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Design and development of a rugged airborne scanning optical assembly for a calibrated IR imaging radiometer

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ABSTRACT

An environmentally sealed, densely packaged optical assembly utilizing an all-aluminum alloy primary optical train has been developed as part of the Infrared Calibrated Airborne Spatial Measurement System (IR CASMS) for deployment in the retractable turret of a C-130 aircraft. The primary optical train, consisting of a Kennedy scanner with a rotating pentagon prism, a Ritchey-Chretien telescope, and a clamshell-type relay assembly, is aligned on a common optical bench that is hard-mounted to the aircraft turret using kinematic mounting techniques. The single-point diamond-machined mirrors and mounts, utilizing a bolt-together design to permit mirror maintenance and eliminate potting instabilities, make use of integrally machined mounting pads and datums that permit alignment by means of an autocollimating alignment telescope. Remotely actuated miniature precision mechanisms for focusing the telescope, changing optical bandpass filters, and presenting field-filling blackbody energy to the 120 element HgCdTe detector array have been designed for optimum packaging efficiency. Two calibrated blackbodies, one thermoelectrically cooled, the other employing an etched-foil heater, are isolated from the desiccated optical environment in a sealed, heat-rejecting plenum and are coupled to the primary optical train by means of zinc selenide relay lenses. This paper presents a functional description of the IR CASMS optical assembly and discusses the construction and alignment details of the optical train, blackbodies, mechanisms, and environmental enclosure.

1. INTRODUCTION

The Infrared Calibrated Airborne Spatial Measurement System (IR CASMS) is a high-resolution, infrared-imaging radiometer developed by KMS Fusion for the USAF, Eglin AFB. The instrument operates in the 8-12 μm band and will be used to collect target and background radiance signature data; to collect data characterizing atmospheric path degradation; to perform development experiments under documented, realistic conditions; and to support side-by-side comparison of competitive missile seekers.

The instrument has two subsystems: The sensor subsystem, which is located in a stabilized turret deployed below a C-130 aircraft; and the console subsystem, which is located in the cargo compartment of the C-130 aircraft. The sensor subsystem contains the scanning optical assembly (which is the subject of this paper), video processors, and electronics for generating all synchronous timing. The console subsystem contains the data buffers, scan converter, interface electronics to other systems, and the operator's interface. The operator's interface is implemented by means of a software-driven menu displayed on an electroluminescent flat panel with an IR touch panel for operator inputs. Using this interface, the operator can select spectral filters, set video offset and gain, set focus, and set internal blackbody reference temperatures.[1]

2. DESIGN REQUIREMENTS

The two main challenges facing the designers of this optical assembly were (a) providing a large horizontal field-of-view (FOV) in a volume limited by the interior dimensions of the aircraft turret and (b) maintaining high resolution while operating in a severe vibration environment. Table 1 summarizes some of the critical design requirements that were addressed.

Table 1. Design requirements

Resolution	80% energy for 0.5 mrad target
	95% energy for 1 mrad target
Horizontal FOV	30° ± 5°
Vertical FOV	1.5° ± 0.225°
Vibration	5-14 Hz, 0.10 in. double amplitude
	14-23 Hz, 1.0 g-peak acceleration
	23-52 Hz, 0.036 in. double amplitude
	52-500 Hz, 5.0 g-peak acceleration
Shock	15 g, 11 msec half-sine pulse
Crash load	9 g, all axes
Temperature	-25°C to +50°C

3. OPTICAL CONCEPT

The ray diagram for the optical assembly is shown in Figure 1. Target energy enters the instrument through a flat zinc selenide window. Next it is directed by the rotating pentagon prism to travel two separate paths within the six-element system of flat mirrors that constitute the Kennedy scanner. After two reflections at the corner mirrors, the energy in each path is recombined at the roof mirror. The Ritchey-Chretien telescope assembly, consisting of an ellipsoidal primary mirror and a hyperboloidal secondary mirror, collects this energy and forms a first focus 10 mm behind the primary mirror. The energy at the first focus is transferred by a unity-gain clamshell relay consisting of two hyperboloidal mirrors and one flat mirror; it requires five reflections to relay the image at the first focus to the detector. The detector-dewar is a modified HgCdTe common module type cooled by means of a Joule-Thompson cryostat. Two parallel columns of 60 elements are placed side-by-side and displaced vertically by one element to provide effectively contiguous 120 element scanning. The detector-dewar collects optical energy through a bandpass filter and the dewar's germanium window; an internal cold shield limits the detector's FOV to minimize stray energy.

The first focus of the system was designed to provide access for injecting field-filling blackbody energy. Energy emitted by the blackbodies is collected by the zinc selenide relay lenses and is reflected into the clamshell by small mirrors mounted on the spinning mirror-wheel. The mirror-wheel assembly acts as a three-position optical switch to direct the detector's FOV first to the low-temperature blackbody, then forward through the primary optical train to collect scene energy, and finally to the high-temperature blackbody. An aperture in the mirror-wheel permits the passage of scene energy at the appropriate time.

Off-axis aberrations of the telescope are small because the sensor uses object plane scanning and has a small vertical FOV. Remaining telescope aberrations are minimized by appropriately figuring the surfaces in the clamshell relay. The operation of the blackbodies is not degraded by using only the clamshell relay portion of the corrected telescope-clamshell system since the primary requirement is that blackbody energy fill the detector's FOV uniformly. Refractive elements were avoided in the primary optical train due to their high dispersion and dependency of the refractive index on temperature; also, the instrument was originally intended to work in the both the 1-5 and 8-12 μm bands.

4. MECHANICAL DESIGN

The optical assembly comprises a primary optical train and a calibration assembly. The primary optical train (refer to Figures 2 and 3) consists of a six-element Kennedy scanner, a telescope assembly, a clamshell assembly, a filter-wheel assembly, and a detector-dewar assembly. The calibration assembly (refer to Figures 2 and 4) consists of a plenum, a high-temperature blackbody (HTBB), a low-temperature blackbody (LTBB), and a mirror-wheel assembly.

