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Optical Fabrication and Metrology For A Visible Through Thermal Infrared Multi-Band Imaging System

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Abstract

The optical fabrication, metrology, and system wavefront testing of an off-axis three mirror anastigmatic telescope will be presented. The telescope is part of a multi-band imaging system which includes a single mechanically cooled focal plane with 15 spectral bands covering a wavelength range from 0.45 microns to 10.7 microns and an on-board calibration subsystem. The imaging system is to be operated in a low earth orbit in a pushbroom scanning mode. The telescope has a 36 cm aperture, a 1.38 degree cross-track by 1.82 degree along-track field of view (FOV), near diffraction limited performance in the visible, and strictly diffraction limited performance from 1.3 microns to 10.7 microns.

The primary and the tertiary mirrors are general aspheres which have undergone 80% lightweighting. The secondary mirror is a hyperbola. The primary mirror was extremely difficult to fabricate and test due to its large departure from sphericity, fast f-number, and large off axis distance. The tertiary mirror has a small departure from sphericity and is only slightly off-axis, but it has a very fast f-number also. The surface wavefront measurements for the three mirrors after final figuring and lightweighting are 0.048 waves rms @0.6328 microns for the primary mirror and 0.025 waves rms @0.6328 microns for the secondary and tertiary mirrors. The telescope wavefront requirement at the center of the along-track FOV is 0.178 waves rms @0.6328 microns and at the edge of the along-track FOV is 0.677 waves rms @0.6328 microns.

Introduction

This paper will describe the requirements, the optical fabrication, metrology, and system wavefront testing of an off-axis three mirror anastigmatic telescope which is part of the multi-band imaging system. The first section is a general description of the multi-band imaging system. The next several sections describe the telescope optical performance requirements, the mechanical and optical design, the optical component alignment and test, and the telescope assembly, system level testing, and performance. The last section is a summary.

Multi-Band Imaging System General Description

The three major subsystems that make up the multi-band imaging system are the telescope, the focal plane assembly (FPA), and the cryocooler. The telescope has a 36 cm unobscured aperture and a wide field of view. The telescope provides high quality images from the visible through the thermal IR and also provides an accessible exit pupil in which to place a cold stop. The telescope also consists of a state-of-the-art on-board calibration system (OBCS). The OBCS provides extremely stable sources to obtain accurate calibration on-board of the entire end-to-end imaging system and also of the FPA alone.

The FPA consists of linear detector arrays with optical filters immediately above the arrays. The detector arrays are placed at the focal plane of the telescope. The linear arrays provide spatial resolution in one direction (cross-track). The motion of the imaging system relative to the ground produces a scanning operation in the other direction (along-track), thereby producing two-dimensional images in multiple wavelength bands. The FPA also contains a cold shield, which extends from the detector arrays to the exit pupil of the telescope. The FPA is enclosed in a vacuum shroud, with a BaF₂ window on one side of the shroud which allows the light from the telescope to pass into the FPA. The window also allows the FPA to be evacuated separately and provides additional contamination control for the FPA. The thickness of each individual optical filter is adjusted so that the focal shift due to dispersion in the BaF₂ window and the optical filter substrates is equalized for all the bands and the focus is placed at the correct physical location for each detector array material type. A cold stop is located inside the cold shield at the exit pupil

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location. This design reduces the thermal background from the surrounding telescope structure by allowing for 100% cold shielding.

The linear arrays on the FPA are arranged in three pairs of sensor chip assemblies (SCAs). Each pair of SCAs consist of a visible wavelength to mid-wavelength infrared SCA and a long wavelength infrared SCA. The arrangement of the SCAs on the focal plane is shown in Figure 1. Three pairs of SCAs are used to span the full cross-track field of view. Bands A-D are the visible (VIS) bands whose spectral bandpasses are in the wavelength range of 0.45 - 0.86 microns. Bands E-G are near-infrared (NIR) bands whose spectral bandpasses are in the wavelength range of 0.86 - 1.04 microns. Bands H, I, and O are the short wavelength infrared (SWIR) bands whose spectral bandpasses are in the wavelength range of 1.36 - 2.35 microns. Bands J-K are medium wavelength infrared (MWIR) bands whose spectral bandpasses are in the wavelength range of 3.50 - 5.07 microns. Bands L-N are long wavelength infrared (LWIR) bands whose spectral bandpasses are in the wavelength range of 8.00 - 10.7 microns. Silicon photodiodes are used for bands A-D. Indium antimonide is used for bands E-K and O. Mercury cadmium telluride is used for bands L-N.

