ULTRA-LIGHTWEIGHT TELESCOPES AND PRECISION POINTERS AS ENABLING TECHNOLOGIES FOR SMALL, LOW COST MISSIONS

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ABSTRACT

Very high precision, lightweight optical pointing devices, in conjunction with ultra lightweight telescope assemblies are enabling technologies for small, low cost space missions. Lightweight pointing mirror technologies enable very accurate optical pointing and tracking from very low cost satellite platforms. These platforms do not provide a stable pointing platform. High bandwidth, servo controlled pointers compensate for the platform instabilities. A new generation of high bandwidth, very precise pointers are possible because of very low mass mirrors made from silicon carbide (SiC), aluminum or beryllium and ultra-precise optical fringe counting encoders. Silicon carbide pointing mirrors are very attractive because of their extreme thermal stability. This allows operation over large temperature ranges and gradients. SSG has developed a range of very lightweight telescope systems for DOD and NASA missions. These systems are applicable to small space platforms with minimal weight impact, thus enabling a new generation of very cost effective missions not yet achieved.

2. INTRODUCTION

The requirement for low cost space instrumentation has created a wave of low cost, small satellites. In order to optimally utilize the small satellite technologies, small and lightweight instruments must be available. SSG has been a pioneer in the development of very lightweight optical systems and pointing systems using silicon carbide as a base material. The superior properties of silicon carbide allow the fabrication of ultra-lightweight sensors and very high bandwidth servo mirror systems. These high bandwidth systems can provide many valuable functions, including pointing, scanning, tracking and stabilization. These functions enable the use of small, but relatively imprecise satellites for very high precision functions.

Silicon carbide is being developed for optical sensors use because of its very good stiffness to weight ratio and its very high thermal stability. It is superior to aluminum, beryllium, and glass/graphite epoxy in almost all areas with respect to specific stiffness and thermal stability. SSG has been using various forms of silicon carbide for both structural and optical functions. Use of the material for both the structures and optics provides an inherently athermal system. Servo systems prefer the very high stiffness of silicon carbide for all moving parts, because very high natural frequencies can be achieved.

Using either or both of the optical and scanning systems can enable very low cost sensor implementations on small satellites. Weight issues are mitigated, and very high performance can be achieved. High performance scanners allow an instrument to perform independently of a SmallSAT's stabilization system, leading to autonomous operation.

3. SCANNER ADVANTAGES OVER CONVENTIONAL GIMBALED SYSTEMS

SSG is currently developing a wide range of ultra-lightweight scanners that offer:

(1) vastly improved (10x) precision pointing and stabilization performance (<0.5 μrad) over large fields of regard (>±30 deg. sq.) and under space environments;

(2) very lightweight, compact, low power design when compared to conventional gimbaled mirror or sensor approaches;

(3) significantly reduced (10x) satellite pointing requirements which lower overall cost and complexity;

(4) reduced complex, expensive and often corrupted IMC processing.

These features are enabling technologies for autonomous, agile piggyback sensors on NASA, DOD and commercial non-EO host satellite platforms.

The core technology advancement for scanners is based on $\geq$26 bit angular sensing resolution, currently only available with very large, heavy conventional optical encoders, The new pointing/stabilization mirror(PSMA), utilizes the next generation optical fringe counting encoder, which is very small, lightweight, ultra-precise (<0.05 LSB resolution) and inherently insensitive to space vibration and thermally varying conditions. When compared to conventional encoders, savings of >100 times in volume and >100 times in mass can be realized.

Current large 2-axis field of regard (FOR) pointing uses a gimbaled mirror or sensor concept, which are big, heavy, high powered, expensive, only moderately accurate (poor stabilization control), have high disturbance torques and are sensitive to space, vibration, and thermal operating conditions. Current geometric optical encoders must be very big and heavy to provide >24 bit resolution. A ≥28 bit resolution is beyond conventional capability. Kaman sensors provide high resolution capability, but over a very limited dynamic range. In addition, Kaman sensors are sensitive to translational and rotational errors, as well as temperature excursions, and require a high degree of calibration to achieve <1 μrad precision measurements. The fringe counting optical encoder avoids all calibration issues.

The newly developed optical fringe counting encoder represents the enabling technology for the ultra-precise pointing and stabilization control over very large FOR's. The device is developed and patented by Micro-E Corporation. SSG has exclusive rights for this device for NASA, DOD and commercial space flight applications. SSG has recently proven the device capability under simulated space environments using a single axis pointer system.