Since active thermal control was ruled out due to space, weight, and power considerations, all-aluminum alloy construction was selected as the means of athermalizing the optical assembly. A design utilizing Invar metering rods and flexures for mounting glass mirrors was considered but abandoned due to the apparent simplicity of the all-aluminum design. A wavefront error budget was established, based on diffraction-limited performance, which assigned peak-to-valley surface figure errors of quarter-wave and half-wave ($\lambda = 0.6328$ μm) to the flat and figured mirrors, respectively; analysis had

indicated that diffraction-limited performance was required to meet the resolution requirement. A literature review and discussions with manufacturers indicated that fabrication to these tolerances for a 160 mm diagonal clear aperture was possible with careful attention to fixturing of the substrates. Rectangular-format mirrors for the telescope and clamshell were specified to provide an efficient means of coupling to the rectangular output of the Kennedy scanner and also to minimize the modulation of the scanner output beam, which oscillates laterally as the prism rotates. In general, however, they complicated the design, fabrication, inspection, and alignment procedures.

The following design rules were rigorously adhered to throughout the project: (a) All section properties of alignment-critical components were configured such that stress levels never exceeded the precision elastic limit (PEL); (b) only the minimum number of adjustments were provided; and (c) no threaded adjusters were allowed to carry structural loads due to the vibration environment and the critical alignment requirement (±12 arc seconds) of the Kennedy scanner mirrors; adjustments by shimming were used extensively. In accordance with rule (b) an alignment plan was prepared prior to detail component design.

4.1 Optical bench

The main requirement for the optical bench was that it should have very good temporal stability to ensure that optical alignment could be maintained over long periods of time. To meet this requirement, MIC-6 cast aluminum alloy tooling plate was selected for its inherently stress-free nature; section properties of the bench were adjusted to maintain all environmentally induced stresses below the PEL. A stress relief at 150°C and five thermal cycles over a -195°C to +90°C temperature range were specified in the fabrication processing. As shown in Figure 6, an equilateral-triangular rib pattern was chosen to increase bench stiffness and minimize weight.

The optical component side of the bench utilizes raised pads (refer to Figure 5) for semi-kinematic mounting of all elements. The following double-anodize process was specified to ensure that pad surface integrity was maintained during assembly. First the entire bench was Type-I anodized, and then the raised surfaces of the pads were flycut to the parent alloy. Next the Type-I layer was used as the mask for a Type-III layer, thereby confining it to the flycut surfaces. Then all pad surfaces were machine-ground to a coplanarity requirement of 1 μm in sets of three pads and a parallelism requirement of 5 μm for all pads. Controlling the parallelism between pads limited the Kennedy scanner mirror adjustments to a single adjustable mirror, as discussed below.

To reduce optical adjustments further, advantage was taken of the typically 5 μm true-position locational accuracy of the jig borer machine-tool by machining precisely located holes for pins used to kinematically locate all bench-mounted optical components. Hardened pins were then wring-fitted to these holes and installed with retaining compound to eliminate the possibility of stressed material in close proximity to the 1 μm pads and to avoid the installation forces required for press fitting. At assembly each element was located using two or three pins (depending on the number of degrees of freedom that had to be limited) and a pad-set in the plane of the bench. Deformed-thread helical coil inserts were rejected in favor of free-running inserts used in combination with retaining compound, since the variation in prevailing-torque of the former would prevent the accurate measurement of screw torque required for mirror mounting.

4.2 Kinematic mounts

The optical bench was mounted using three kinematic mounts (refer to Figure 6). Each mount consists of a hardened steel ball captured between an upper and lower plate of hardened steel. The ball hardness was specified to be less than the hardness of the two plates since, should contact stresses exceed the design values, the lower-cost ball would become the sacrificial member. Three specially-made #10-24 shoulder screws, with a stack of five Belleville washers under each screw head, were used to clamp the two plates and ball together at a controlled preload. The ball was set in a v-groove seat in one plate and a conical seat in the other. When the mounts were installed on the bench, the centerlines of the v-groove seats were arranged to intersect at 120°. Sliding interfaces were treated with a dry lubricant to minimize friction. As a result of this design, the only forces imparted to the optical bench by distortion of the aircraft interface surface are very small frictional forces.

4.3 Mirrors

All mirrors capitalize on the strengths of diamond machining by incorporating integral mounting and alignment features in each mirror. The scanner mirrors were designed with an integral right-angle mounting base (refer to Figure 5) and three raised pads. The coplanarity of every mirror's pad-set was specified to be equal to its surface figure error; the plane of every mirror's pad-set was specified to be either perpendicular to the mirror's face (or optical axis, as applicable) within ±10 arc seconds.

All mirrors except the prism were electroless nickel plated to permit zone polishing after diamond machining. During temperature testing of these mirrors, it was determined that the surface figure requirement was exceeded due to the bending induced by the coefficient of thermal expansion (CTE) mismatch between the nickel plating and the aluminum alloy substrate. Three of the scanner mirrors were stripped of the nickel plating and re-flycut with the mirrors potted into redesigned fixtures. The ambient temperature flatness of these unplated mirrors was stable over temperature but no better than the nickel-plated versions at the temperature extremes. The completed primary optical train consists of both plated and unplated mirrors.

Since mounting tabs would obscure optical energy if used on the secondary mirror, integral flexures with raised pads were fabricated by electric discharge machining. Threaded inserts were installed in the flexures. A small hole, located in the unused central portion of the mirror, provided the centering datum for machining and alignment.

The primary mirror and front and rear clamshell mirrors were constructed similarly. Three tabs with mounting surfaces located behind the reflecting surface were machined on the periphery of each mirror and designed to isolate mounting stresses away from the mirror surfaces. A precision surface and shallow bore machined into the back of each mirror served as both machining and alignment datums. The bores were specified to be centered within 5 μm true-position of the optical axes and the surfaces were specified to be perpendicular to within ±10 arc seconds of the optical axes. By centering and autocollimating to a diamond-turned alignment target registered to both the surface and bore, each mirror was adjusted in two translational and two rotational degress of freedom.