Figure 1. Focal plane layout.

A mechanical cryocooler is used to cool the FPA to a nominal temperature of 75 K. The cryocooler provides over 2.25 watts of cooling power at 65 K. A thermal strap connects the cold block of the cryocooler to a metal block that supports the focal plane. A 10 K increase in temperature across the thermal strap is assumed. The cryocooler also cools the cold shield to reduce the infrared background on the focal plane. The cryocooler uses temperature sensors to provide closed loop temperature control of the cold block. It is designed for low vibration to minimize jitter of the imaging system.

Telescope Optical Performance Requirements

The optical performance requirements that drove the optical design were primarily the aperture size, focal length, focal plane size, wavelength coverage, band layout, flat focal surface, ensquared energy, accessible exit pupil, and high throughput. The ensquared energy requirement along with the need for high throughput and 100% cold shielding dictated that the design must provide a large unobscured entrance aperture (off-axis design). The need for a wide field of view (FOV) along with the physical size of the focal plane and the entrance aperture size dictated the

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need for a fast optical system F/3.47. The requirement for ensquared energy, flat focal surface, accessible exit pupil, and wide FOV drove the design choice to an off-axis three mirror anastigmatic (TMA) design¹.

The layout of the wavelength bands on the focal plane presented a particular challenge in meeting the ensquared energy requirement. The different pieces of a single spectral band are spatially separated in the along-track field of view, necessitating aberration correction for each spectral band to be done not over a slit image but a rectangular image in the focal plane. Band D presented the greatest challenge to meeting the ensquared energy requirement and was therefore placed nearest to the center of the focal plane to minimize the along-track field of view the aberration correction would have to take place over. The optical fabrication requirements were driven primarily by the ensquared energy requirements, the wide FOV requirements, the focal plane band layout, and the straylight requirements. The primary optical performance requirements that affected the optical design of the telescope and dictated the optical fabrication requirements are stated in Table 1.

Requirement	Value
Entrance Aperture	36 cm diameter nominal
Paraxial Focal Length	125 cm nominal
Focal Plane Configuration	30.7 mm cross-track 43.2 mm along-track Band configuration shown in Figure 1
Focal Surface	Flat in the cross-track and along-track directions
Operating Wavelength	0.45 - 10.7 microns
Image Quality VIS NIR, SWIR, & MWIR LWIR	(Measured at the detector surface. Includes BaF ₂ window and filter substrates.) 80% ensquared energy in 12.5 X 12.5 micron area 84% ensquared energy in 50 X 50 micron area 84% ensquared energy in 100 X 100 micron area
Effective Aperture Area VIS, NIR SWIR, MWIR, & LWIR	(Includes losses from BaF ₂ window but does not include losses through the detector spectral filters.) 825 cm ² (850 cm ² in band A) 860 cm ² (805 cm ² in band N)
Exit Pupil	Real accessible exit pupil at which a cold stop can be placed.
Stray Light PST (out of field rejection) Veiling Glare (in field scatter) VIS NIR, SWIR, & MWIR LWIR	 ≤ 10 ⁻⁶ for a point source at any angle ≥ 46 degrees off-axis For a uniformly illuminated field, > 6% of a pixel illumination shall be from light outside a radius given below for that pixels operating wavelength measured from the center of the pixel. 56.25 microns 225 microns 450 microns

Table 1. Optical Performance Requirements

From the ensquared energy requirements, transmitted wavefront specifications were derived. From the point source transmittance (PST) and veiling glare requirements, a mirror surface roughness specification was derived. These specifications are shown in Table 2. The transmitted wavefront specification must be met at any of the specified bands at any wavelength within those bands, and at any field position for the specified bands. An error budget was established for meeting the transmitted wavefront specification. The error budget included contributions from fabrication of the telescope mirrors, and the FPA, mirror, structure, and FPA mount induced errors, alignment errors (including assembly and long term stability errors), gravity-release errors, optical design residual, and reserve. Band D had the least amount of reserve available, and therefore, was the most difficult band to meet the transmitted wavefront specification in. The transmitted wavefront specification for band D drove the fabrication errors allowed for the mirrors, as well as the alignment error budget. The error budget established for fabrication and alignment of the telescope mirrors will be discussed further in the remaining sections of this paper.

