

Design and Validation of a Compact Dual-Channel VIS–UV Telescope for Stellar Photometric Monitoring

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ABSTRACT

PhotSat, the first astrophysical satellite fully developed by the Institute of Space Studies of Catalonia (IEEC) and the Catalan space industry, is a dual-channel Visible (VIS) and Ultraviolet (UV) telescope for wide-field stellar monitoring. Designed for continuous observation of the 10 million brightest stars over a mission lifetime of at least two years, the payload comprises two independent telescopes integrated within a common structure and equipped with siderostat mirrors for efficient sky scanning without spacecraft slewing. The VIS channel (500–840 nm) employs an eight-lens, highly telecentric optical design optimized for filtered focal-plane imaging, while the UV channel (240–315 nm) uses a nine-element configuration focused on maximizing throughput and minimizing distortion. Both systems achieve high image quality across a wide field of view and are passively athermalized between 0 and +40°C. Optical analyses and preliminary integration results confirm compliance with mission performance requirements.

Keywords: optical design, small satellites, wide-field imaging, space instrumentation

1. INTRODUCTION

An increasing interest in compact, high-performance space instruments for wide-field stellar monitoring has led to the development of a dual-channel telescope operating in the Visible (VIS) and Ultraviolet (UV) spectral ranges for the PhotSat mission, the first astrophysical satellite developed from design to operations by the Institute of Space Studies of Catalonia (IEEC) and the Catalan industrial ecosystem. The mission's multi-band observations will provide valuable datasets for a broad range of scientific programmes, including the search for exoplanets, characterisation of stars, and the observation of transient phenomena, among many others.

The spacecraft uses a scanning observation strategy based on a rotating mirror system to repeatedly sample nearly the entire sky with a characteristic revisit cadence of approximately two days. Over its nominal mission duration of at least two years, this observing scheme is expected to generate densely sampled light curves for on the order of 10 million of the brightest stars [1]. This paper presents the optical design, performance validation, and preliminary integration results of the two optical systems.

2. SYSTEM OVERVIEW

The telescope comprises two independent optical assemblies with custom optics and a commercial detector. The optics have been designed, assembled and validated by ASENSE in Barcelona, Spain, and are mounted in a common structural frame to ensure mechanical and thermal consistency. The VIS channel covers 500 nm to 840 nm, while the UV channel spans 240 nm to 315 nm. Both systems employ the same sensor model, a 2048x2048 CMOS with 6.5 μm pixels, and they both have a small aperture under 70 mm but a large field of view around 8 degrees.

Each telescope is equipped with a siderostat, a rotating flat mirror mechanism at the entrance of each telescope that scans great circle strips across the sky while the satellite maintains rigid pointing during orbits. By rotating the mirror, light is directed from different sky regions into the fixed telescopes, enabling efficient mapping without needing to slew the entire satellite.

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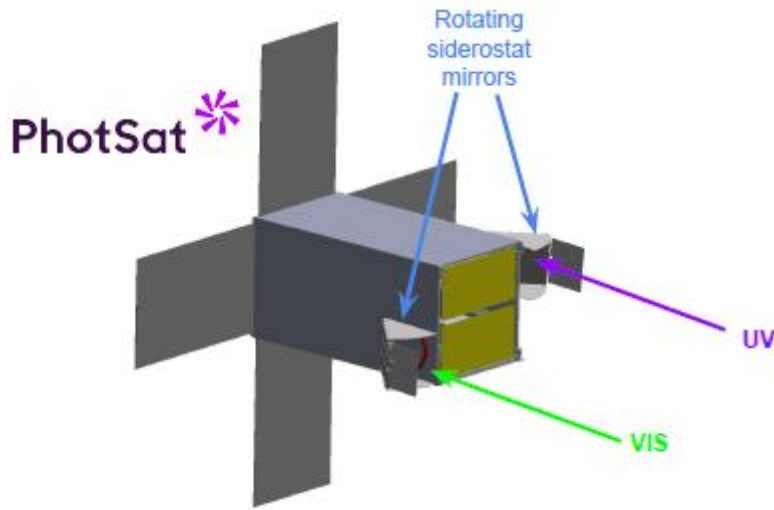


Figure 1. Satellite configuration including siderostat and optical assemblies

3. OPTICAL DESIGN

VIS Channel Optical Design

The VIS optical system (Figure 2) is a compact eight-lens system, a 95 mm focal length and a nominal f/n of 1.6. The main design constraints were mass and total track length limitations, while concerns regarding thermal stress precluded the use of bonded optics, necessitating the use of two aspheric surfaces to achieve the desired optical quality. The detector is equipped with spectral filters arranged in a chessboard-like pattern with four quadrants, transmitting either the full (wide, 500-840 nm) spectral range, or a narrower (red, 670-840 nm) band. The image telecentricity is constrained to a maximum nominal chief ray angle of 1.5°, compliant with the $<2^\circ$ requirement mandated by the spectral filters. The materials and power of the lenses are selected to optically athermalize the objective over the operational temperature range of 0 to +40°C. Across the temperature and pressure range, the nominal EFL (and f/n) variation is under 0.15%.

