

Design and optical performance of the SHY-4D Stereo Hyperspectral Imaging System for lunar exploration

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ABSTRACT

This article presents the design and analysis of a Stereo camera system for HYperspectral imaging, SHY-4D, dedicated to lunar exploration. The instrument is developed within the Basic Space Research framework (PRORIS), funded by the Italian Ministry of University and Research (MUR), coordinated by the Italian National Institute for Astrophysics (INAF) and the National Research Council (CNR). SHY-4D consists of two cameras capable of acquiring stereo images enriched with spectral information. The system will be mounted on the rover mast and combined with a rotation mechanism, will enable the acquisition of images over the surrounding scene. Merging hyperspectral imaging data with stereoscopy, enables the generation of Digital Terrain Models (DTMs) augmented with spectral data, thus providing both morphological and compositional information of the observed scene. The integration of stereo and hyperspectral data is important for the identification of REE-bearing lithologies, the morphological and stratigraphic analysis of micro-craters, and compositional heterogeneities within the regolith.

Keywords: Hyperspectral Imaging, Stereo Vision, Lunar Exploration, Digital Terrain Models, Rare Earth Elements

1. INTRODUCTION

In the current renewed interest in lunar exploration, driven by both scientific objectives and future in-situ resource utilization, rare earth elements (REEs) have emerged as a topic of growing attention. Their potential presence and distribution within lunar lithologies make them particularly relevant for understanding the Moon’s geological evolution and for evaluating future exploration scenarios. Their identification and spatial characterization require advanced observational techniques capable of linking compositional and morphological information with high spatial and spectral resolution. To address these requirements, advanced planetary remote sensing approaches increasingly rely on the integration of complementary measurement modalities capable of jointly constraining surface morphology and composition. Stereoscopic imaging systems provide the capability to reconstruct high-resolution three-dimensional reconstructions of the observed terrain, enabling accurate Digital Terrain Model (DTM) generation and quantitative morphological analysis. In parallel, hyperspectral imaging instruments allow the retrieval of spectral signatures associated with mineralogical composition and surface material variability.

The combination of these two techniques within a single rover-based platform is therefore particularly powerful, as it enables the direct co-registration of spatial and spectral information. This integration facilitates the establishment of a direct link between geomorphological context and compositional properties, significantly enhancing the interpretability of in-situ observations. Within this framework, stereo-derived 3D reconstructions provide the geometric reference frame onto which hyperspectral data can be accurately mapped, ensuring a consistent spatial correspondence between terrain features and spectral responses allowing the generation of the Hyperspectral Digital Terrain Model (HDTM).

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To obtain these results, we designed SHY-4D, a stereo camera system for hyperspectral imaging conceived to operate on the mast of a rover-based platform. The instrument is composed of a dual-camera configuration specifically developed to enable simultaneous stereoscopic acquisition and spectral sampling of the observed scene. The system architecture is optimized to ensure geometric stability and radiometric consistency, allowing the generation of co-registered datasets suitable for combined 3D reconstruction and hyperspectral analysis.

2. OPTICAL CONCEPT

SHY-4D optical requirements definition

The heritage of the stereo concept is based on the development of the STereo Camera (STC) [2], one of the channels of the SIMBIO-SYS instrument [3, 4]. SIMBIO-SYS is the imaging system onboard the ESA BepiColombo mission [5, 6, 7] to Mercury. The idea of exploiting the stereo capabilities to acquire stereo image pairs has partially driven the Field of View (FoV) requirements, ensuring a sufficient overlap between the two images. The required image quality has instead guided the definition of the remaining optical parameters. The instrument will operate in the spectral range 400–900 nm with the spectral resolution of 10 nm that will be obtained thanks to the integration of a hyperspectral line scan sensor. The main instrument parameters are reported in Table 1.

Table 1: Instrument main parameters.

Parameter	Value
Focal length [mm]	25
F-number	6.25
Bandwidth [nm]	400-900
Spectral resolution [nm]	10
Field Of View [°]	13.7 x 27
Focus distance [m]	5.7

Regarding the focusing distance, the objective was to cover the widest possible range of object distances to be able to have a more comprehensive view of the scene. The optical design is optimized for a nominal focusing distance of 5.7 m, while maintaining adequate performance over the 1.5–11 m range through the integration of a refocusing mechanism.