Requirement	Value
Transmitted Wavefront Specification	RMS waves @ 0.6328 micron wavelength 0.205 waves
VIS (Bands A - D)	0.885 waves
NIR/SWIR (Bands E-I)	0.411 waves
MWIR (Bands J, K, & O)	0.743 waves
LWIR (Bands L - N)	
Mirror Surface Roughness	< 20 Angstroms RMS

Table 2. System Level Performance Specifications from which the Fabrication, and Alignment Specifications will be derived.

Overview of the mechanical and optical design

Overall system requirements are typically flowed down to the subassembly and component level in a tolerance budget. These can be apportioned in many ways. From an analysis of this system, we know that the alignment of the components requires particular precision. As a result, the alignment budget, shown in Figure 2 allows greater latitude of alignment errors and less for the manufacture of the optical components. The components, once manufactured, should be a constant.

Figure 2. The wavefront error budget for the four spectral band groups

The tolerance budget also reflects expected degradations due to thermal variations, mechanical degradation due to vibration, and the fact that the system is manufactured on earth in a gravity field but will be used on orbit in a near zero gravity environment. Instead of spending time and money to attempt to design out these degradations, they are absorbed by judicious apportioning of tolerances in the budget.

Figure 3 shows a drawing of the telescope with the FPA attached. It shows the location of the mirrors, the on-board calibration system, and the mechanical structure which holds it all together. To minimize weight as well as thermal instability, a graphite epoxy single piece box is used as the support structure, optical metering structure, and baffle system. The box weighs twenty-seven pounds.

Figure 3. Multi-band Imaging System Telescope Assembly

The mirrors mount to the outside edges of the box. This allows them to be aligned to each other initially outside of the structure supported by external stands. They are then epoxied to the structure through invar bipods when the box is placed between the mirrors. This forms a rigid single piece structure. The configuration imitates zero gravity alignment. The mirrors are then picked up by the structure when the external stands are removed. There should be a gravity induced misalignment at this stage which should reverse on orbit. This misalignment is carried, nonetheless, in the error budget.

Other features of the telescope are the secondary focus assembly and the optical calibration assembly. In order to deal with the full thermal environment range expected on orbit, to accommodate the outgassing and shrinkage of the structure, and to reduce risk, the secondary mirror is mounted on a focus adjustment mechanism. The invar housing on which it is fastened contains a diaphragm flexure and a voice coil driver. The state-of-the-art calibration assembly consists of a calibration wheel which contains blackbody sources for the mid-infrared and long-wave infrared bands and lamp sources for visible, near-infrared, and short-wave infrared bands. These sources can be presented to the focal plane just before and just after each image. The front of the telescope contains an end-to-end calibration system consisting of an aperture blackbody source that is presented to the telescope and focal plane when the door is closed and a white painted surface that can be used for solar calibration.

The optical components are lightweighted. Eighty percent of the material is removed from the primary and tertiary blanks. This is done in a triangle pocket pattern which minimizes the structural compromise of the mirrors. The primary mirror, though over sixteen inches in diameter and two inches thick, weighs only a little over seven pounds.

The optical design of this telescope system was described in a previous paper by Ker-Li Shu and Tammy Henson². The optical design is shown in Figure 4. In order to minimize the number of components and the size of the system while maximizing field, fast high order aspherics are used. The primary mirror is an eighth order off-axis asphere which deviates from its best fit sphere by about 0.40 millimeters. The secondary mirror is a convex off-axis hyperboloid which deviates about a quarter of a millimeter from its best fit sphere. The tertiary mirror is a mild off-axis high order ellipsoid.

Figure 4. Optical layout of the TMA Telescope

The entrance pupil of this optical design is a few inches in front of the primary mirror. This limits the excursion of the instantaneous aperture on the primary despite the wide field coverage and therefore serves to restrict its size. The excursions of the instantaneous apertures on the secondary and tertiary mirrors are considerable.