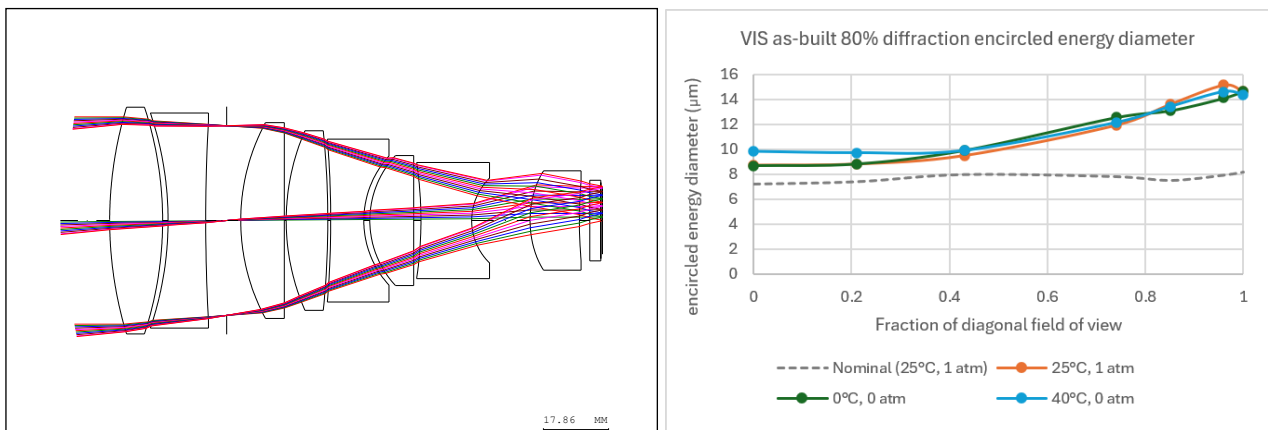


Figure 2. VIS Channel Optical Design. (Left) Optical layout including filter and sensor window. (Right) As-built 80% diffraction encircled energy diameter across different environmental conditions, compared to the nominal performance under laboratory conditions.

The tolerance budget used to simulate as-built performance considers lenses manufacturing errors and tolerances assigned to the mechanical parts, as well as the detailed assembly procedure. The final design achieves an as-built polychromatic diffraction encircled energy diameter for 80% energy of under 13 μm over the central 80% of the field of

view, and under 20 μm over the entire field (Figure 2). Distortion is less than 1.5% throughout the field of view for an f $\tan$ projection, which means that the object FOV that corresponds to the detector FPA is 7.89° x 7.89° (11.16° diagonal).

