International Conference on Space Optics—ICSO 2018

Chania, Greece

9–12 October 2018

Edited by Zoran Sodnik, Nikos Karafolas, and Bruno Cugny

Common interface visible sensor

R. Shivitz

International Conference on Space Optics — ICSO 2018, edited by Zoran Sodnik,
Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 11180, 1118074 · © 2018 ESA
and CNES · CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2536175

Common Visible Sensor Instrument

R. Shivitz
Lockheed Martin Space, Optical Payload Center of Excellence,
1111 Lockheed Martin Way, Sunnyvale, CA 94089

ABSTRACT

The Lockheed Martin Optical Payload Center of Excellence (OPCoE) collaborated with government customers and leading companies in the aerospace and optics industries to field a space imaging instrument, achieving multi-spectral, wide field, high resolution imaging capability in a compact, lightweight, all reflective architecture. The heart of the instrument is an unobscured three mirror anastigmat collimator. The afocal design consists of a physical entrance pupil accepting a collimated input, an intrinsic internal focus and pupil, and in a compact folded geometry to achieve a balance between critical sampling, radiometric sensitivity, and field of view. Light-weighted, thermally stable materials and robust coatings coupled with low stress, thermal and dynamically stable optical mounts have demonstrated diffraction limited performance during test and over predicted mission conditions. Metrology features were made a central part of the optical component design to facilitate the use of spatial analysis tools and alignment techniques for merit function prescription optimization. The optical components are mounted to a composite egg crate bench, designed to reduce structural mass while ensuring rigid alignment of the optical components. Active thermal control reduces diurnal variations to the optical alignment and ensures stable optical performance. Design innovations include a filter wheel assembly designed to minimize exported force and torque and an internal radiometric calibrator based on high reliability light emitting diodes for focal plane gain calibration. The instrument currently hosts a large format staring focal plane for wide field imaging, but the flexibility of the design can accommodate various sensor packages.

Keywords: Visible, Imager, Calibration, Phase Retrieval

1. INTRODUCTION

Lockheed Martin Space capabilities are focused on developing detailed system models, performing physics-based aerospace system assessments, multi-tier and relational databases, information extraction and automated tools to customers. For more than 60 years Lockheed Martin Space has delivered enabling space system technology including advanced materials, thermal systems, control systems, RF and. The top priority of these organizations is to provide technology discriminators and design capabilities to the space systems lines of business (LOB): Military Space, Special Programs, Strategic & Missile Defense Systems, Civil Space, and Commercial Ventures. Figure 1 highlights the variety of communication, navigation and space science and exploration satellites built throughout the years. At the forefront of these activities, and relevant to this paper, are the Advanced Technology Center (ATC) and Optical Payload Center of Excellence (OPCoE) who deliver precision electro-optical imaging systems. Recent additions are the Mars Reconnaissance Orbiter (mapping the red planet's surface), the Interface Region Imaging Spectrograph (IRIS), James Webb Space Telescope Near Infrared Camera (NIRCam), the Solar Ultra-Violet Imager (SUVI) and the GOES Geostationary Lightning Mapper (GLM) (Figure 1).

2. VISIBLE SENSOR INSTRUMENT

Building on the long history of successful optical instrument programs, OPCoE set out to design and flight qualify a design in partnership with a government customer. The goal of this effort was to develop a robust architecture that achieves state of the art optical performance while reducing development and fabrication time. The Visible Sensor Instrument (VSI) is the first of this class of optical payloads; taking advantage of heritage component designs, advanced modeling and analysis tools, and a mixture of traditional and cutting-edge alignment techniques. The result is an instrument that significantly reduced cycle time from concept to delivery and forms the basis of a common architecture for hosting optical sensors for earth and space imaging missions. In the following sections we will describe the key components, relevant performance and approaches used in the development of the Visible Sensor Instrument (VSI, Figure 2).

