

Infrared All-Sky-Monitor for the Verification of Optical LEO Downlinks

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Abstract—Optical satellite downlink systems require robust means for testing and calibration. In dynamic point-to-point link scenarios both - satellite terminal as well as ground connecting station - can suffer from mis-tracking or -pointing, leaving open where such failure really occurred. A mean to reduce this ambiguity is thus advantageous. A ground camera observing the whole sky, without the need for assured orbit tracking, can fill this gap, additionally providing information about signal intensity and thus pointing quality of the satellite terminal.

Index Terms — Optical Ground Station, OLEODL – Optical Low Earth Orbit Downlinks, infrared camera allsky lens, inter-satellite links, deep space optical communications, optical space-ground link, elevation angle

I. INTRODUCTION

Optical Low-Earth Orbit Satellite Downlinks (OLEODL) are necessary for high-resolution Earth observations sensing, or for ground connection of satellite mega-constellations, besides many more uses in high-bandwidth satellite applications [1]-[5]. The according communication task is provided on satellite side by small laser terminals which steer their signal beam (collimated by a telescope-like optical assembly) towards an optical ground station (OGS) during overflight, with high dynamic pointing precision of the according CPA/FPA combination (Coarse / Fine Pointing Assembly). Such are controlled either open-loop by a combination of attitude sensors (mostly based on Star-trackers), or by closed-loop tracking an optical beacon that is provided from the OGS itself, which enables much higher angular precision and thus smaller signal beams [6]-[10]. Figure 1 illustrates the typical three sequences of such an OLEODL session: The OGS illuminates with its beacon beam the expected location of the LEO, when the satellite has detected the beacon signal it sends its data laser in the direction of the OGS, and for the rest of the downlink session the ground and space terminal track each other, until the satellite disappears beyond the horizon. For typical LEO-orbits between 400 and 800km this takes only few minutes and requires an angular movement of the beam directions of nearly a half-circle. We find some orbital, geometrical, and link budget characteristics of such OLEODLs in [11]. In this investigation we work with optical signals in the near-infrared from 1540 to 1590nm wavelength.

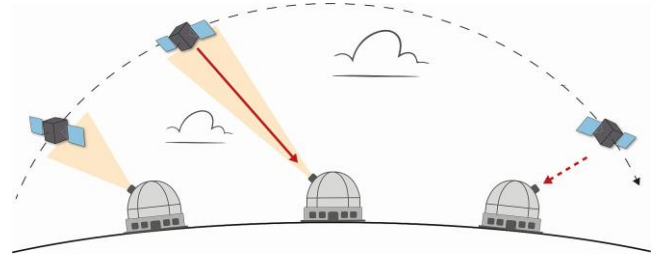


Fig. 1: LEO Data Downlink Sequence with Detection and Tracking of the OGS-Beacon [11].

When optimizing the performance of such Optical LEO DownLink terminals (OLEODL), angular pointing offsets can reduce received intensity down to total signal losses of the communication. Such Offsets are often dominated by the angular speed as well as the link budget, causing jitter of beam-direction and preventing reliable OGS-beacon power to reach the satellite terminal's tracking sensor. Furthermore, other errors can prevent correct execution of links, like de-calibration of optics from rocket launch vibrations or even component malfunctions. Moreover, the reference coordinate systems of the laser terminal and the satellite's attitude and orbit control system (AOCS) need to be aligned after launch (boresight calibration). On the ground side, operational impairments might prevent correct pointing of the beacon signal to the satellite or an incorrect OGS-viewing direction might prevent reception of the satellite's signal [10][12]. On top of such technical uncertainties, the atmosphere leads to intensity scintillation by Index-of-Refraction Turbulence (IRT) depending on meteorological and geometric conditions - which again aggravates link execution. Or the channel might just be obstructed by clouds

Altogether, the exact reason for insufficient link performance or even link failure is often hard to identify

List of potential issues during OLEODL:

- Reduced downlink pointing quality from satellite terminal
- Tx-power instability from satellite terminal
- Instability of OGS uplink Beacon
- Atmospheric channel influence (clouds, IRT)

The purpose of an All-Sky-Monitor-Device (ASM) for OLEODL signals is the identification and evaluation of the optical intensity from LEO Satellites without having to rely on tracking from a ground station mount. Instead, any signal at the wavelength of interest, shining from space, can be identified and evaluated in terms of stability and average illumination. The ASM is placed closely beside

an OGS installation, to be illuminated by the same laser signal that is used for the OLEODL communication.

The strength and location of the signal spot on the sensor chip over time allows to assess several link parameters, like the power- and pointing-stability, the angular offset pointing, or even the precision of orbit prediction, as well as the stability of the OGS' beacon pointing.

II. ALL-SKY-MONITOR IMPLEMENTATION AND SIGNAL ACQUISITION

All-Sky camera implementations can be found for manifold applications, like astronomical observation of stars, asteroids, or satellites. Another application is the observation of cloud-blockage at day and night, to assess the performance of solar power sites, or statistical reliability of astronomical observatories or OGS sites for satellite communication [13][14].