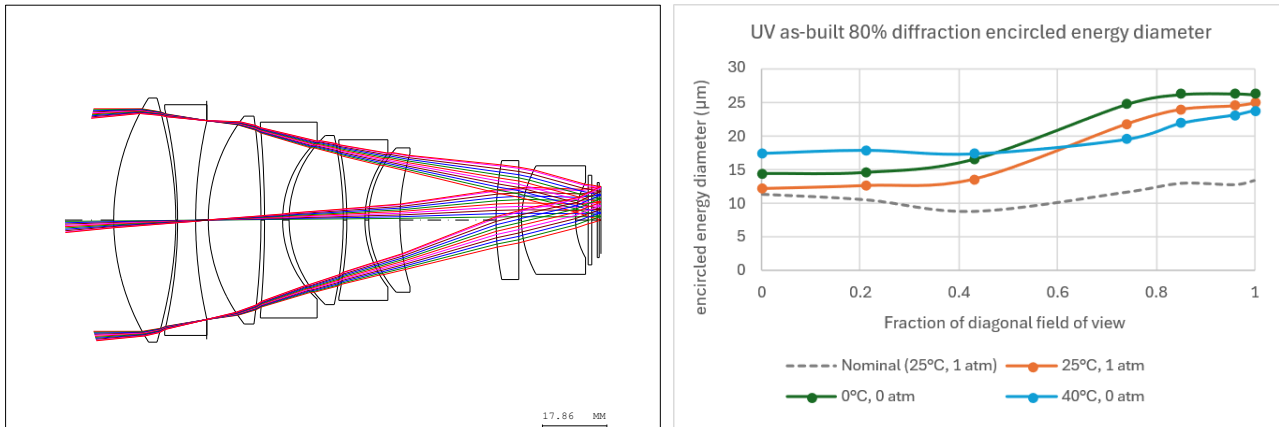


Figure 3. UV Channel Optical Design. (Left) Optical layout including filter and sensor window. (Right) As-built 80% diffraction encircled energy diameter across different environmental conditions, compared to nominal performance under laboratory conditions.

Regarding transmission, including bulk absorption of the glass components, lens AR coatings and filter transmission in each waveband, total system transmission is greater than 90% at any operational wavelength, excluding the sensor and siderostat mirror performance. Relative illumination is >93.8% for the diagonal image point.

UV Channel Optical Design

The UV system (Figure 3) employs a nine-element layout with only two aspheric surfaces, optimized for high throughput and low distortion, a nominal effective focal length of 94.8 mm and a f/n of 1.54 in laboratory conditions. The system is passively mechanically athermalised between 0 and +40°C (see more details on mechanical athermalisation in Section 4). Distortion is less than 0.5% throughout the field of view for an f $\tan$ projection, which means that the object FOV that corresponds to the detector FPA is 8.03° x 8.03° (11.36° diagonal). The maximum nominal chief ray angle at the image is 9.5°, and across the temperature and pressure range, the nominal EFL (and f/n) variation is limited to 0.64%.

The as-built polychromatic diffraction encircled energy diameter considers the lenses manufacturing errors and tolerances assigned to the mechanical parts, as well as the detailed assembly procedure. The polychromatic 80% diffraction encircled energy diameter is within 26 μm for sampled field points for 80% of the diagonal field of view, and within 30 μm for sampled field points up to 100% of the diagonal field of view (Figure 3).

The spectral range from 240 nm to 315 nm is achieved via the selection of UV-transmitting glasses, namely calcium fluoride and UV-grade fused silica, which are both naturally radiation resistant glasses suitable for applications in space [2], as well as the transmission from the siderostat mirror to the UV sensor, including UV AR coating on the lenses and a spectral filter blocking up to 1000 nm. Transmission is greater than 40% between 250-310nm and 50% between 259-309nm, excluding the sensor and siderostat mirror performance but including glasses internal transmission, lens AR coatings, and filter and sensor window transmission. The main limitation for this transmission is the spectral filter, which needs to simultaneously cover the desired spectral range and block as far as possible into the IR. The chosen filter (XUV0310) has a blocking specification up to 1000 nm, but severely limits system transmission at lower wavelengths with its 52% transmission at 250nm. The relative illumination of the optical system is >99.5% for the diagonal image point.

4. MECHANICAL AND THERMAL IMPLEMENTATION

Optomechanical design and material selection

The individual lenses are individually bonded to subcells using low-outgassing RTV566 adhesive, and the lens subcells are precisely machined in order to achieve tight alignments in lens tilt, centration, and airgap. Both systems include an internal XY alignment compensator that is adjusted during assembly to correct residual decentering errors and restore nominal optical performance. The subcells are assembled onto an external barrel and held by a closing ring threaded into

the external barrel to lock in the subcells. The machined parts are made of Aluminium 6061 with good resistance and low weight, whose wall thicknesses are defined to reduce the loads effects induced during launch. Venting holes are used to connect cavities avoiding air traps while preventing external light going into the lenses. Including individual component mass uncertainty and an additional system margin, the total mass of the systems is 1.7 kg for the VIS and 1.8 kg for the UV.

The VIS system is passively athermalised by directly balancing lens refractive index variation and the lens and mechanical thermal expansion with temperature with the glass lenses and the aluminium cells and barrels. Since the glasses available at lower wavelength ranges are much more limited, the UV system requires a more sophisticated athermalisation strategy: the optical shift in focus position depending on the temperature is offset by using a hollow cylinder made of the high-CTE material Windform XT 2.0 (Figure 4), whose thermal expansion pushes away and pulls closer the lens barrel with increases and decreases in temperature respectively.