An example of a very high performance 2-axis scanner is shown in Figure 1. This scanner was developed for and infrared tracking sensor. It is capable of operation at less than 200 Kelvin. It has a servo bandwidth of greater than 120 hertz. With coverage of over 12 degrees in each axis, it can perform both pointing and jitter stabilization functions. It has an accuracy of better than 2 μrad RMS. A 10 centimeter working aperture was achieved with a beryllium mirror and yoke to reduce moving mass and keep the natural resonances high.

Figure 2 shows a miniature scanner referred to as the Monolithic Seeker Scanner. This scanner achieves a working servo bandwidth by using a very stiff and lightweight silicon carbide mirror and yoke. It has an aperture of 1.25 inches. It can operate at less than 8 watts of power and the scanner head weights less than 150 grams. Table 1 summarizes the scanner parameters.

A third scanner shown in Figure 3 was developed for use on a sensor for the SPAS 3. It was further improved by the addition of the fringe counting encoder for application on the High Altitude Infrared Limb Sounder (HIRDLS) experiment for NASA. This beryllium mirror supported an 18 cm working beam. It covered a 16 degree field of regard in one axis with better than 5 μrad RMS jitter accuracy using Kaman sensors. Using Bendix flex pivots, it was capable of operation from room ambient to 200 Kelvin. The addition of the MicroE fringe counting encoder improved performance to 0.3 μrad 1 σ repeatability and 0.1 μrad RMS jitter. Figure 4 shows the correlation between the command signal, the encoder output and a measurement autocollimator. This level of performance should prove very valuable for precise spatial measurements.

Using scanners from this range of performance can enable a large variety of sensors requiring very precise pointing and stabilization. Using such scanners to point sensor fields of view will make a large variety of satellite possibilities.

4. ULTRA-LIGHTWEIGHT OPTICS

Historically, space optical systems have been fabricated from either glass/graphite epoxy (ULE/GrEp), aluminum (Al), or beryllium (Be). Ultra-lightweight ULE/GrEp can be achieved, but at considerable expense. Glass must be lightweighted with very exotic techniques, and graphite epoxy must be carefully designed to thermally match the glass over the operating range. This process is costly and time consuming. Aluminum has the advantage of very low cost, but is limited when weight is an issue. Beryllium is very stiff and can be made very lightweight. It is limited by difficult material availability, restricted production means, and temporal instability issues derived from anisotropic characteristics, which limit visible applications. Table 2 summarizes some of the key parameters for the trade between these materials.

SiC based products follow more conventional process steps, and specific material property issues must be addressed. Once specific material processing issues are addressed, SiC processing follows cycles very similar to aluminum. It has the potential of development cycles competitive to aluminum in both cost and schedule.

Currently, aspheric optical elements are overcoated with pure silicon. This is strictly to facilitate optical figure generation. Silicon has a very close CTE match to SiC, and this has been verified at SSG to 20 inch apertures to temperatures of 100 Kelvin to stability levels required for diffraction limited visible systems. Small mirrors have been fabricated to 50:1 diameter to thickness ratios, with silicon overcoats. Silicon is diamond machinable, which expedites production of complex aspheres.

Figure 5 shows a comparison of some available optical materials based on two critical figures-of-merit: specific stiffness and thermal stability. The former is measure of available component rigidity per unit material density. This

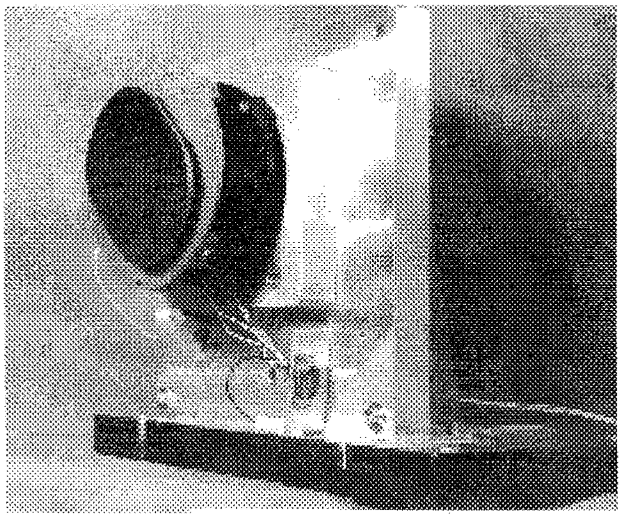

Figure 1. IR Tracker Fast Steering Mirror.