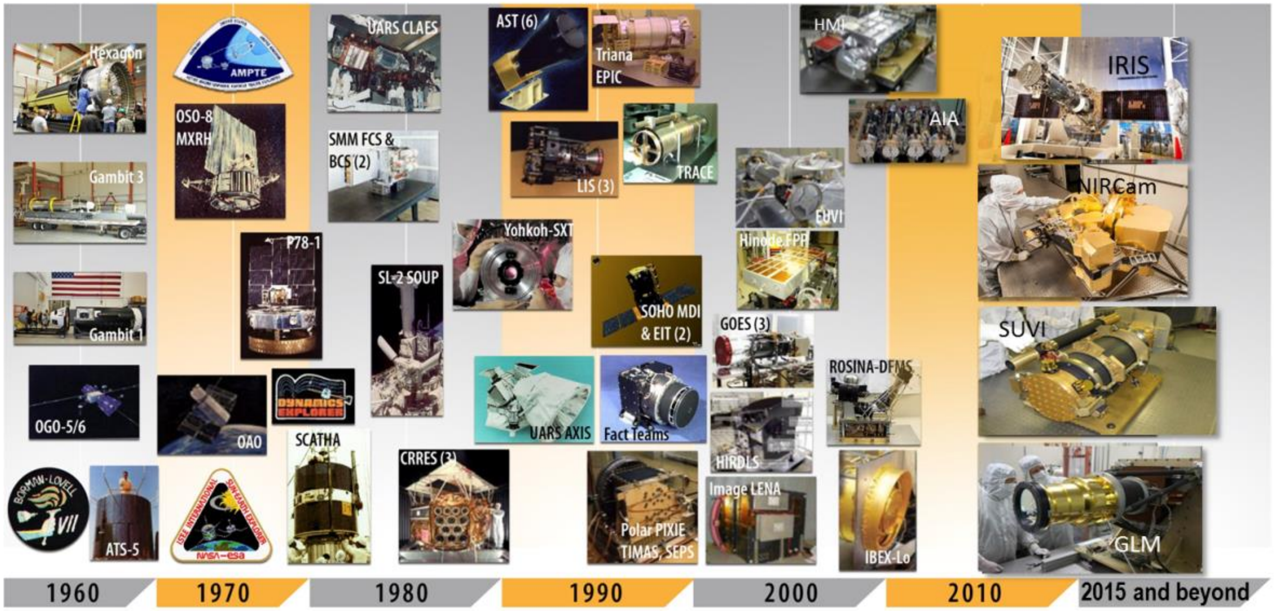

Figure 1. Lockheed Martin Space experience spans multiple mission Applications and has delivered >100 optical payloads across the entire optical spectrum