The spatial resolution of the system has been evaluated across the operative distance range assuming a detector pixel pitch of 11 μm . The Ground Sample Distance (GSD) varies from 0.66 mm/px at a 1.5 m object distance to 4.8 mm/px at 11 m. At the nominal focus distance of 5.7 m, the GSD is 2.5 mm/px, representing the reference operating condition for system performance characterization.

A Signal-to-Noise Ratio (SNR) analysis was also calculated. Assuming an integration time of 100 ms and accounting for the detector characteristics as well as the lunar radiance at 28° latitude [18], corresponding at the Mare Serenitatis, the resulting signal level varies across the spectral range from approximately 140 at the lowest wavelength to about 280 around 600 nm. This trend is consistent with the combined effects of the detector spectral response (quantum efficiency) and the increasing radiance contribution toward longer wavelengths, leading to a higher collected signal at the longer-wavelength end of the spectral band.

Optical layout

The optical system was developed starting from the classical dioptric Double-Gauss architecture [8], which was selected as the baseline configuration because of its excellent correction of the primary monochromatic aberrations, high image quality, and relatively compact layout [9]. The design was subsequently modified and optimized to satisfy the specific requirements of the hyperspectral camera, including the desired field of view, working distance, and image quality over the entire spectral range. Despite that, also the mechanical allocation was considered during the design phase. The Total Track Length (TTL) is 34 mm, expressed as the distance between the first surface of the L1 lens and the image plane (see Figure 1).

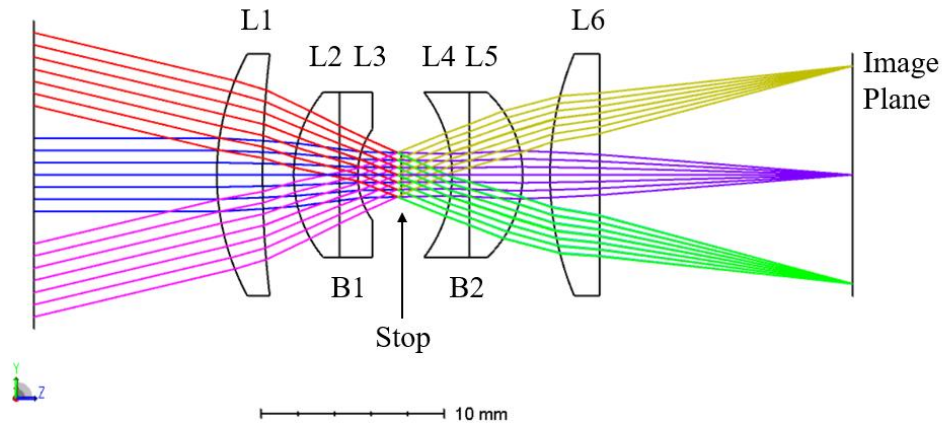


Figure 1: 2D layout of the camera SHY-4D.

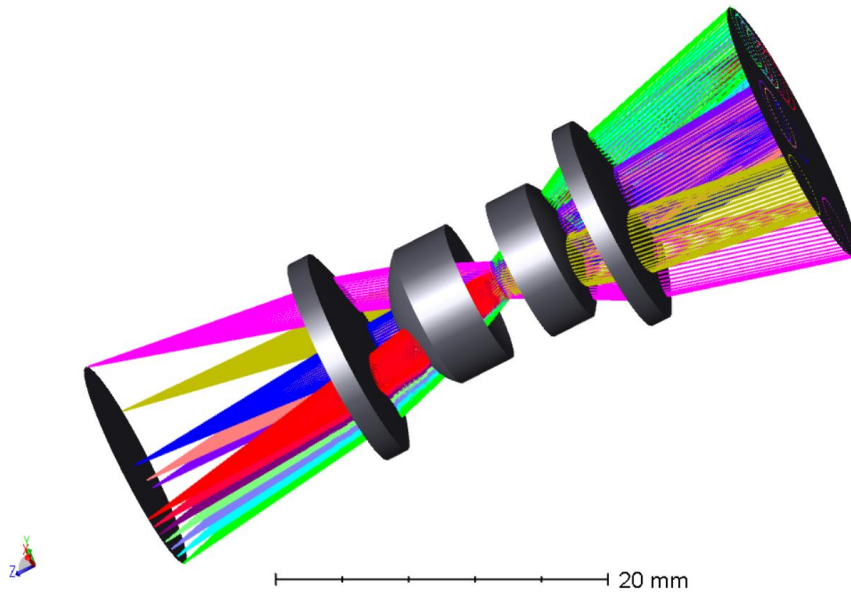


Figure 2: 3D layout of the camera SHY-4D.

