies are of considerable size and complexity. The reduction of the field of view to 0.8 degrees dramatically improved the MTF performance of the assemblies with little design change. In particular, the performance of the MWIR channel at the extreme ends of its spectral range now exceeds the MTF requirement and is nearly diffraction limited. As of this writing, we have not optimized the designs to reduce the number of optical elements and size.

In both designs, the MWIR and LWIR channels have cold Lyot stops at pupils near the cold detectors inside the dewars. The windows on the dewars run warm enough that room temperature operation of the cooled dewars will be possible. This will make optical alignment and test in the laboratory less costly and time-consuming.

Use of the scan mirror reduces total instrument mass to 90%, and total volume to 60%, of the scanning spacecraft version of instrument, making the scan mirror instrument only slightly larger than the current GOES imager. The power and mass of the supporting satellite are also significantly reduced by the use of the scan mirror. Approximately 50 watts are needed to run the scan mirror, but the spacecraft power budget reduces by 300 watts or more since we no longer have to scan the entire spacecraft. The mass of the supporting satellite can be reduced through smaller momentum wheels and less solar array and power electronics hardware.

Scan mirror version calibration

As in the scanning spacecraft version, calibration of the VIS and SWIR channels is carried out using the same perforated plate covering the telescope as the instrument views the sun (Bremer & Si, 1997). In the thermal channels, the calibration is performed using a separate full-aperture blackbody source in the near field. Both calibration sources can be viewed by turning the scan mirror through 90 or 180 degrees from Earth view. Thus the calibration plate no longer requires its own motor mechanism to move it over the aperture.

CONCLUSION

Two different 18 channel geosynchronous imaging design concepts were developed, one that uses a scan mirror for pointing control and one that relies on an agile spacecraft for pointing control. Significant efforts were made to optimize each design for the scanning concept being used. The performance of each instrument concept greatly exceeds the optical, spatial, radiometric, spectral, and temporal performance of the existing GOES imagers. Comparison of the two designs reveals that the scan mirror implementation appears to result in a more compact, lighter weight, and lower power imaging system than the spacecraft scanning implementation for the specific design requirements used in the study. The optical performance of the scan mirror implementation is also superior to the scanning spacecraft version due its smaller total field of view.

The scan mirror implementation gives image rotation, a property that is inherent to 2-axis gimbaled mirror systems. The scan mirror solution described here results in impacts to ground data processing. These impacts must be further evaluated to determine whether additional instrument design changes may be required in a trade with ground system complexity.

In both instrument design cases, the designs were driven first to meet challenging performance requirements and only secondarily to minimize size and mass. Slight relaxation of performance requirements such as spatial resolution, number of channels, spectral resolution, signal to noise, solar rejection, or ground coverage rates may result in significantly smaller and lighter instrument concepts. However, unless performance requirements are changed dramatically, it is anticipated that the conclusion favoring the scan mirror approach would hold.

Acknowledgments

The authors wish to thank Gary Baldwin for his Optical Design Study which led to much of the optics trades discussion in the paper. Dennis Evans took the optical designs, provided them with stray light baffles and laid them out in 3D. Jim Bremer devised the calibration techniques and calculated the solar heat loads and corresponding deformations of the optics. Finally, the entire AGS team iterated the designs with us and we are indebted to them for their work in the many engineering fields they represent.

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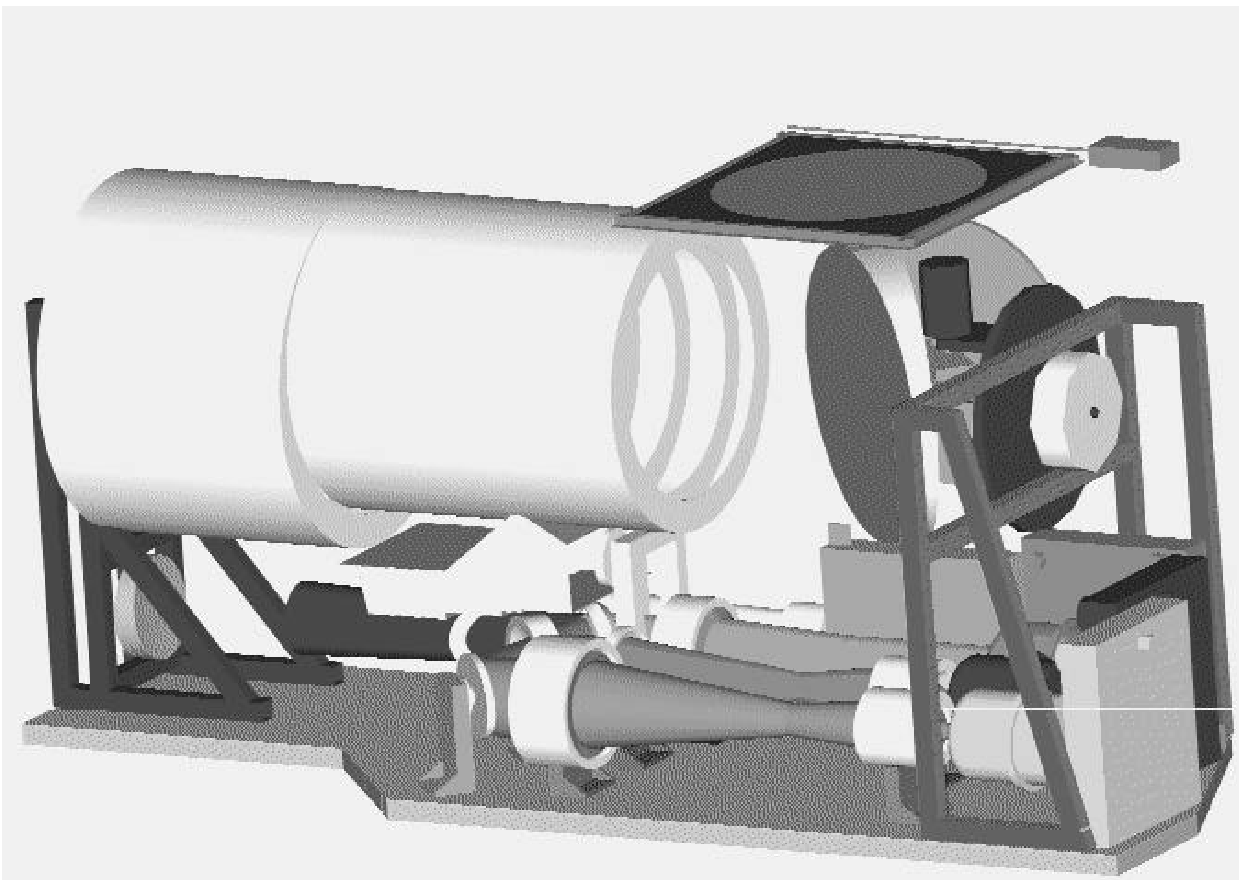

Figure 4. A solid-model representation of the new 30cm aperture 18 - band imager. The scan mirror and its motors are on the top right. The light from Earth (over your left shoulder) reflects off the flat scan mirror into the primary mirror baffle and proceeds towards the left. The primary mirror (not seen) reflects the light downward through a hole in the baffle tube to the secondary mirror in the center under the main baffle aperture. The light then proceeds to the left and downward towards the tertiary mirror under the primary on the far left. Now collimated, the beam proceeds into a series of dichroic beamsplitters feeding the multi-element refractive objectives. (the light is seen as solid ray bundles after the tertiary) The detectors are housed in boxes under the scan mirror mechanism on the right. The plate on the top right is the perforated plate for solar calibration. ***courtesy Dennis Evans***