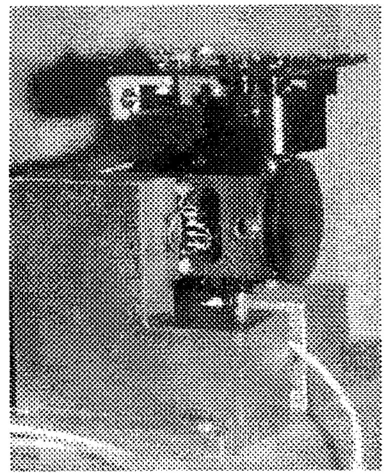

Figure 2. Monolithic Seeker Scan Mirror.

Table 1. Monolithic Seeker Current Performance

Parameter	Magnitude	Units	Remarks
Mirror aperture	1.25	in.	round
Mirror material	*SiC*		SSG Proprietary
Exterior dimensions	1.75x1.75x2.2	in.	Excludes electronics
Power (avg)	<8	watts	
Weight	150	grams	
Angular Range: Pitch axis Yaw axis	 ±11.5 ±1.4	 degrees degrees	
Servo bandwidth	1000	Hz	
Noise eq. angle: Pitch axis Yaw axis	 2 3.6	 asec rms asec	 Goal: 1 asec rms Goal: 1 asec rms
Angular acceleration: Pitch axis Yaw axis	 >5,000	 rad/sec^2 rad/sec^2	
Bias error Pitch axis Yaw axis	 TBD TBD		 Goal <60 asec Goal <5 asec
Thermal drift	TBD		Goal: compensation

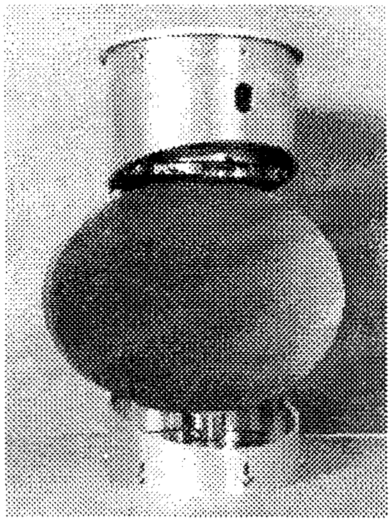

Figure 3. HIRDLS/SPAS 3 Demo Pointing & Stabilization Mirror Assembly.

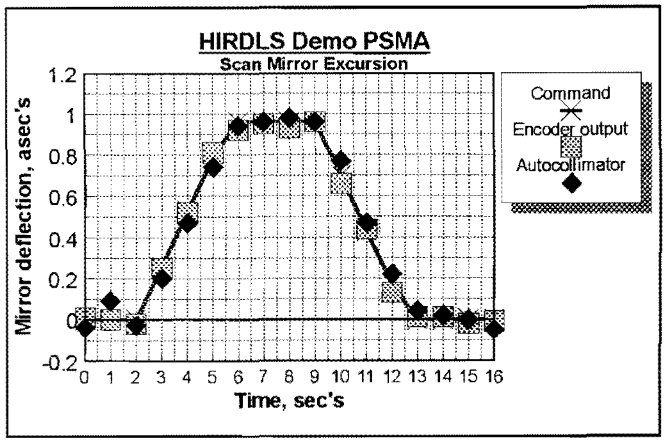

Figure 4. Jitter control of optical-encoder-based scanner assembly.

Table 2. Comparison of Mirror Candidate Material - Properties at Room Temperature

	ULE	Beryllium	Aluminum	Silicon Carbide	
				Reaction Bonded	HP & Pressure Cast
Young's Modulus of Elasticity, E (psi) x 10^6	9.8	44.0	10.6	52.8	62
Poisson's Ratio	0.18	0.07	0.33	0.14	0.2
Coefficient of Thermal Expansion, α/°C x 10^{-6}	0 ± 0.03	11.2	23.2	2.1	2.0
CTE Variation, ppb/°C	10	100	100	50	< 50
Thermal Conductivity, K (BTU/hr ft°F)	0.76	87 - 112	109	99	105
Density, ρ (lb./in.^{3})	0.0795	0.067	0.100	0.106	0.115
Mechanical Figure of Merit (E/ρ) x 10^6	123	656	106	498	539
Thermal Figure of Merit K/α	25.3	7.7 - 10	4.7	47.0	52
Diffusivity D (in^2/hr)	4.3	39	320	*	460
Specific Heat Cp (BTU/lb °F)	0.0183	0.048	0.024	*	0.035
Stress Level (K psi) - Microyield - Ultimate	 --- 2	 5 - 24 > 15	 12 45	 --- > 15	 --- 60 - 100