The final optical layout (Figure 1, Figure 2) consists of six lens elements arranged in a nearly symmetric configuration around the aperture stop (which is a physical stop). Although derived from the conventional Double Gauss design, the symmetry has been partially lost to improve the correction of aberrations and to accommodate the required object distance and detector characteristics. Positive and negative lens elements alternate to balance spherical aberration, coma, astigmatism, and field curvature while maintaining a compact optical path. The lenses are made of rad-hard glasses.

The optimization process ensured that the spot size remains compatible with the detector pixel size across the full field of view, allowing the system to operate close to the diffraction limit within the design constraints (Figure 3).

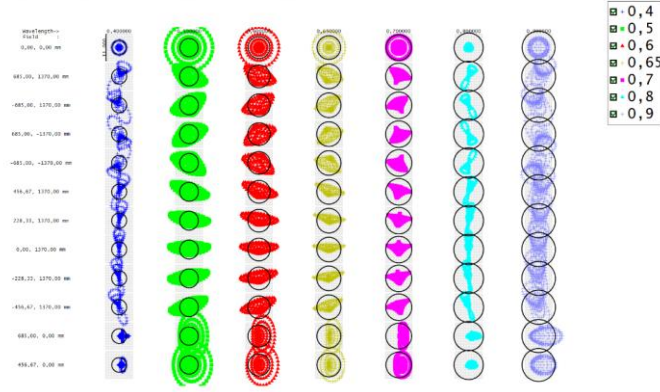


Figure 3: Spot diagrams of the camera as a function of field of view (vertical) and of the wavelength (horizontal). The box size is 11 μm (corresponding to pixel dimensions). The circle represents the Airy disk.

The optical design was optimized for a nominal object distance of 5.7 m, while maintaining acceptable performance over the 1.5–11 m working range through the implementation of the detector refocusing mechanism. Attention was devoted to minimizing aberrations over the 400–900 nm spectral interval. Field–wavelength correspondence correction has been addressed through a merit function that jointly optimizes image quality across field positions and their corresponding wavelengths position over the sensor. This approach enables simultaneous correction of field-dependent and wavelength-dependent aberrations, ensuring consistent system performance across the full operational spectral band.

The hyperspectral line scan sensor

The hyperspectral capability of the camera is achieved through the integration of a series of filter directly onto the detector chip. The hyperspectral line scan sensor assembly has been designed by imec and is based on the LS96 model.

The LS96 is fabricated by depositing a thin-film Fabry–Pérot interference filter directly onto the surface of the AMS CMV2000 CMOS detector. The filter consists of two highly reflective dielectric Bragg mirrors separated by a transparent cavity (see Figure 4). The Bragg mirrors are formed by alternating thin layers of materials with high and low refractive indices, providing high reflectivity over the desired spectral range [10].

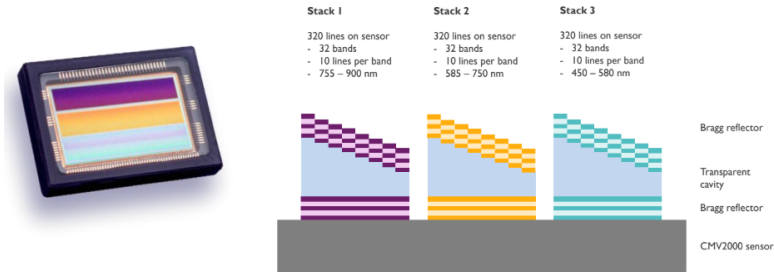


Figure 4: LS96 Detector filter deposition (©imec).

The central wavelength transmitted by the filter is determined by the optical thickness of the Fabry–Pérot cavity, according to the interference condition [11]

$$k\lambda = 2nL \cos\theta \quad (1)$$

where (k) is the interference order, (n) is the refractive index of the cavity material, and (L) is the cavity thickness. θ is the angle between the normal to the surface of the sensor and the incoming ray.

In the hyperspectral line scan sensor, the cavity thickness (L) is intentionally varied in a linear fashion along one direction of the detector. As a result, the transmitted wavelength changes continuously from one detector row to the next, while the bandwidth remains approximately constant. This configuration enables each row of pixels to measure a different wavelength, allowing hyperspectral data acquisition without the need for dispersive elements such as prisms or diffraction

gratings. The direct deposition of the Fabry–Pérot filter onto the CMOS sensor ensures accurate spectral alignment, minimizes optical losses, and significantly reduces the overall size, mass, and mechanical complexity of the instrument.