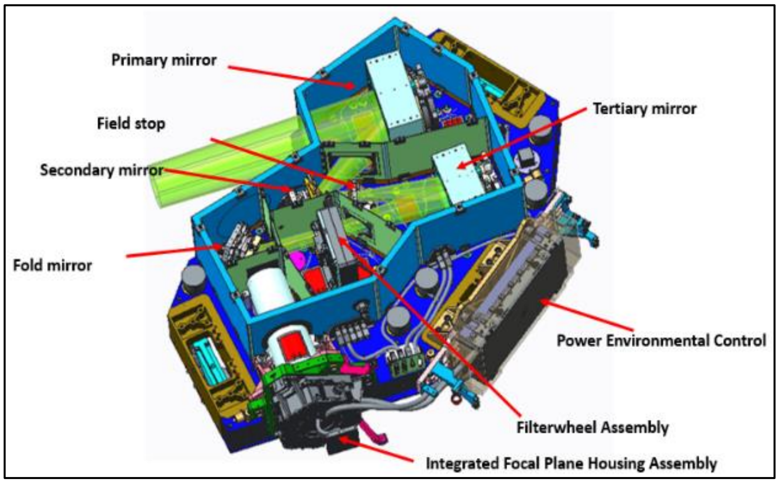

Figure 2. VSI Design

2.1. Instrument Functions

The VSI point design is a camera system consisting of a Wide Field optical collector mated to a large format staring focal plane array. Collimated light enters the VSI entrance aperture and is processed by an unobscured collimator consisting of a primary mirror (PM), a secondary Mirror (SM), a Field Stop, and a Tertiary Mirror (TM) before passing through a Filter Wheel Assembly (FWA). At the exit of the filter wheel, surrounding the exit aperture, is a Calibration Source Assembly (CSA). This assembly injects narrowband, radiometrically stable light into the optical path of the sensor for sensor gain and offset calibration. In between the CSA/FWA assembly and the focal plane a fold mirror has been inserted for efficient packaging. Light passes through a series of stray light control baffles and is incident upon the integrated focal plane. The focal plane housing is primarily constructed of titanium with integrated tungsten shielding and the assembly is cooled by a thermal strap that ties to host level radiators. A control electronics box for the focal plane is also mounted to and thermally isolated from the bench assembly. The optical design of the instrument is discussed in Section 3.2.

In addition to the pieces that are directly related to guiding light through the instrument, several other components make up the VSI. A composite optical bench serves as the backbone structure for the instrument and is described in Section 3.3. Baffles, enclosed spaces and a radiation shield provide stray light control to the entrance aperture of the sensor and have been incorporated into the structural design. Thermal management for the VSI is achieved by passive blanketing and active zone-based heater control. Thermal control is critical to maintain the instrument optical performance during flight operations.

2.2. Optical Design

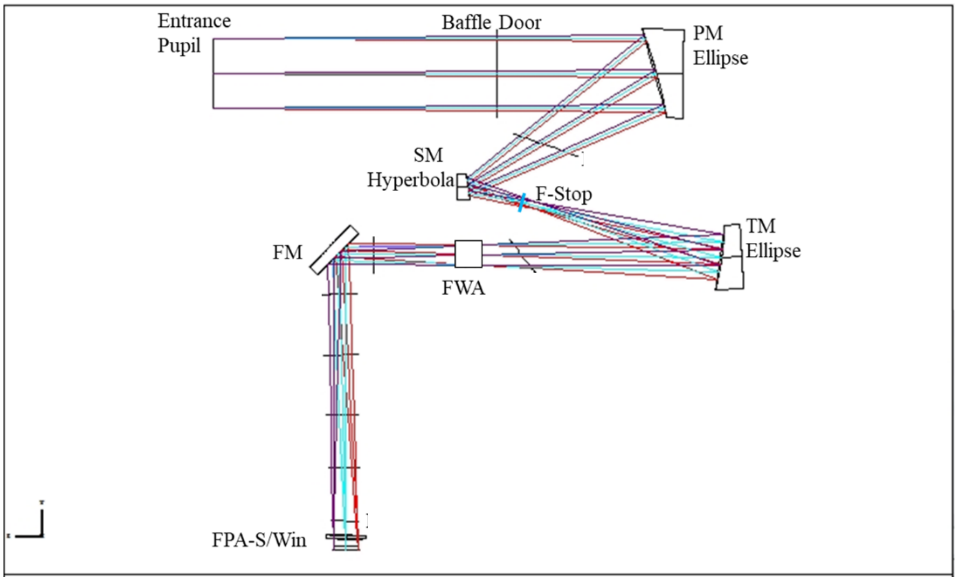

Figure 3. VSI Optical Design

The VSI optical collimator design is a three-mirror anastigmat developed using Zemax. Sensitivity analysis was performed, and the prescription optimized, with input from Opto-Mechanical, Assembly/Integration/Test, and Structural teams to arrive at a solution balancing mission requirements and manufacturability. Key optical performance metrics for the design include:

- Fully Corrected Wide Field: 25 (mR)
- Mission Working F/#: 22
- Wavelength: 400 – 950 (nm)
- Design Residual RMS Wavefront Error: < 11.7 (nm)
- Total WFE Budget: 41 nm (including mounting, alignment, environments)
- Input Alignment Tolerances: 5 (mm) decenter, 1 (mR) boresight, collimated input

Reflective surfaces were fabricated by Tinsley Custom Optics, a division of Coherent Inc. Mirrors are constructed of monolithic Zerodur glass and the substrates have been light-weighted and figured to achieve the desired optical and structural performance. During surface shaping, metrology features were polished into the substrates and referenced to the optical prescription. The inclusion of these features in the design aids in precision placement of the optical surfaces during alignment. The VSI mirrors employ FSS-99 silver coatings applied by Quantum Coating Inc. to achieve high throughput across the specified spectral bandpass.