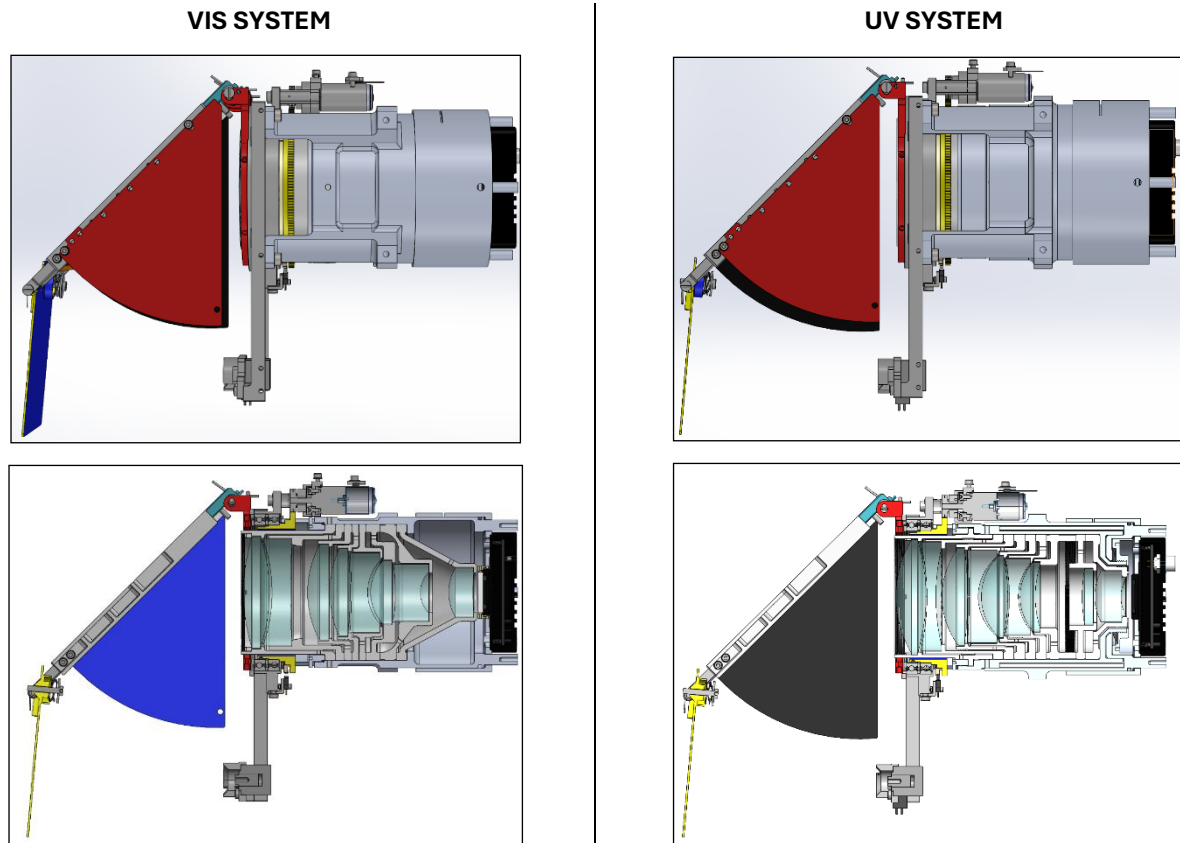


Figure 4. Optomechanical subsystems, with siderostat deployed – top is an external view, bottom is a section view. (Left) VIS system. (Right) UV system, showing the high-CTE cylinder along the optical barrel that adjusts the back focal length to provide passive athermalisation.

The system that enables the rapid observation of these telescopes is the siderostat, which uses a double ball bearing, gears and stepper motors to rotate the mirrors and change the observed field of view. The zero-lever-arm deployment ensures it remains compact during launch and deploys to conduct science operations once separated from the launch vehicle, thus complying with the tight volume requirements of a CubeSat mission. Both optics interface with the double bearing housing element of the siderostat via four screws.

The detectors interface with the optical barrel via an intermediate barrel which is fixed with respect to the detector, and that allows lens focusing by rotating a removable eccentric key; a clamp is used to secure both pieces together after fine alignment. Additionally, both systems interface with a thermal strap connected to a copper piece for heat dissipation.

Finite element analysis

The telescope was evaluated using a finite element model representing the primary structural components and interfaces. Non-critical features were simplified to reduce computational effort while preserving global stiffness. Material properties, boundary conditions, and interface constraints were defined to represent the operational configuration. A modal analysis was performed to verify the telescopes' dynamic response. The first natural frequency of the VIS system was 216 Hz, while for the UV system it was 160 Hz. All predicted frequencies exceeded the required minimum of 150 Hz.