4.4 Kennedy scanner

The Kennedy scanner, as shown in Figure 5, is a compact six-element assembly consisting of a rotating pentagon prism, four corner mirrors, and a roof mirror. All six elements utilize flat single-point diamond-machined surfaces. Unlike an oscillating mirror, the pentagon prism is not subject to mirror distortion from inertia effects due to direction reversal during scanning and yet provides the required wide FOV. Although the Kennedy scanner provides a compact mechanism for obtaining the required FOV, its alignment requirements are quite demanding. An analysis was performed to determine the maximum permissible wavefront misalignment between the two halves of the beam after they are combined at the roof mirror. It was determined that, if the system was to meet the resolution requirement, the two wavefronts needed to be parallel within ±12 arc seconds. This requirement made the the use of adhesives questionable due to their temporal instabilities and required that at least one of the reflecting surfaces of the scanner be made adjustable. To achieve one-element adjustment, all scanner mirrors (except one of the corner flats) were aligned by carefully specifying the machining tolerances of the mirror and bench pads and the positional tolerances of the pins used to set the face angle of the mirrors. The corner mirror nearest the LTBB was provided with shims under its base for one angular adjustment; an 80 pitch adjusting screw and pivot were provided for the second angular adjustment. The adjustable path of the scanner is aligned to the fixed path with the result that, under worst-case conditions, the scanner and the telescope will be misaligned by an acceptable 1 arc minute.

All scanner mirrors were attached to the optical bench using three #10 screws that clamp through the three semi-kinematic pads machined on the base of each mirror. The coplanarity of the three corresponding pads on the bench was specified to be 0.25 μm but could only be fabricated to 1 μm. As an acceptance test, the mirrors were mounted to the bench, the screws were torqued, and an interferometer was used to monitor figure changes. Screw torque was reduced to 6 inch-pounds to minimize mirror distortion and still provide adequate clamping force for all environments. The bench was accepted as-is since all distortion was confined to areas outside the clear apertures of the mirrors. After alignment, all scanner mirrors were pinned to the optical bench. Since the clearance associated with slip-fit pins would permit movement that could exceed the alignment requirement, the mirrors were potted as follows. Special pull-dowels were fabricated by axially tapping small dowel pins. Oversize holes were machined in the base of each mirror to provide an annular volume around the pull-dowels.

Mold release was applied to the pin and to all surfaces of the annular volume. The holes were then filled with potting. A specially made slide hammer with a threaded tip can be used to remove the pull-dowels.

The pentagon prism was machined from solid 6061 T651 aluminum alloy. The optical facets were diamond flycut and overcoated with a layer of evaporated aluminum and a protective layer of silicon monoxide. Electroless nickel was not used since the manufacturer was confident of meeting the flatness requirement without post-polishing. The prism rotates in two pair of duplexed bearings that are mounted to a stainless steel bearing housing. A brushless DC torque motor drives the prism directly. An encoder wheel and lamp-detector set provides the feedback for the phase-locked loop speed-control circuit.

Over the instrument's temperature range, significant forces can be generated at the interface of the stainless steel prism bearing housing and the aluminum alloy optical bench. A finite-element analysis determined that distortions in both the housing and the bench due to forces generated at the three attachment points resulted in an unacceptable misalignment of the prism. To minimize the distortions and misalignment, a single Belleville washer was used under the head of each of the three mounting screws to limit the frictional forces that generated the distortions and yet still satisfy the environmental and crash load requirements. The sliding surfaces were treated with dry film lubricant to reduce frictional forces further.

4.5 Telescope assembly

The two-mirror telescope assembly, as shown in Figure 7, consists of the primary and secondary mirrors, their support brackets, and a focus assembly. The brackets were fabricated from MIC 6 cast aluminum alloy tooling plate and were stress relieved, stabilized, and double-anodized using the same procedures specified for the optical bench. When the mirrors were aligned, they were clamped to the brackets with screws and flat washers. Dowel pins were installed in reamed holes in the mirrors and set into wet potting compound, which had been injected into oversize blind holes in the bracket. (Once the potting has cured, the mirrors may be removed for maintenance and still meet the ±0.05 mm centering tolerance when reinstalled.) An eccentric is used to position the entire telescope assembly properly along the instrument's optical axis. Lateral position is maintained during this adjustment by sliding contact between locating pins in the bench and raised pads on the side of the primary mirror bracket.

System focus is adjusted by moving the secondary mirror. Its position is remotely adjustable and may be set by the operator for various target ranges between 40 m and infinity. To provide this adjustment, the base of the secondary mirror bracket was mounted to the moveable carriage of the focus assembly. This assembly uses a modified off-the-shelf miniature motorized translator and a miniature linear variable differential transformer (LVDT) to meet the required positioning accuracy of ±0.05 mm easily. Since the carriage was not coupled to the lead screw with a preloaded nut, springs were added to maintain contact with the tip of the lead screw under vibration and to increase the natural frequency of the assembly. The lead screw is self-locking and provides ample detent torque to resist vibrational disturbances. The LVDT overcomes the backlash problems of a motor-mounted encoder and also has home position capability for positioning the mirror during initial instrument power-up. For alignment purposes, the secondary mirror is adjustable in six degrees of freedom by lapping the shims located under the three mounting tabs of the focus assembly and by rotating the three eccentrics contacting these same tabs.

4.6 Mirror-wheel assembly

The mirror-wheel assembly, shown in Figure 4, laterally deflects the detector's FOV to the blackbodies using small plane mirrors mounted at 45° to the plane of the spinning mirror-wheel; target energy is passed to the detector by an aperture in the wheel located between the small mirrors. Since the space between the telescope and the clamshell is limited to 43 mm, a pancake-type frameless DC torque motor and a kit-type encoder were selected to minimize the axial length of the assembly. Separate bearings in these components are not required since the ABEC 7 ball bearings used to provide precise angular rotation of the deflection mirrors have adequate capacity for the additional loads of the motor and encoder. To minimize CTE mismatch, components of the mirror-wheel assembly were fabricated from stainless steel. The mirrors were bonded to their mounts, which are adjustable about an axis parallel to the plane of the wheel. The entire assembly is adjustable in three degrees of freedom at its interface to the plenum by shimming. Rotation speed of the wheel is synchronized to the pentagon prism at a rate equal to five times the prism speed. With this design, each scene of data (corresponding to the image produced by the rotation of one prism facet) is preceded and followed by blackbody calibration data.