Another salient feature of the design is the fact that the parent optics for the elements are coaxial. This is exploited for system alignment. During optical manufacture the entire optical train was assembled three times to provide a "sanity check" of the buildup of radius variations, off axis distances, etc. A technician could complete the alignment in a morning using sighting instruments which referenced the axis of the tertiary which was also, by design, the axis of the parents of the other optics.

Optical component alignment and test

The test configurations for the components are shown in Figure 5. The secondary was tested in the standard Hindle sphere configuration. It was figured as a seven inch diameter parent optic. A three inch diameter off-axis segment was then cored out. The final figure precision obtained was 0.025 waves RMS at 632.8 nm.

The tertiary mirror was tested at its center of curvature over its clear aperture using a commercial diffractive null lens. This device was manufactured using a MEBES machine and by means of diffraction, it creates an aberrated wavefront which fits the aberrated surface prescribed for the tertiary. A computer driven polishing process used this data to direct its efforts to finish the tertiary. It also was completed to 0.025 waves RMS error. The prescription fidelity of the optic was double checked by testing it at center of curvature without a null lens over the central eight

inches of the fourteen inch aperture. The amount of aberration expected over this area was calculated from the design. The test confirmed the prescription.

The primary mirror was manufactured as an off-axis optic since making a parent would have been very expensive and wasteful of material. The blank was ground to approximate figure using a computer driven grinding process which was guided with data from a WEGU profilometer. The WEGU profilometer is a commercial optical probe profiler which uses Heidenhein scales as a reference. It has a 1.1 meter capacity and is precise to about 0.5 microns RMS. It also provides, through precise sag measurements, the main control for radius of curvature for all the optical components. The computer driven polishing process was guided by testing at the center of curvature of the segment using a diffractive null lens and later by testing at focus in autocollimation using a diffractive null which made the segment look like a segment of an off-axis parabola (its nearest conic is actually a long conjugate ellipsoid). The final figure precision for the primary was 0.048 waves RMS.

Figure 5. Element Test Configuration

Telescope assembly, system alignment, and performance

The first task for the assembly was to obtain a final design for the system. This is a recomputation of the locations and spacings of the optics based on the actual as-built radii, off-axis distances, conic constants, etc.

A simplified layout of the alignment instrumentation is shown in Figure 6 together with the system parameters. Establishing the common axis is done by aligning a theodolite to the center of curvature of the tertiary and its vertex. The primary, secondary, and cold stop are then surveyed in and spaced with inside micrometers. This operation was performed several times during component manufacture to ensure that prescription variations were not all moving in the same direction rather than adding randomly. However during manufacture only the D band locations were monitored. The final assembly was interrogated over its full field and the alignment was fine-tuned to balance performance with the D band.

Since this is a three mirror system, the best solution for the performance (in the presence of data noise) over the field from a given set of field data can only be determined by an iterative process. A special alignment program was used to direct adjustment of each of the optical elements in six degrees of freedom to arrive at the optimal alignment. This typically converges to best alignment in two to three iterations. In this case two only were necessary.

The graphite structure was then placed between the optics (the optical components now had bipods epoxied to their edges) and epoxied to the bipods of the components. Detachment of the components from their external stands, removing the stands, and leaving the graphite structure as the only support produced the expected 20% degradation in wavefront performance.

Figure 6. System Alignment

The entire assembly was tested for stability at operating temperature in a cryogenic vacuum chamber. The test configuration is shown in Figure 7. A collimating lens projected a collimated beam into the system aperture which was retro-reflected by a focal plane simulator composed of precisely located ball bearings. The system was vacuum tested at ambient temperature, at operating temperature (0 degrees Fahrenheit), at survival temperature (-65 degrees Fahrenheit), and at operating temperature again. Before final acceptance the system was vibrated so as to simulate launch loads and was re-tested over its field.

Figure 7. Thermal Vacuum Test Configuration

Summary

A report has been presented on a state-of-the-art system which combines great versatility with economy of cost and resources. This lightweight optical system, achieved through the use of modern materials and efficient design, minimizes launch costs. The use of state-of-the-art methods and equipment together with computer-aided manufacturing and alignment methods minimize manufacturing time and cost.

This report has also shown how manufacture and alignment of a three mirror off-axis anastigmatic telescope takes place in practice. We hope that the readers will find encouragement that an alliance between government laboratories and industry can efficiently produce high quality products desired by the science community.

References

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