Sine and random vibration analyses have been performed and show positive margins in all the assembly components. With respect to the shock loads, the analyses show positive margins in all the mechanical and optical parts. The adhesive initially showed negative margins for the VIS system under the originally defined shock loads, and thus a shock input analysis was performed to determine the attenuation of the shock load transmitted to the payload interface. This demonstrated that the shock environment experienced by the payload is significantly attenuated through the structure, thus justifying a reduced input level. Bolt verification analysis has been performed for the sine, random and shock loads, equally concluding in positive margins of safety for all bolts in both systems.

5. STRAYLIGHT ANALYSIS

The straylight performance was analysed using Ansys Zemax OpticStudio non-sequential mode. As the main mitigation strategy, the internal parts of the aluminium mechanical parts of the system have been designed to be highly scattering and absorbing by the application of a black anodization treatment. Additionally, all lens surfaces include anti-reflective coatings, while the non-optical surfaces of the lenses are either grounded or mechanically blocked when possible.

Three sets of fields were modelled, front, side, and back with respect to the orientation to the siderostat mirror (Figure 5), each sampling from -80° to $+80^\circ$ with sampling steps defined based on a reverse raytrace from the detector, in order to identify the angles at which light that reaches the detector enters the system. Regarding the side and back fields, the siderostat mirror, shaders, and top lid restrict ray entry, forcing either multiple scattering events before transmission through L1, or highly oblique incidence, both of which reduce stray light through scattering and absorption. These paths therefore produced negligible detector ray hits, and no sampled field generated a detector pattern.

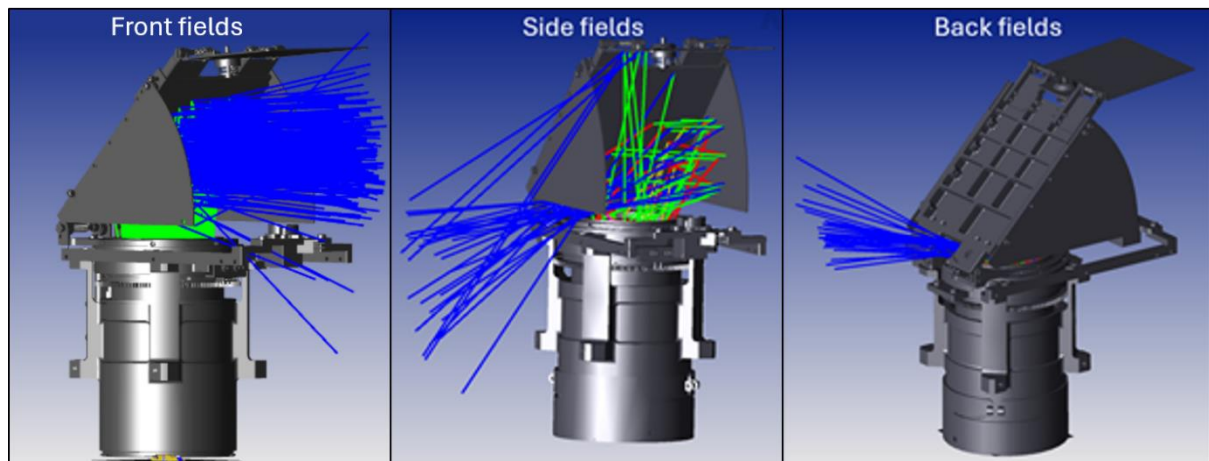


Figure 5. Straylight raytracing paths, where the side and back fields generate negligible rays on detector due to geometrical blocking. (Left) Front fields. (Center) Side fields (Right) Back fields.

Regarding the VIS system, all critical straylight paths identified have irradiances at least 8 orders of magnitude below the signal, with the main contributions shown in Figure 6. Path #1 corresponds to filter ghosts, with irradiance peaking at an object angle of 0° , where the ghosts overlap at the sensor center. Path #2 arises from reflection off the L7 subcell after transmission through the L7 right surface, producing an arc on the sensor with a maximum irradiance at $+8^\circ$. Path #3 results from reflection of the L8 subcell between L7 and L8, producing an arc with peak irradiance also at $+8^\circ$.

Regarding the UV system, all paths at least 6 orders of magnitudes below the signal irradiance. Pictured are the highest irradiance paths, namely path #1 corresponds to ghosts off the sensor window for fields within the FOV, and path #2 corresponds to multiple paths that involve scatter of the ground side surface of L9, maximised for an angle of $\pm 8^\circ$.