Mirror mounts are an evolution of designs previously built and successfully flown on IRIS, a Lockheed Martin Solar and Astrophysics Research Lab instrument. The mount designs are customized to each mirror to provide structural stability over launch and thermal conditions. Bipod based opto-mechanical systems have come to represent the state of the art in the optics industry where very stable and alignment critical mounting is required. Tuned titanium blade flexure bipods are adjoined to invar bond pads, which have been adhered to the sides of the mirror substrate. The bipods are mounted to flexured titanium bases designed to deliver six degree of freedom positioning during integration and alignment which can then be locked out to provide kinematic stability (a representative mount is shown in Figure 4)

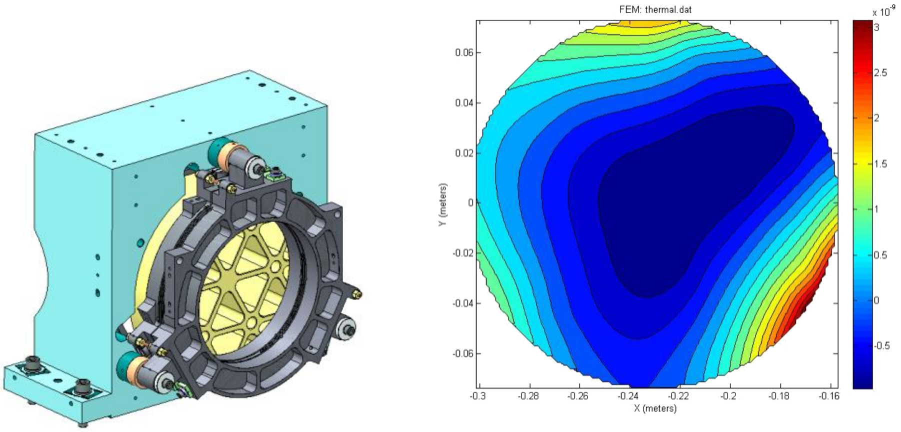

Figure 4. Representative Optical Mount Assembly and FEM Thermal Stress (0.75 nm RMS per degree C)

2.3. Structural Design

Figure 5 depicts the layout of the VSI Bench Assembly (VBA) and its mounted components.