* Data not available, similar to CVD

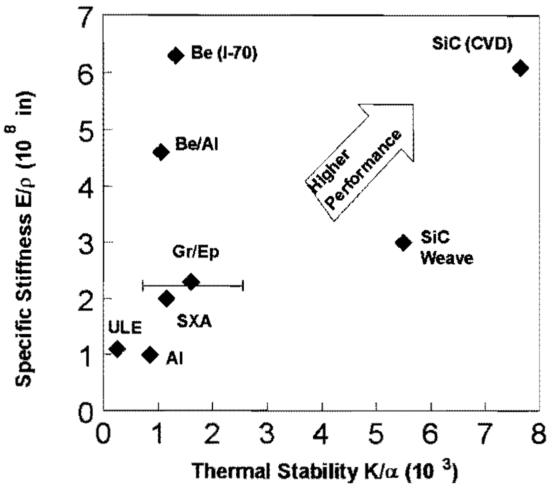

Figure 5. Lightweighting & thermal stability performance of candidate materials.

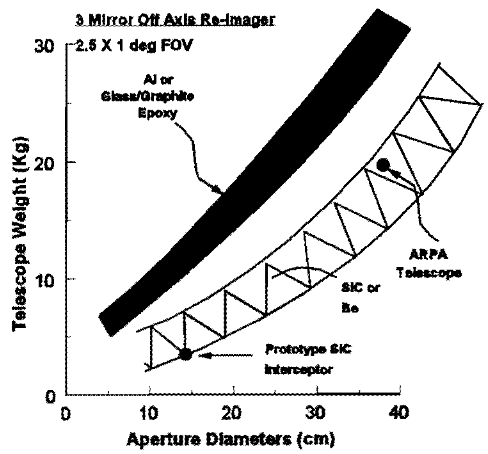

Figure 6. Sample Weight Trades—LWIR Performance.

measure of lightweighting capability shows bulk silicon carbide to be within 6% of the performance of beryllium. As an optical component selection, SiC can approximate the lightweighting characteristics of beryllium without issues of high cost, toxicity, and substrate temporal instability at visible levels caused by material anisotropy. It can support glass-like diffraction-limited visible performance at less than half the mass of lightweighted ULE.

SiC also offers superior thermal stability (6X and 12X better than beryllium and aluminum, respectively) permitting visible image quality operation over extended temperature ranges (>50 K). In addition, it maintains visible-level performance in the presence of gradients typical of partial solar illumination from low Earth orbit (LEO).

Figure 6 shows some estimates for Telescope weights as a function of aperture. SiC systems offer the best potential for the lightest weight telescope systems. The two indicated data points represent prototype systems that SSG has fabricated and tested.

5. EXAMPLES OF ULTRA-LIGHTWEIGHT OPTICAL SYSTEMS

Some examples of lightweight optics and systems will demonstrate the range of possibilities in these type of systems. These new, lightweight subsystems can be used on innovative systems with very high utility at very low weight penalty.

Figure 7 shows the "GOES-like" scan mirror. SSG has fabricated a mirror that resembles the GOES scan mirror used on the GOES Weather Satellite. The flight mirror was fabricated with nickel plated beryllium. This mirror was very lightweight, but suffered from distortion when partially illuminated by the sun. Thermal gradients caused a bimetallic effect. The SSG silicon carbide mockup avoids this problem by avoiding a thermally mismatched coating. This mirror demonstrates many of the advantages of SiC. It is very stiff, lightweight, thermally stable, and highly polishable.

Key features of the mirror are:

- 0.3 x 0.5 meter elliptical aperture
- < 2 kg weight
- 1000 Hz first natural mode
- supports diffraction limited visible wavefront

This mirror was tested over a 300 K ±50 K and was found to be optically stable to better than 0.2 waves peak to valley at 633 nm wavelength.

SSG has recently completed a demonstration of a complete optical system, including optics and optical metering structure, entirely built of SiC. This system used a 4 mirror off-axis re-imaging system. SSG refers to it as the "GBI-like" system. The entire system weighted 1.3 kg and supported an 18 cm aperture. This level of lightweighting has not been achieved in any other material for this size aperture. The system was proven stable to visible diffraction limited levels down to 100 Kelvin. Figure 8 shows the system.