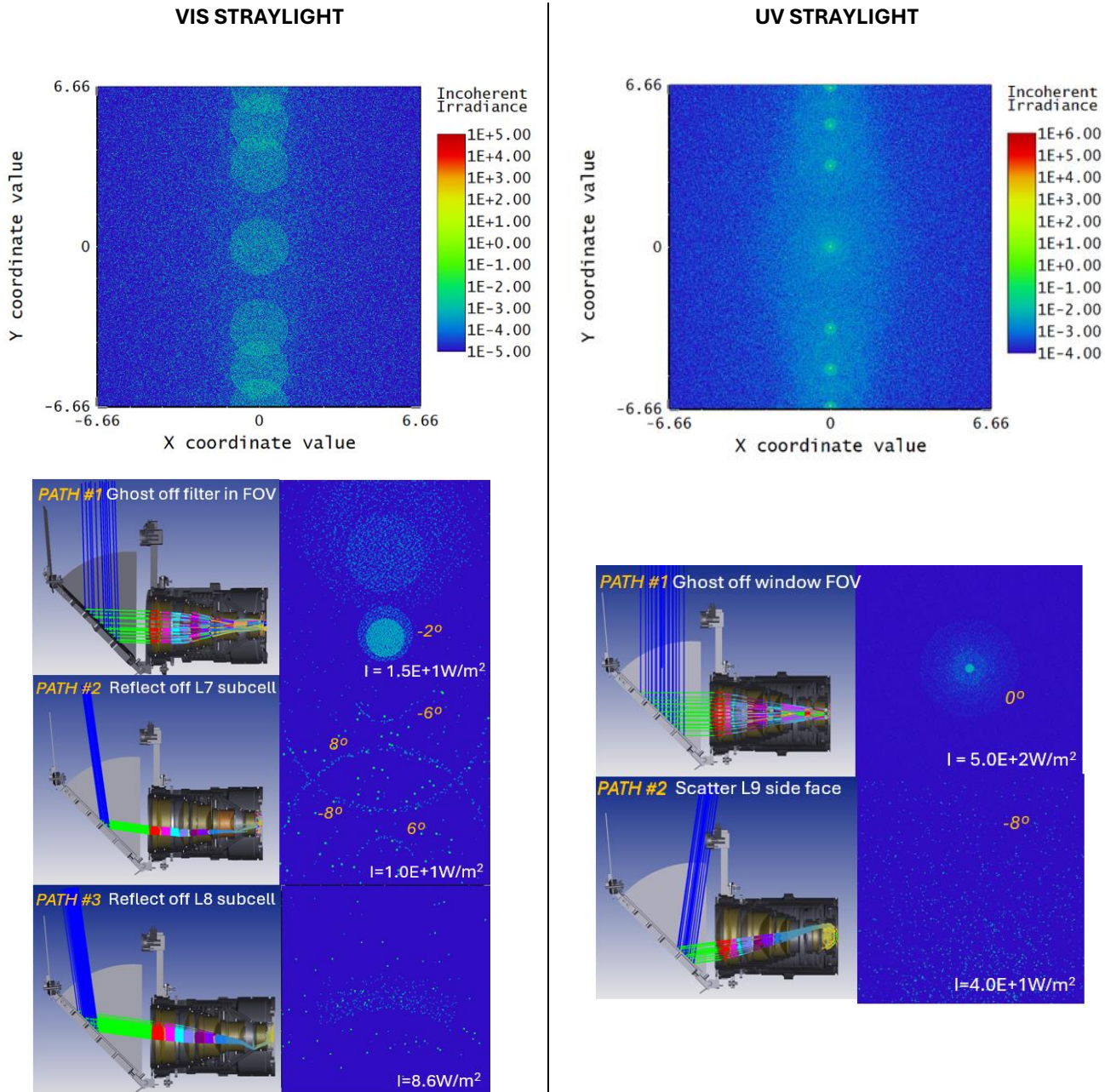


Figure 6. Straylight analysis. (Left) VIS system, with direct raytrace results on top and main irradiance paths in the bottom. (Right) UV system, with direct raytrace results on top and main irradiance paths in the bottom

6. MANUFACTURING AND VERIFICATION

An engineering model of the two subsystems has been manufactured. The designed lenses have been manufactured by suppliers with significant heritage for space flight coatings, particularly for lower-Earth orbits, and the AR coatings employed on the first lenses are formulated to be resilient to the effects of atomic oxygen and gamma radiation. Bonding

the individual lenses to their subcells, and subsequent alignment turning of the cells, has been successfully implemented to reach high precision positioning tolerances within each lens barrel.