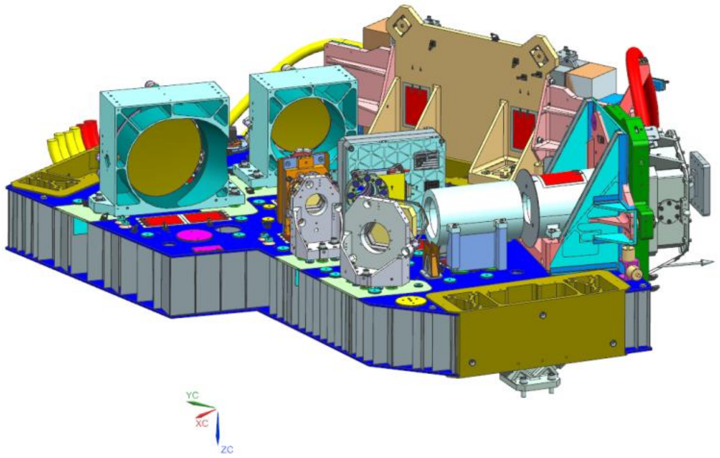

Figure 5. Visible Sensor Instrument structures with Enclosure and Baffles hidden

The VBA was contracted from Alliance Spacesystems Inc. and is primarily composed of 180 mil, thick M55J-RS3C facesheets adjoined to a 30 mil M55J-RS3C core arranged in an egg crate lattice structure. The M55J-RS3C composite/resin system has been used by Lockheed Martin on many previous space missions. Density of the core lattice varies between 1” by 1”, 1” by 2” or 2” by 2” depending on location and required structural rigidity. The composite bench is mounted to the host interface by three titanium bipods, attached to the composite facesheets via bonded titanium brackets. This type of bipod construction is commonly used when the desire is to semi-kinematically mount a large optical structure to a space craft payload. Bench mounted components are bolted to titanium inserts that are bonded to the composite bench structure at the top facesheet. Most components are mounted via three inserts arranged in a triangular pattern. Clips were used to join the facesheets to the core on the outer perimeter and at critical insert locations in the interior. The result is a light weight but structurally stiff structure for mounting critically aligned components. Designs were first evaluated using NASTRAN and ABAQUS Finite Element analysis tools with subsequent performance verified during thermal environments and launch load static and dynamic random vibration proto-qualification tests.

2.4. Filter Wheel Assembly

The FWA (Figure 6) and FWA motor designs draw their heritage from designs that have flown on another Lockheed Martin Solar and Astrophysics Research Lab instrument, SUVI. The overall design of the wheel bearings, housing, and encoder read heads are similar between the two systems, with the performance of the VSI FWA enhanced to improve the switching performance and positioning resolution and to add redundancy in the encoders and stator windings. The linear motor and control system is designed to minimize exported force and torque from wheel motion, allowing the optical system to maintain stable alignment without active compensation or significant settle time.

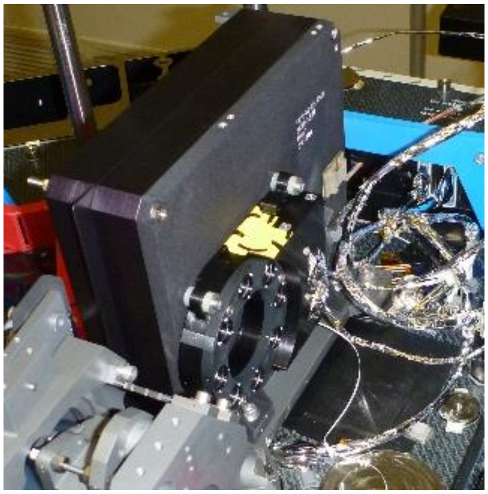

Figure 6. FWA and CSA Assemblies

2.5. Calibration Source Assembly

The use of diodes for calibration is not new to the industry, but the CSA was designed specifically to meet the stability and dynamic range requirements of this point design mission. It serves to inject radiometric and temporally stable 810nm light into the focal plane array. The CSA consists of four sets of four LEDs. A primary set of four unattenuated LEDs, a primary set of attenuated LEDs, a redundant set of four unattenuated LEDs, and a redundant set of four attenuated LEDs. The LEDs are an aerospace qualified variant of commercial diodes from Optodiode, radiation lot acceptance tested (RLAT) and screened for output uniformity. Radiometric output covers three decades of dynamic range with performance monitored by integral thermistor and active current control.

2.6. Thermal Control

VSI thermal control is achieved with both passive and active control systems. To maintain the overall bench temperature while limiting spatial gradients, heaters are applied to the bench surface inside the enclosure as well as the mounted sensor interfaces. Kapton patch heaters were placed in a zonal configuration, with the zones and heater density based on detailed thermal/structural simulation of optical performance. Blankets (aluminized Mylar inner, outer and interior layers separated by layers of Dacron netting) cover the entire exterior of the bench and enclosure as well as the focal plane detector. The focal plane control electronics box exterior is uncovered to allow for radiative cooling while a flexure interface to the bench mounting bracket minimizes thermal distortion.

3. OPTICAL ALIGNMENT

The alignment techniques applied to the VSI optical system rely on accurate knowledge of the wave front error through the system over the field. A three-tiered process was developed to integrate and align the optical system; involving precision metrology for initial component placement, interferometric feedback for prescription optimization, and a method of phase retrieval to verify end to end performance once the focal plane was installed.