Another optical system recently demonstrated by SSG is a 0.5 meter aperture Cassegrain type telescope, again built entirely from SiC. This system, shown in

Figure 9, weighted less than 15 kg. It was tested successfully to visible diffraction limited stability levels from room temperature to 100 Kelvin. This system used a coating of pure silicon on the SiC optical substrates. The silicon matches the coefficient of thermal expansion of SiC very well. It offers the advantages of significantly easier optical surfacing than SiC. This allowed the mirror to be diamond machine figured to within 1 wave of the desired surface accuracy. It was then hand figured to final figure. This process allows rapid processing of SiC based optics.

An example of the utility of new scanners and optics shows that new missions are possible with these technologies. Figure 10 shows an case mission of a LEO satellite system. An mosaic array of IR and Visible detectors would be rapidly pointed to various selectable scenes on the Earth. Figure 11 shows a conceptual optical system that could be used. This system utilizes a full circle azimuth scan bearing and a two axis object plane scanner to provide full FOR coverage. A small internal stabilization mirror has been included to allow corrections to platform instabilities. This combination of features allows the instrument to be placed on an arbitrary platform, such as Iridium, which is not optimized for optical observations.

The example system uses a 30 cm aperture, with a 2 x 5 degree field of view. 5 μrad spatial resolution is provided giving a 2.5 meter ground footprint at LEO. It is estimated that this entire optical system and pointingmechanisms would weigh less than 15 kg. This weight would not include electronics, cryo coolers and other non-optical components. The moving parts are compatible with 5 year lifetimes, and we estimate that this system would cost less than $3 million per system. This low cost, high performance system can provide very cost effective solutions to many problems.

6. CONCLUSION

Using a combination of either ultra-lightweight optics or high precision scanners, very effective instruments can be produced. Development of these concepts has passed the research stage and is now well into the development phases. SSG is currently pursuing flight demonstration programs to qualify these concepts. These systems enable very high performance optical instrumentation of very low cost platforms, opening a wide array of possibilities.

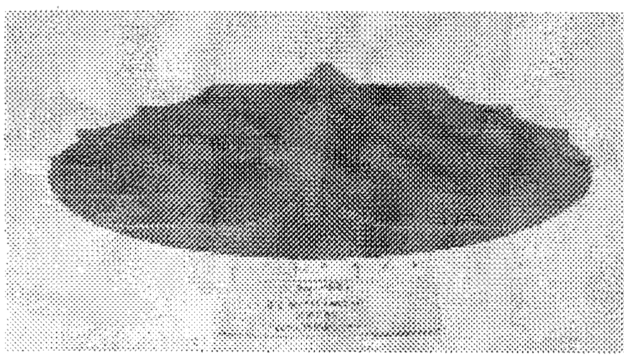

Figure 7. "GOES-like" scan mirror.

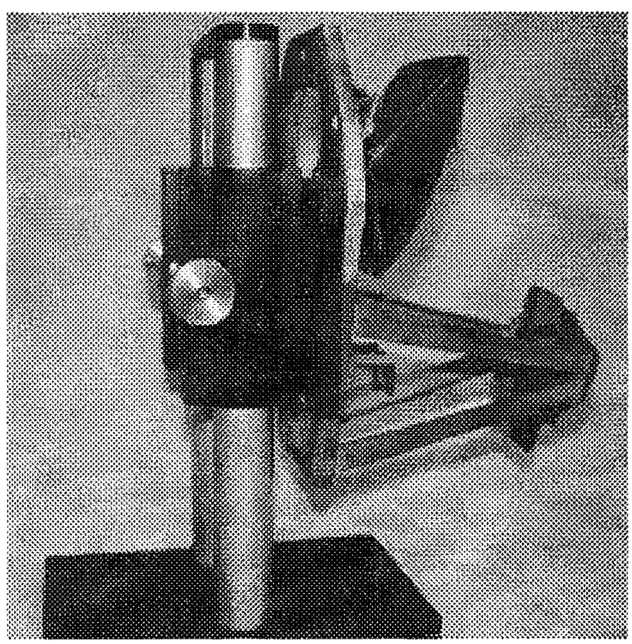

Figure 8. GBI Breadboard Telescope.