4.7 Clamshell mirror assembly

The clamshell mirror assembly, as shown in Figure 3, is a three-mirror assembly consisting of two figured mirrors, one flat mirror, and a one-piece bracket to maintain relative alignment. It overcomes the short back focal length limitations of the telescope by providing space for mounting the filter-wheel and detector-dewar while shortening the overall optical bench length. The bracket was machined from solid 6061 T651 aluminum alloy and was stress relieved and stabilized using the same procedures specified for the mirrors. All mirror-mounting pads on the bracket were designed to be accessible to a diamond flycutter. It was intended that the critical angular relationships among the three mirror-mounting faces be maintained with a precision index during diamond machining. It was designed as a bolt-together assembly and uses the same post-alignment pinning procedure as the telescope assembly.

During fabrication, the critical surfaces of the bracket had to be "chased" on the flycutter in order to maintain the flatness and angular requirements. This resulted in improper spacing between the three mirrors. To salvage the assembly, the mounting screws for the two figured mirrors were undercut to permit lateral repositioning of the mirrors. The flat mirror was then stripped of paint along the four edges and mounted to the bracket with three o-rings beneath the mounting tabs. It was then aligned and potted with RTV to the bracket with the o-rings in place. The heads of the mounting screws on the flat mirror were bonded to the mirror to prevent loosening, since they could not be torqued to specification.

4.8 Filter wheel assembly

The remotely actuated four-position filter-wheel, shown in Figure 8, provides the ability to divide the spectral band into 8-10, 10-12, or 8-12 μm regions. Three of the filter positions are occupied by interference-type filters with germanium substrates that were edge-bonded with RTV to individual mounts. These mounts were screw-mounted to the filter-wheel. The fourth position contains no filter and is the all-band position. The focusing system automatically compensates for the focus change required by the all-band position. Each filter as well as the entire wheel may be easily removed and replaced in accordance with mission requirements.

To make efficient use of the available volume, a 12 mm diameter gearmotor with integral incremental encoder was coupled to the filter wheel by means of a 2:1 gearset. An opto-interrupter was used to sense the absolute position of the wheel. Backlash within the geartrain was compensated by using an oversize filter. A rotary solenoid was considered but rejected due to its large size and power requirements. A stepping motor did not provide adequate detent torque to maintain filter position under vibration nor did it have the right form factor for the space available.

4.9 Detector assembly

The detector assembly, as shown in Figure 3, consists of a detector-dewar, a mounting bracket and an adapter plate. Both the bracket and plate were machined from solid MIC 6 cast aluminum alloy tooling plate and were stress relieved and stabilized using the procedures specified for the optical bench. Due to the small dimensions of the detector array (6.25 mm × 0.125 mm) it was determined that two angular alignments could be maintained with machining tolerances. Four degrees of freedom (including focus) can be adjusted, however, by means of four eccentrics of the same design used on the telescope assembly. To balance the disturbance torque of the 120 miniature coaxial cables during detector alignment, both the plate and the bracket were preloaded into their mating surfaces using pairs of curved washers under the heads of their mounting screws. Since the eccentrics must exert forces to overcome the frictional forces due to the curved washers, both the plate and the bracket were Type-III anodized all-over to prevent damage due to bearing stress and galling.

4.10 High Temperature Blackbody (HTBB) assembly

The HTBB assembly, as shown in Figure 9, uses a resistance heater constructed of laminated etched-foil and mica to heat a tellurium copper emitter. This approach was determined to be much simpler than hand winding a nichrome heater coil and potting it in place. The mica-insulated heater was clamped to the emitter using a stainless steel clamp. Ceramic cloth was used as a cushion between the delicate mica and the clamp. The heat leak to the stainless steel optical barrel and the plenum was minimized by using a polyimide isolation plate. All parts of the assembly were sealed with o-rings since it must be evacuated and back-filled with nitrogen to eliminate condensation damage to the emitting surfaces coated with 3M solar coating. Evacuating the assemblies to prevent convective heat losses from the emitter was considered but deemed

impractical. Temperature sensors were bonded to the edges of each lens and to the emitter; the radiance contribution of the lenses was calculated from their measured temperatures. The forward lens, evacuation port and temperature sensors were sealed using high-temperature RTV.

4.11 Low Temperature Blackbody (LTBB) assembly

The LTBB assembly, as shown in Figure 10, uses four three-stage thermoelectric devices (TED) to cool a tellurium copper emitter. Each TED was thermal greased and clamped between a machined flat on the emitter and a finned heat sink. The heat sinks were attached to a machined polyimide housing to minimize the heat leak to the cooled emitter. To prevent ice build-up on the cold surfaces, silicone gaskets were employed between the heat sinks and the polyimide housing to seal out potentially moisture-laden turret air. Polyimide foam was installed in the cavity between the heat sinks and the emitter to minimize convection heat leaks. Prior to detail design, prototype heat sinks were fabricated and tested with a representative plenum and fan. Transistors mounted to the heat sinks simulated the TED heat inputs, and the steady-state temperatures of the heat sinks were measured to verify the design. All remaining construction is similar to the HTBB.