Focusing mechanism

As already introduced, the system has been designed at the nominal focus distance of 5.7 m. To cover the focus range between 1.5 m and 11 m a focus mechanism has been designed. The concept is to move the focal plane to intercept the focus position of the camera, reaching the required performance at every object distance.

The mechanism is based on a piezo actuator (PiezoDrive SCL050518) equipped with strain gauges to allow closed-loop control, needed for accurate position control and to mitigate the hysteresis and creep effects that affect piezoelectric actuators. The stroke of the selected actuator is about $26\mu\text{m}$, which means a mechanical amplifier is needed to reach the $350\mu\text{m}$ displacement range required by the optical design. This compliant amplifier is then coupled to the bearing subassembly, composed of two diaphragm flexures rigidly fixed at the edges and jointed at the center by a cylindrical support. This design (Figure 5), inspired by [16], ensures the detector motion, which is mounted on the front flexure, is constrained in the transverse directions, while providing low stiffness to the out-of-plane direction, necessary for the actuation. The design also ensures the tip and tilt degrees of freedom are suppressed, making the mechanism robust to possible misalignments of the amplifier. The flexures will be manufactured in Ti-6Al-4V and extensive Finite Element Analyses were performed to optimize the geometries and ensure no risk to the structural integrity of the mechanism is posed by the actuation, in terms of yield stress or fatigue life. The mechanism will then be enclosed with a housing that allows to integrate the objective and ensure its correct alignment. The mechanism is depicted in Figure 5.



Figure 5: Front (left) and side (right) views of the focusing mechanisms with the detector board. The piezo actuator (yellow) is to be glued to the amplifier (red) after a precise deformation is imposed on the latter. This ensures the correct preload is applied to the actuator. The external case is removed for clarity.

Tolerance Analysis

The feasibility of the camera design has been verified through a comprehensive tolerance analysis performed using Ansys Zemax OpticStudio software. The study began with a sensitivity analysis aimed at identifying the most critical system parameters affecting optical performance. The results indicate that the curvature radius of the lens surfaces is among the most sensitive parameters, with particular emphasis on the alignment of the centers of curvature within the lens doublet. In particular, decentering along x- and y- direction between the two elements of the doublet was found to significantly impact system performance, highlighting the stringent alignment requirements necessary to maintain the desired image quality in terms of MTF and spot size. The final requested tolerances are reported in Table 2.

Table 2: Tolerances requirements

Parameter	Tolerance
Radius of curvature	0.08 %
Surface Irregularity	0.2 fringes
Thickness and decenter	0.03 mm
Tilt	1 arcmin

Glass index	0.0005
Abbe	0.3%

The Monte Carlo simulation was performed over 300 independent runs to evaluate the robustness of the optical design under realistic manufacturing and alignment tolerances estimated through the sensitivity analysis. The performance assessment was based on two main metrics: modulation transfer function (MTF) and wavefront error. The resulting MTF values were evaluated across the spectral range from 400 nm to 900 nm, showing a generally stable performance with a peak response in the mid-to-long wavelength region. In particular, the mean MTF varies from approximately 0.78 at 400 nm to values between 0.50 and 0.65 in the visible–NIR range, decreasing to about 0.43 at 900 nm. The associated success rate, defined with respect to the imposed optical quality threshold, ranges from about 51% at 500 nm up to a maximum of approximately 86% at 800 nm, indicating the best robustness in the near-infrared region.

3. ACQUISITION STRATEGY

The SHY-4D approach enables the generation of Digital Terrain Models (DTMs) enriched with hyperspectral data (Figure 6). This represents a highly valuable scientific product, while also providing significant benefits from a photogrammetric perspective, as demonstrated by the HYPSON precursor [1, 12].

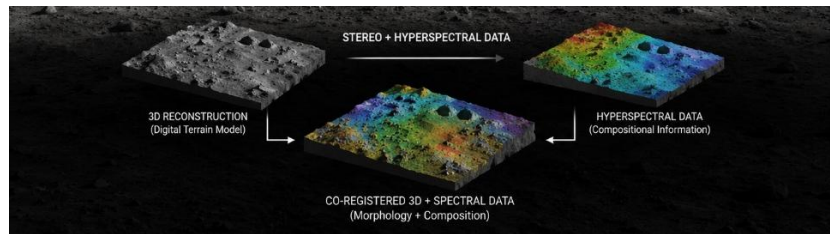


Figure 6: Schematic view of the Digital Terrain Model (DTM), with the addition of hyperspectral data.