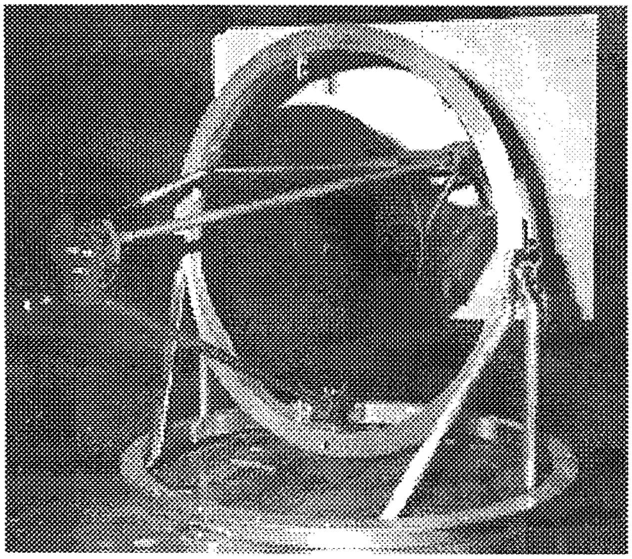

Figure 9. Advanced EOS SiC 0.5 m Demo Telescope.

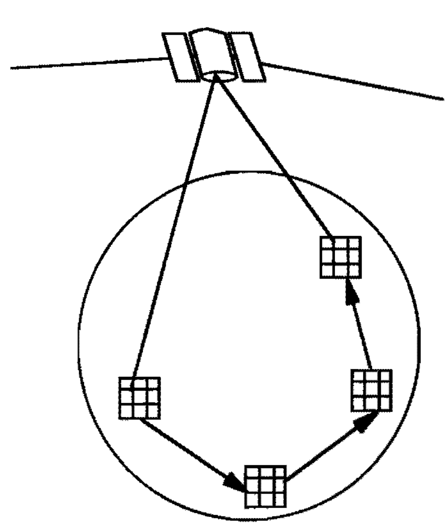

Figure 10. LEO satellite system case mission.

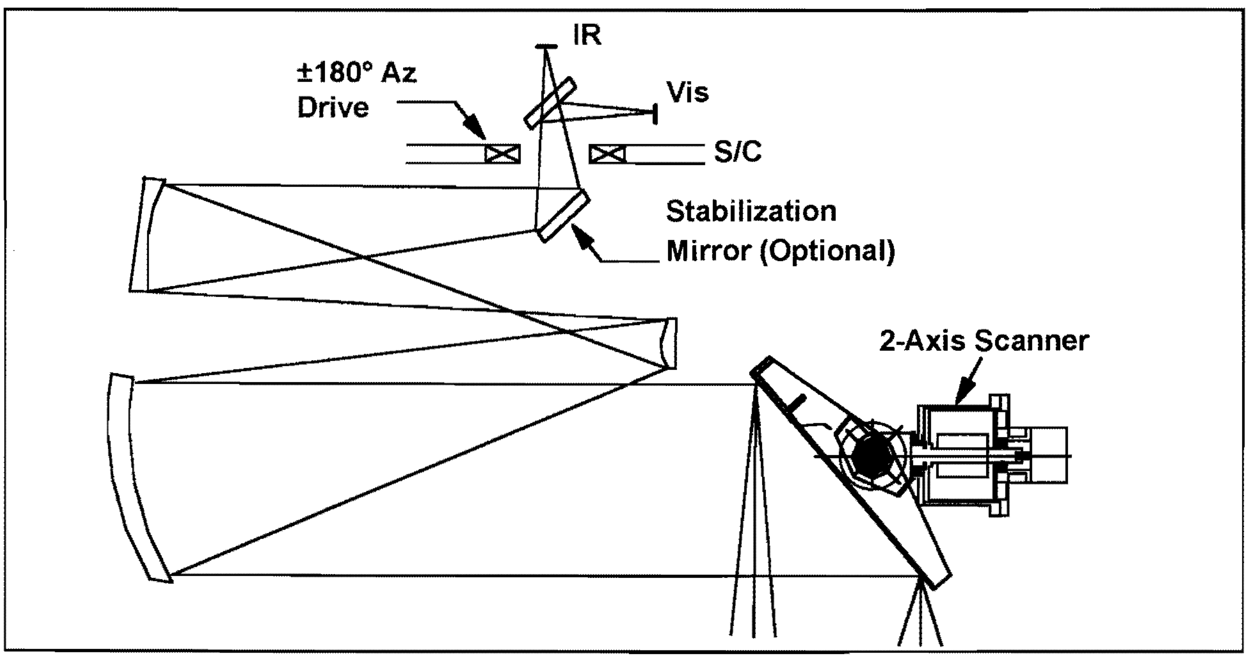

Figure 11. 2-axis scanner optical layout.