4.12 Environmental enclosure

Infrared energy enters the optical assembly through a zinc selenide window sealed to an aluminum alloy cover with a flat silicone rubber gasket. The cover was o-ring sealed to the optical bench and permitted the enclosure of all optical elements within a clean, desiccated environment. To minimize system weight, a structure adequate to withstand the pressure loads due to altitude changes was not considered. Instead, the optical assembly is maintained at nearly ambient pressure by venting the interior through a dynamic desiccator. Pressure differences must exceed 3.5 kPa before a two-way check valve will permit the enclosure to exchange air. Two static desiccators were used to eliminate moisture due to o-ring or other leakage. A potted feed-through assembly was constructed to enable the passage of 120 miniature, low-noise, coaxial cables through the optical bench, thereby permitting the heat-generating preamplifiers to be located outside of the optical assembly. The heat-rejecting plenum shown in Figure 4 is both an optical mount and an environmental enclosure for the blackbodies. With the plenum's eight o-ring seals installed, turret air may be used to remove blackbody waste heat by forced convection without contaminating the desiccated optical environment.

5. STRUCTURAL ANALYSIS

To verify the structural integrity of the optical bench, several finite element analyses were performed using the STARDYNE family of computer programs to compare the stiffness of rectangular, diamond-shaped, and equilateral-triangular shaped rib configurations; to calculate the stresses due to the frictional forces transmitted by the kinematic mounts; to determine the stresses, displacements and phase angles of all scanner mirror tie-down points during vibration; and to calculate the stresses and displacements due to the shock environment.

The results of these analyses demonstrated that the equilateral-triangular shape was the most efficient and yielded a natural frequency of 152 Hz. It was also determined that the stresses due to (a) the frictional forces transmitted by the kinematic mounts, (b) the vibration environment, and (c) the shock environment were all well below the PEL. The displacements and phase angles determined by the vibration analysis were input to KMS-written computer programs that calculated the optical response. These programs demonstrated that the resolution requirement could just be met in the 5 g environment. The shock analysis demonstrated that the optical bench is essentially a rigid body with respect to the 11 msec pulse due to its high natural frequency.[2]

6. CONCLUSION

The design and development of a rugged airborne scanning optical assembly was a success. A 25° horizontal FOV was achieved. Flight tests indicated no degradation in optical performance due to the thermal or vibration environments. Calibrated blackbodies with adjustable temperature ranges were constructed and thermally isolated from the optical elements. Compact focus, mirror-wheel, and filter-wheel assemblies were designed to fit in the restricted volume and operated successfully in all laboratory and flight tests. A light-weight environmental enclosure was constructed to enable operation in a humid, salt-air environment. All aspects of the design and construction were performed in strict adherence to the specifications of MIL-E-5400 and MIL-I-45208.

Resolution of the optical system is limited by the out-of-tolerance surface figure errors of the mirrors. Improvement in resolution can be achieved by more accurately machining the optical surfaces of the aluminum alloy mirrors and by eliminating the electroless nickel plating. The feasibility of this improved construction is evidenced by interferograms of the prism. These interferograms demonstrate that a flat surface, of the required dimensions, can be machined to a peak-to-valley accuracy of at least 0.28 λ ($\lambda = 0.6328$ μm) without nickel plating. Despite the limitation in resolution, tests at a range of 300 m have demonstrated that the IR CASMS can distinguish two 0.5 mrad targets separated by 0.5 mrad when their temperatures are at least 1°C above or below the background temperature.

7. ACKNOWLEDGEMENTS

The successful completion of this optical assembly was the result of the dedication and hard work of many talented individuals at KMS. Other members of the project team included Mr. Douglas Thomas, who was responsible for the optical system design, and Mr. James Maszatics, who performed the structural analysis.

8. REFERENCES

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2. J. M. Maszatics, "IR CASMS Subsystem Design Analysis Report, Structural Stress Analysis, Data Item A019," August 1988.

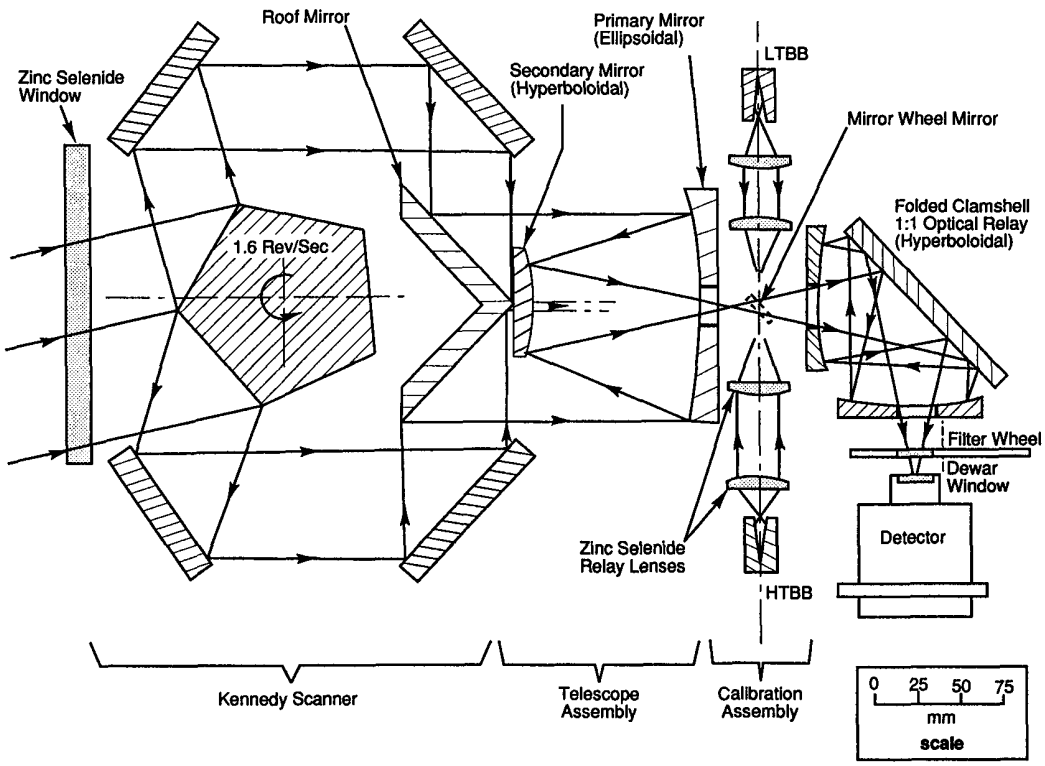

Figure 1. Ray diagram of the IR CASMS optical assembly. The additional mirror for deflecting the detector's FOV to the HTBB is not shown.