Figure 7 illustrates the rover-mounted SHY-4D system operating on a lunar-like surface. The individual fields of view of the left and right cameras are shown, highlighting their geometric overlap region, which defines the stereo reconstruction angle.

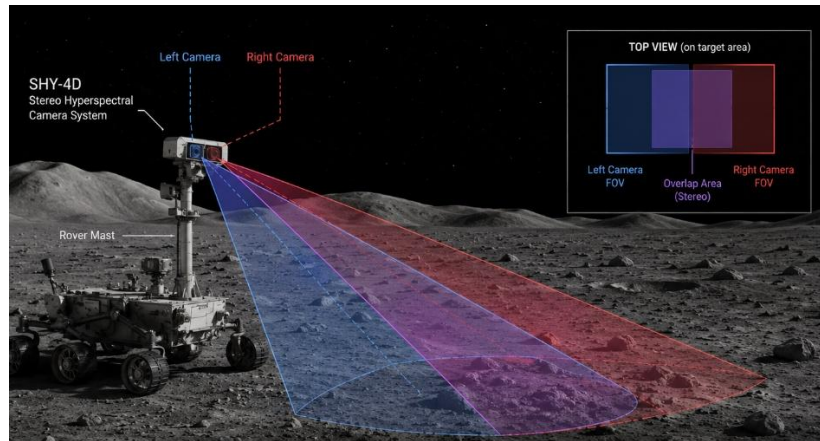


Figure 7: Schematic representation of the SHY-4D stereo-hyperspectral rover-based observation concept.

The intersection of the two cones enables stereoscopic depth estimation, providing the basis for three-dimensional terrain reconstruction. At the same time a rotation mechanism is present on the top of the camera to provide a 360° rotation of the camera and enable the panoramic reconstruction of the scene. SHY-4D has been optimized to operate with two different strategies:

- Short-range strategy: stereo reconstruction is performed using the two SHY-4D cameras rotation while the rover remains stationary. This approach provides high-accuracy 3D measurements of nearby targets;

- Long range strategy: stereo reconstruction exploits images acquired from different rover positions, effectively increasing the stereo baseline and improving reconstruction accuracy for distant targets.

In both cases, the final product will be obtained using the photogrammetric pipeline 3DPD [15], which is currently used for the generation of CaSSIS [17] DTMs and will soon be employed for the global 3D mapping of Mercury using the SIMBIO-SYS Stereo Imaging Channel (STC). Both CaSSIS and STC are frame-based panchromatic stereo cameras. In contrast, the hyperspectral panoramic architecture of SHY-4D provides full-band information that can be exploited during image matching. By combining the radiometric information available in all spectral bands, future developments of the 3DPD pipeline are expected to improve the robustness and accuracy of image matching, ultimately leading to more accurate DTMs.

Short distance approach

A mechanical scanning (panchromatic sweep) approach is being considered. This enable full panoramic coverage of the observed scene, allowing the spectral acquisition to vary across the horizontal direction such that each spatial region is associated with its corresponding wavelength according to the filter mapping. The panoramic reconstruction can be obtained thanks to a rotation mechanism that will allow the cameras to rotate through 360°. This configuration enables panoramic hyperspectral stereo reconstruction with a theoretical vertical accuracy of approximately 0.35 mm at a working distance of 1 m, without requiring any rover motion, as the rover remains stationary during image acquisition. as the rover remains stationary during image acquisition.

This operational mode is intended for the reconstruction of scientific targets such as cold traps, fractures, and other geological features located within 2 m of the rover. Figure 8 reports both the Pixel on Ground (PoG) and the expected vertical accuracy up to a distance of 2 m. The figure also highlights the additional accuracy that could be achieved through the previously described pan-sharpening approach.

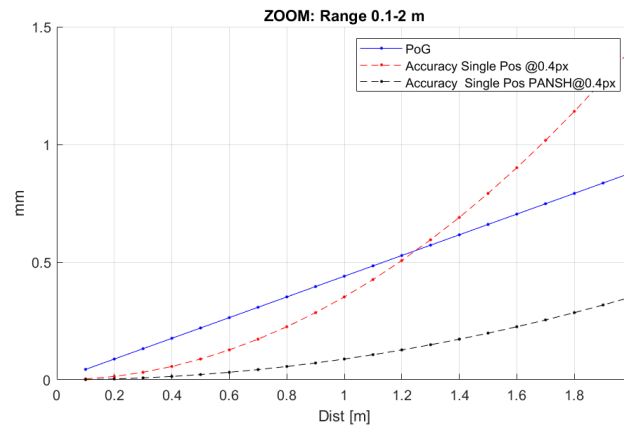


Figure 8: Case of short distance from the rovers: Pixel on ground (in blue) and Accuracy of the reconstruction (in red) using the two cameras together. In black the possible accuracy is reachable using the PANSHARPENING approach. Simulations are performed assuming an upper bound matching error of 0.4 px.