As previously described, each mirror assembly included prescription referenced optical surfaces. During post polish figure verification each control surface was measured relative to the optical gut ray and the orientation of each was added to the optical model. Exploiting this accurate information, we surveyed the relationship between the reference surfaces/features and the metrology fixtures to obtain a high-fidelity transformation between the fixtures and optical surfaces. By combining in Zemax the prescribed location of each surface with the as measured metrology reference features, each component could be physically placed using standard optical measurement tools such as alignment telescopes, theodolites, and laser tracker systems independently and without nulling optics. Additional optical metrology fixtures were temporarily attached to the flight mirrors and bench, and then removed after the alignment is complete. To facilitate this precise manipulation, mechanical actuators and alignment guides were temporarily attached to the flight mirrors and removed after the alignment is complete. This approach allowed initial component alignment to less than 0.100 mm translation and less than 1 arc min angular.

Following initial component placement, prior to installation of the focal plane, interferometric techniques were employed to obtain optical beam train wavefront error. A customized commercial Zygo Fizeau interferometer was used to interrogate the optical path, from the entrance pupil to the spatial location of the sensor focal plane. A retroreflecting spherical mirror, optically referenced to locate it in space for model correlation, was used to form the double pass cavity. Wavefront error for the double passed system was decomposed into Zernike terms and incorporated back into the Zemax model, which was then reoptimized using merit function based global optimization to determine delta positioning of the optical components. This approach allowed rapid convergence of the optical solution and the repositioning to be constrained to specific components and degrees of freedom. At the conclusion of this phase of the alignment the optical assemblies were locked down and the focal plane installed.

Final end-to-end optical alignment of the focal plane was verified using Phase Diverse Phase Retrieval. An interrogation optical beam was projected into the VSI entrance aperture and directed along the optical boresight and to specific field points on the focal plane. A series of precise defocuses were recorded at each point to obtain field dependent wavefront error. This approach allowed full system performance measurement and was used at the conclusion of assembly to confirm alignment and following environmental qualification testing.

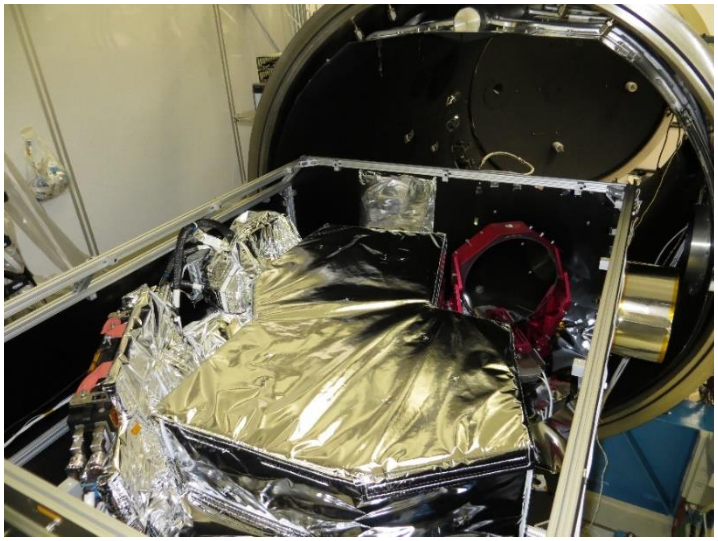

Figure 7. VSI Thermal Vacuum Test

The VSI was subjected to thermal vacuum temperature cycling (Figure 7 depicts the instrument test configuration) and launch vibration environments to qualify the instrument for flight. In-situ phase retrieval measurement during thermal vacuum verified that minimal optical alignment drift occurred due to dry out or inelastic relaxation due to thermal stress. Following thermal vacuum testing, adhesive was applied to the lockouts of the optical components, permanently fixing the alignment state of the instrument. The VSI was then subjected to three axis sinusoidal and random mechanical spectrums, with the optical performance once again verified post-test. With the completion of environmental testing and performance verification, the VSI has been certified as flight worthy and has delivered to its host for system integration.

4. CONCLUSION

OPCoE has designed, built and flight qualified a new optical instrument design, which has been delivered for final integration to the host payload. The VSI program achieved a robust architecture for state of the art optical instruments and developed processes that demonstrated reduced design and fabrication cycles. The Visible Sensor Instrument is expected to be the first of this class of optical payloads and as the basis of design for future missions and customers.