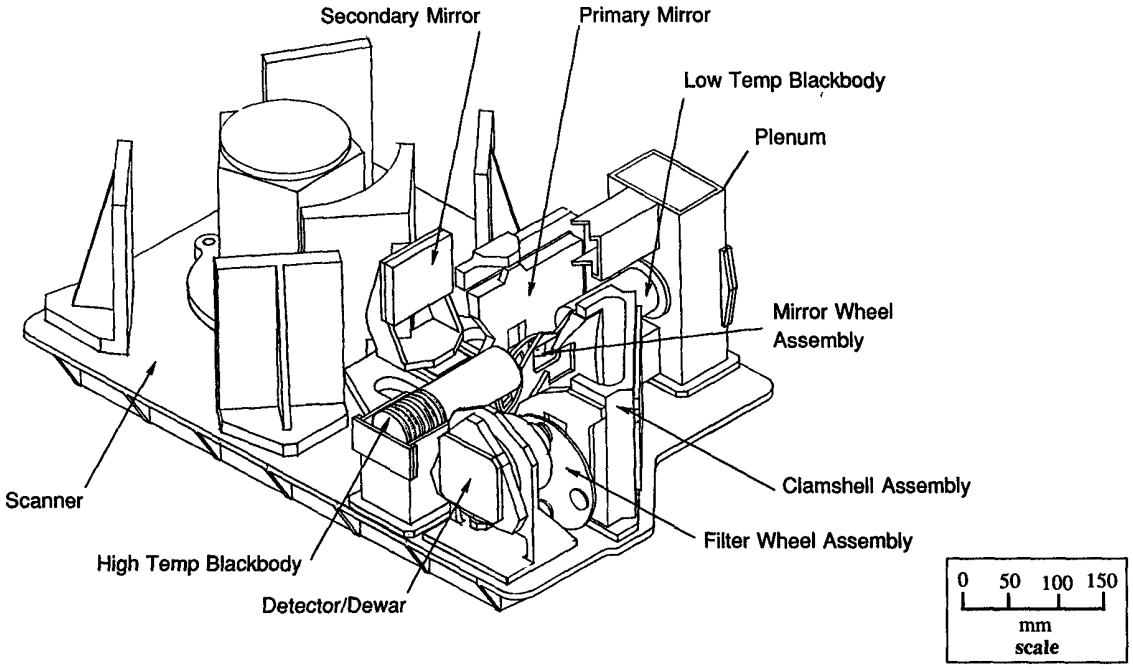

Figure 2. Conceptual drawing of the IR CASMS optical assembly with the cover removed.

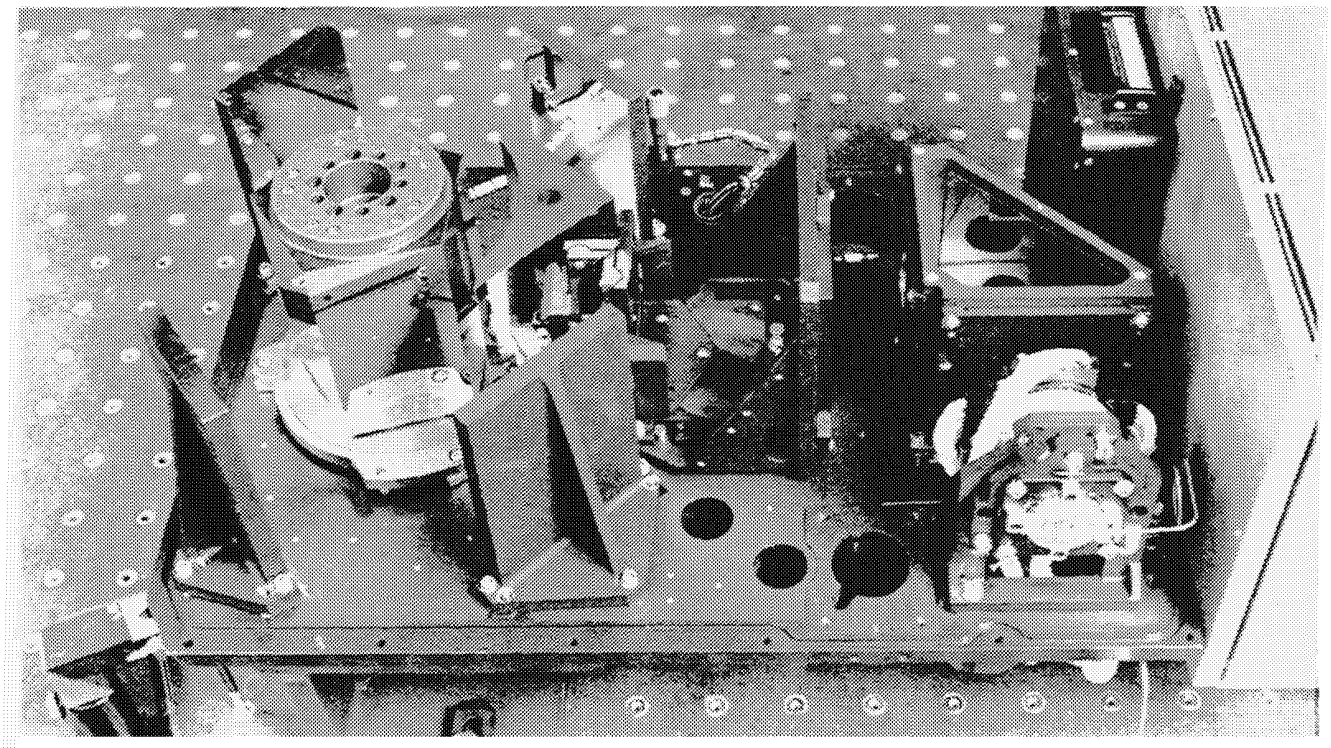

Figure 3. Primary optical train. The aluminum alloy mirrors and brackets were semi-kinematically mounted using raised pads and pins.