Long distance approach

Considering two identical cameras mounted side-by-side with a 50 cm stereo baseline, the overlap region has been evaluated as a function of operating distance using a horizontal FoV of 13.7° (dictated by the filter extension on the detector). Under these conditions, the observable scene width increases linearly with distance resulting in a variable common field of view between the two sensors over the operating range. At larger distances, the convergence angle between the two cameras progressively decreases. As demonstrated by several planetary stereo imaging systems, a convergence angle below approximately 20° (Figure 9, magenta curve) causes the vertical accuracy (red curve) to deteriorate more rapidly than the PoG. Consequently, the quality of the reconstructed DTMs decreases, even though the panoramic imagery itself remains suitable for scientific purposes. In this analysis, however, we conservatively assume a nominal image-matching error of 0.4 pixels as commonly adopted in conventional stereo systems [14]. This assumption provides an upper-bound reference against which the benefits of the hyperspectral matching strategy can be evaluated.

This limitation arises from the assumption of a stationary rover during stereo acquisition. If rover motion is allowed, the effective stereo baseline can be significantly increased. Images will be aligned thanks to SLAM (Simultaneous Localization And Mapping), which takes advantage of the panoramic field of view [13]. For example, by translating the rover by 5 m between acquisitions (green curve in 9), the effective convergence angle remains within a favorable range. Under this scenario, the vertical accuracy remains better than the Pixel on Ground up to approximately 10 m, reaching about 4 mm, which is comparable to the image ground sampling distance.

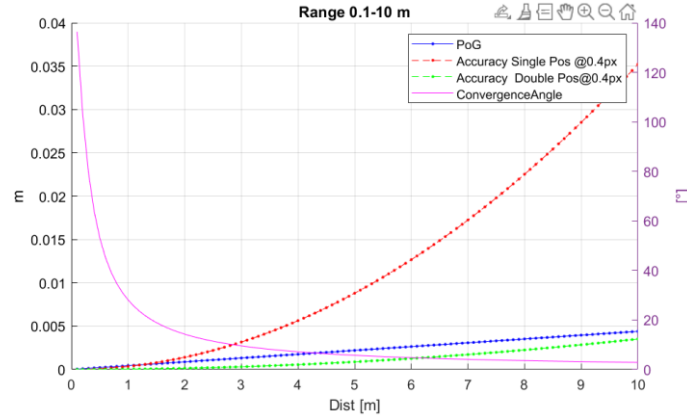


Figure 9: Case of long distance from the rovers: the convergence angle is shown in pink (right axis); the Pixel on Ground in blue; the Accuracy of the reconstruction using the two cameras together in red. In green, the potential accuracy achievable using acquisitions from different rover positions. Simulations are performed assuming an upper bound matching error of 0.4 px.

4. CONCLUSIONS

This work presented the design and preliminary performance assessment of SHY-4D, a stereo hyperspectral imaging system for rover-based lunar exploration. The instrument combines two compact cameras equipped with the hyperspectral line scan sensor, enabling the acquisition of co-registered spatial and spectral information in the 400–900 nm range and the generation of Hyperspectral Digital Terrain Models (HDTMs). The optical design provides a 25 mm focal length, a $13.7^\circ \times 27^\circ$ field of view, and a nominal Ground Sample Distance of 2.5 mm/pixel at 5.7 m. A piezo-based refocusing mechanism allows the system to operate over the 1.5–11 m distance range. Tolerance and Monte Carlo analyses confirmed the feasibility of the optical design, with satisfactory MTF performance across the operational spectral range.

The stereo simulations demonstrate the potential of SHY-4D for both short- and long-range observations. Rover motion can increase the effective stereo angle and improve the reconstruction accuracy at larger distances, while the proposed rotational scanning approach enables high-accuracy panoramic reconstruction of nearby targets. Finally, the use of hyperspectral information during image matching is expected to improve the robustness and accuracy of future DTM generation. Overall, SHY-4D provides a promising compact solution for the combined morphological and compositional characterization of the lunar surface.

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