Figure 7. Assembled optical subsystems. (Left) VIS channel. (Right) UV channel.

VIS Channel Optical Validation

The optical quality of the VIS channel has been verified using a commercial instrument for high-precision MTF testing, the ImageMaster HR from Trioptics. Using the MTF results, the 80% diffraction encircled energy has been calculated by using linear regression equations from as-built (Monte Carlo) analysis of the system, in which the relationship between diffraction encircled energy and MTF contrast at 38 lp/mm was determined for several field points. As shown in Figure 8, the resulting 80% encircled energy diameters are below 20 μm over the entire field of view. Other parameters that have been experimentally validated are a maximum distortion of 1.2% at the edge of the field of view, a maximum chief ray angle across the field below 2° , an entrance pupil diameter of 58.1 mm and an effective focal length of 95.7 mm, all in agreement with the optical design and compliance of the system-level requirements.

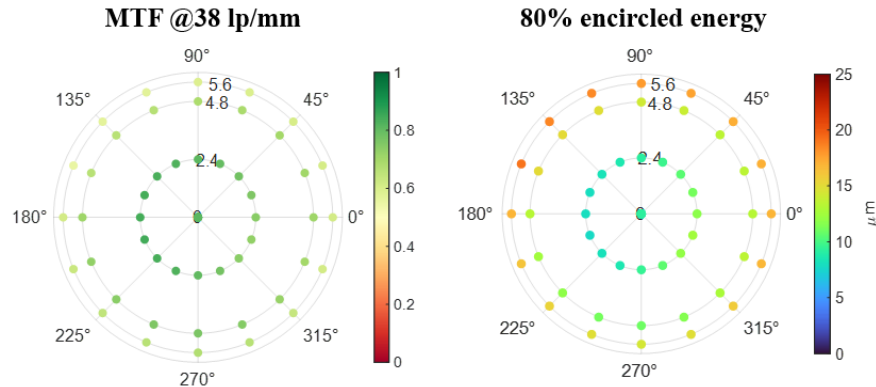


Figure 8. Optical Validation of VIS channel. (Left) MTF contrast at a frequency of 38 lp/mm as a function of radial and azimuthal fields, with contrasts between 50% and 90%. (Right) 80% encircled energy diameter as a function of radial and azimuthal fields in units of micrometers.

VIS Channel Environmental Testing

An engineering model using representative lenses was subjected to vibration testing to de-risk the mechanical design. The similarity of the mechanical design of the UV and VIS meant that this test was able to provide confidence for the final design of both units.

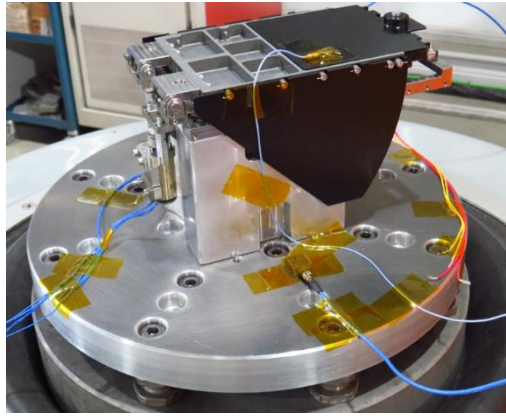


Figure 9. Optical Engineering model mounted on vibration plate, with siderostat mounted on top in stowed position as per launch configuration.

The optical system underwent environmental validation through vibration testing using a shaker table in accordance with simulated enveloped vibration loads considering a range of launch vehicles. Although this likely subjected the engineering model to higher loads than those expected during the launch of the flight model, it provided significant additional confidence in the robustness of the design. The applied vibration profile included low-level sine resonance searches, sine vibration, quasistatic sine burst, and random vibration tests conducted along all three orthogonal axes. Environmental testing demonstrated that the objective maintained its structural integrity under all specified environmental conditions. Post-test optical characterization showed only minor changes, with a 1–2 μm increase in the 80% encircled energy diameter at several field positions after vibration testing, causing 6 of 56 measured fields to fall outside the desired specification of $<13\ \mu\text{m}$ in the center of the field and $<20\ \mu\text{m}$ off axis, while telecentricity, distortion, and focal length remained within requirements. Full compliance was restored by readjusting the internal lateral compensator of the system, indicating that the observed degradation was caused by a small lens-cell displacement within the barrel, estimated to be well below the lens alignment tolerance ($<20\ \mu\text{m}$).