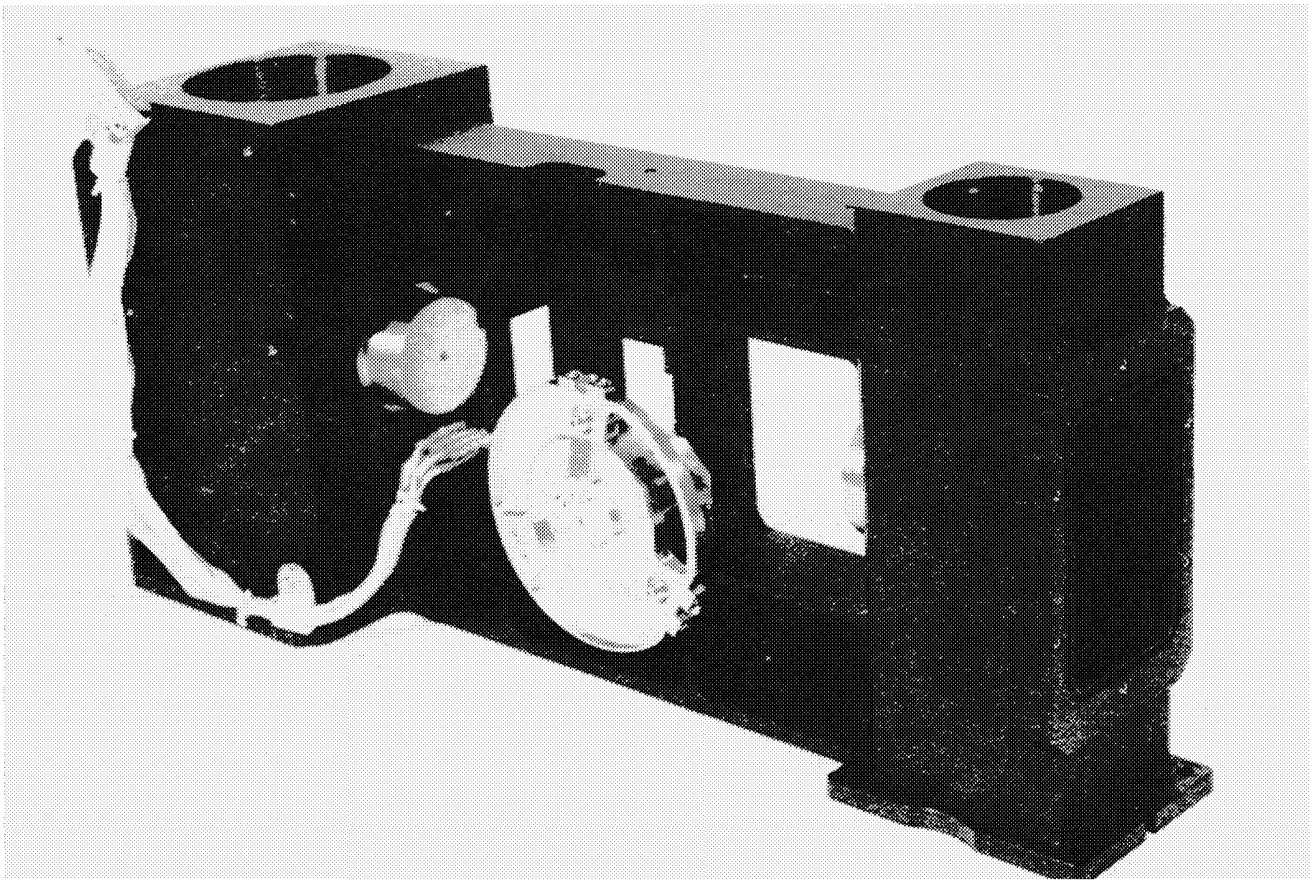

Figure 4. Calibration assembly. High and low temperature blackbodies were mounted inside the sealed plenum. The rotating mirror-wheel, synchronized to the scanning prism, directs blackbody energy to the detector.

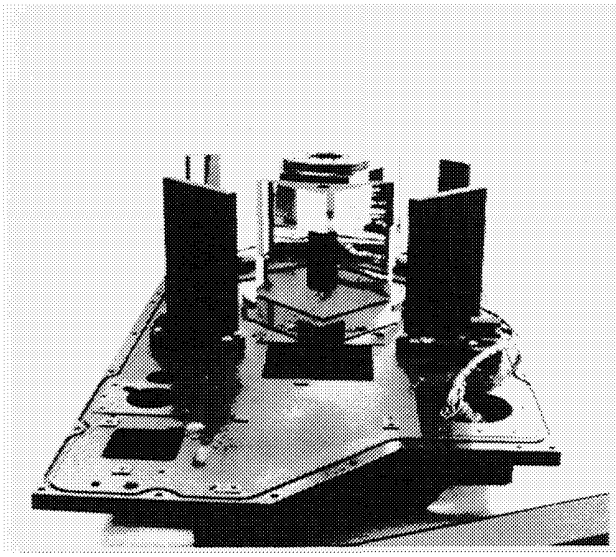

Figure 5. Kennedy scanner. Six separate optical elements define two optical paths that were aligned to ±12 arc sec. Overall length of the optical assembly was reduced by notching the roof mirror to accept the telescope's secondary mirror.

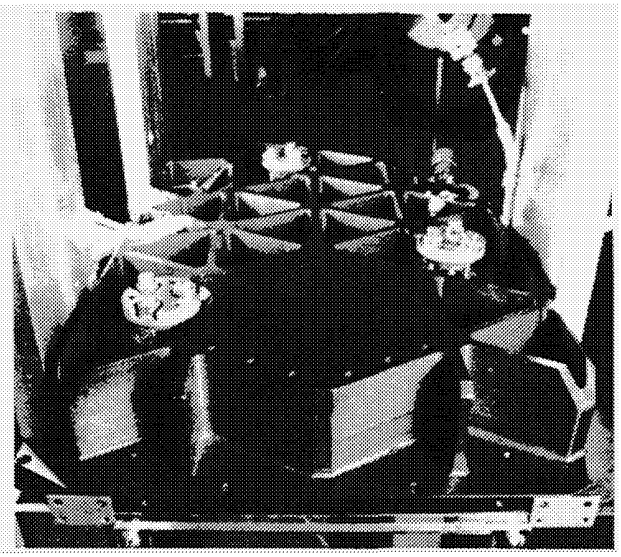

Figure 6. Optical bench. Equilateral-triangular ribbing and three kinematic mounts were used to maintain optical alignment in a 5 g environment.

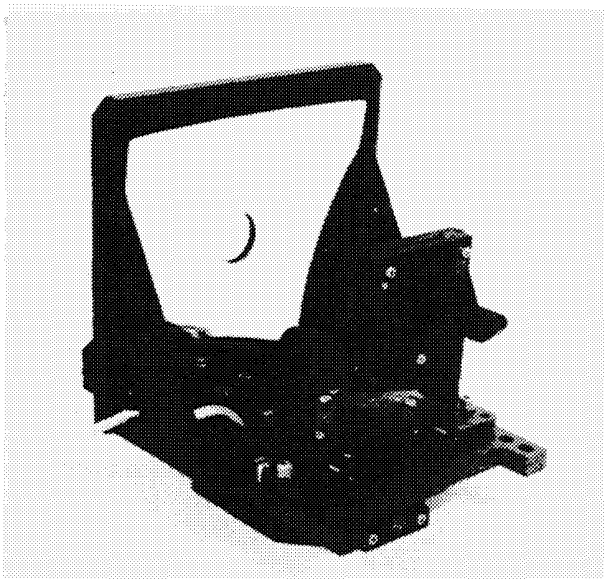

Figure 7. Telescope assembly. The optical assembly focus is adjusted for targets within a range of 40 m to infinity by moving the secondary mirror using a miniature ball slide and LVDT.

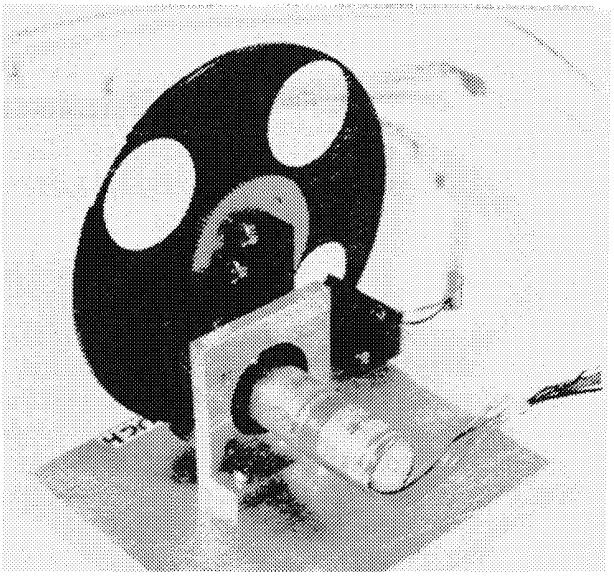

Figure 8. Filter wheel assembly. Bandpass filters are selected by rotating the filter-wheel using a gearmotor with an integral incremental encoder. An opto-interrupter defines the home position of the wheel.

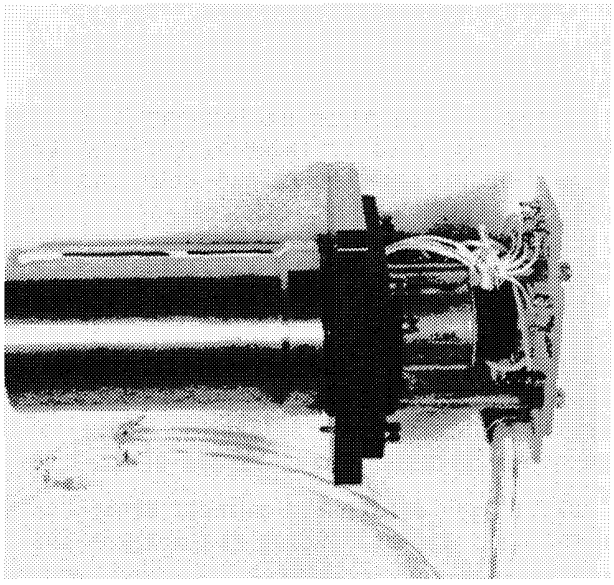

Figure 9. High temperature blackbody assembly. An etched-foil heater was used to provide calibrated operation from 40°C to 200°C. Two lenses located in a stainless steel lens tube present the emitted energy in a field-filling format.

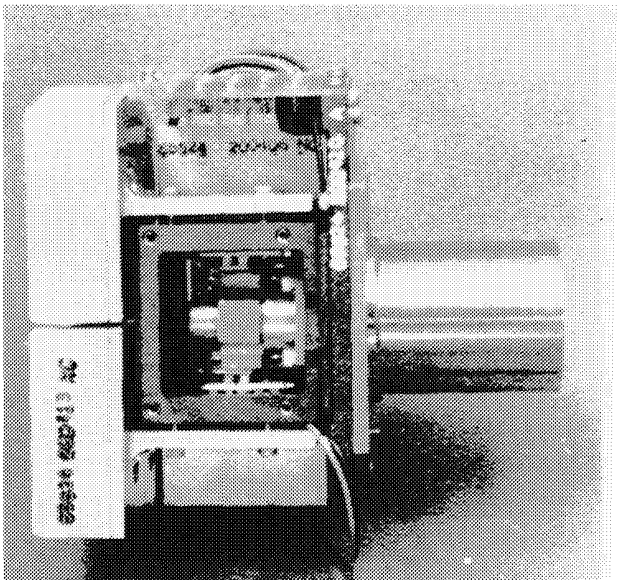

Figure 10. Low temperature blackbody assembly. Four three-stage thermoelectric devices were used to provide calibrated operation from -20°C to +80°C. A machined polyimide housing limits the heat leakage from the heat sinks to the emitter.