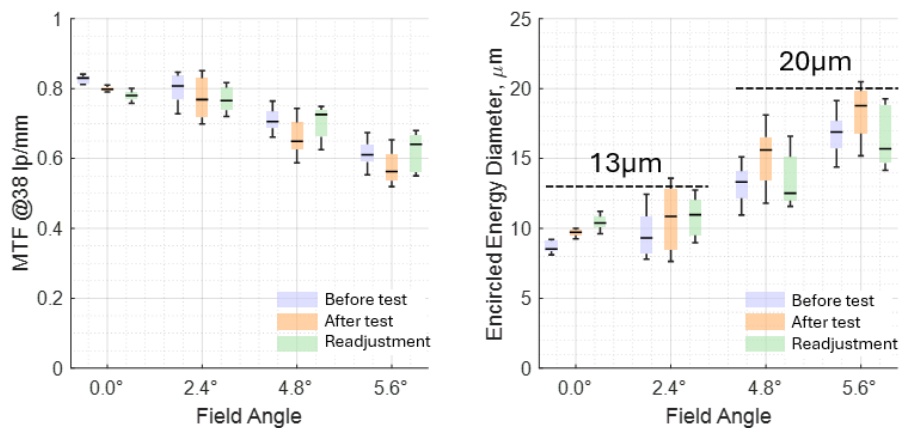


Figure 10. Environmental Validation of VIS channel. (Left) MTF contrast at a frequency of 38 lp/mm as a function of radial fields, as average and standard deviation across the azimuthal fields, with contrasts between 50% and 90%. (Right) 80% encircled energy diameter as a function of radial fields, in units of micrometers, as average and standard deviation across the azimuthal fields.

The vibration tests confirmed the validity of the design, with the observed sub-20 μm lens-cell displacement mitigated for subsequent flight model manufacturing through improved machining tolerances and assembly preload, without requiring any hardware modifications.

UV Channel Optical Validation

The optical quality of the UV channel has been verified on a custom characterisation bench, using a commercial wavefront sensor (SID4 UV HR, Phasics) in a double-pass configuration. The system is illuminated with a collimated

266 nm solid state source, and a high-NA, high-surface-quality mirror is used to return the beam from the focal plane back through the system. The wavefront error introduced by the system is measured by reimaging the entrance pupil of the telescope onto the sensor, by using a 10x refractive telescope whose performance has been separately characterized. The encircled diameter for a given energy level is then returned by the sensors' own software. The results along the diagonal fields of the system, as shown in Figure 11, are below 25 μm over the entire field of view, in agreement with the optical design and compliance of the system-level requirements.

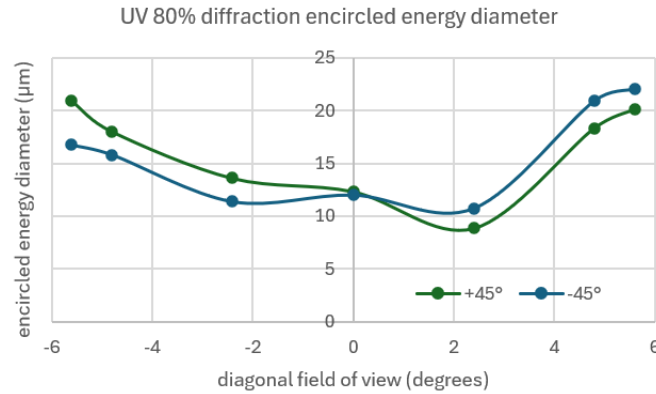


Figure 11. Optical Validation of UV channel: 80% encircled energy diameter as a function of radial fields along the two system diagonals, in units of micrometers.

Straylight Validation

The straylight performance of both the VIS and UV channels has been validated against the -50 dB requirement by performing angular scans from -90° to $+90^\circ$ in an ISO 7 black laboratory, using fiber-coupled light sources at approximately 10 m and a range of exposure times. No optical-system-induced straylight was detected over the full angular range. In the VIS system, however, scattered light was observed near the filter boundaries when the incident beam illuminated the internal edges of the filter, an inherent effect of the filter construction that cannot be mitigated through optical straylight suppression.

7. CONCLUSIONS AND FUTURE WORK

This paper presents the design and development of two telescope systems through the stages of optical design, optomechanical implementation, engineering analysis, manufacturing, and the verification of individual components. The presented results thus far show how optical performance, structural integrity, thermal stability, and stray-light control were considered throughout the design process, together with material selection and manufacturing constraints. The work reported here provides the design and verification basis for the subsequent integration and system-level evaluation of the telescopes.

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