All-Sky cameras based on only one lens and sensor have to our knowledge not been implemented operationally for monitoring OLEODL signal quality performance by direct observation [15][16]. This might be mostly due to the low intensity of such signals, which are often below the classical camera's sensitivity threshold. Such applies foremost for the signal wavelength around 1550nm which requires cameras based on Indium-Gallium-Arsenide (InGaAs) semiconductor sensors, whereas in the silicon cameras domain (below 1000 nm wavelength) less-noisy sensors exist. Today's communication technology however is dominantly based in the optical C-band around 1550nm spectrum for different reasons, whereas systems working around 850nm are hardly in use anymore. However, this wavelength selection might also change in future for the implementation of quantum communication systems which tend to be rather working around 850nm.

In Table-1 we summarize some expected intensity values in typical test scenarios with ground-beacons and thus with reduced signal beam divergence. Additionally, beaconless downlinks from open-loop pointed laser terminals exist with a larger beam divergence angle, and their link budget with ground-intensity is found in [11].

Links for these experiments always took place to the Optical Ground Station Oberpfaffenhofen (OGSOP), situated on top of the Institute of Communications and Navigation (IKN) building. Here the Tx signal source was either a seed-laser and a subsequent Erbium Doped Fiber Amplifier (EDFA), or a "HPLD" source which is a directly modulated High Power Laser Diode. In a certain experiment with QUBE (which is further evaluated here) we experienced a stronger overall atmospheric attenuation than was assumed for the general case in CubeL

Name of Satellite	QUBE		CubeL (PIXL)	
Tx-Terminal	OSIRIS-QUBE		OSIRIS4CubeSat	
Orbit Height	480 km		560 km	
Uplink beacon λ	1590 nm		1590 nm	
Downlink signal λ	1550 nm		1550nm	
Source power	42 mW		60 mW	
Source type	HPLD		EDFA	
Beam Div. FWHM	135 μ rad		113 μ rad	
at elevation angle	10°	90°	10°	90°
Distance	1644 km	480 km	1837 km	560 km
Atmos. attenuation during experiment	-5.6 dB	-0.97 dB	-2.6 dB	-0.46 dB
Intens. on ground	208 nW/m ²	7.1 μ W/m ²	532nW/m ²	9.5 μ W/m ²

Table-1: Axial signal intensities on-ground for two experimental OLEODL scenarios, from link budget estimates

Here an All-Sky observation system based on slightly modified standard components was developed, with acquisition control by a Python script allowing automated image recording, and a Matlab script for image evaluation. Two types of InGaAs cameras were used [17] with standard all-sky fish-eye lenses from Fujinon and ADL, where an optical bandpass was inserted intermittently in one camera between lens and sensor, to enhance contrast from background light sources. Details of the hardware can be found in Table 2.

We compensated for low signal strength, noise, and background offset, to enable identification of the satellite signals with high resolution, so to provide angular coordinates of the satellites and also identify radial offset pointing or other sources of signal loss. Effects of IRT intensity scintillations were cancelled through frame exposure longer than typical IRT-effects. Half a second was found to be the optimum in terms of noise deviation.

Sensitivity of fish-eye lenses is reduced towards the circular edge of the viewing radius – in all-sky application this means towards the horizon. This is adverse in several respects, since close to the horizon the signal intensity is reduced due to highest free-space loss (distance) as well as due to increased atmospheric attenuation [17]. Thus, extra attention must be given to the system's performance at low-elevation angles.

In summary the following prerequisites must be regarded

- Field-of-View (FoV) covering the complete sky hemisphere but not much more to avoid wasting sensor area and system sensitivity
- Optimum sensitivity in terms of pixel-SNR of the camera at the required frame-time, where an optimum was found to be around 1s
- Transmissivity of objective lens foremost at low elevations, i.e. to the rim of observation area
- Large effective fish-eye lens aperture to gather enough signal power
- When an optical bandpass is employed: optimum transmissivity at the respective beam transition angles

The optimum combination of sensor and lens achieved full hemispherical FoV without wasting sensor area outside of the horizon image.

Cam type	GoldEye G-008	GoldEye G-034
Manufacturer	Allied Vision	Allied Vision
Lens	HFE1414C, F1.4, by ADL	FE185C057HA-1, F1.4, by Fujinon
Sensor	InGaAs-SWIR	InGaAs-SWIR
Spectral Sensitivity Range	900 – 1700 nm	900 – 1700 nm
Pixel edge size	30 μ m x 30 μ m	15 μ m x 15 μ m
No of Pixels	320. x 256	636 x 508
Sensor size edges in mm (diagonal)	9.6 mm x 7.68 mm (12.3 mm)	9.54 mm x 7.62 mm (12.2 mm)
focal lengths of lenses	1.4 mm	1.8 mm
complete viewing area of combination camera-lens	More than the complete sky-circle with 158 pixels circle diameter	More than the sky-circle with 405 pixels circle diameter
Average resolution in degree per pixel	1.14 °/p	0.44 °/p
Exposure time	500 ms or 1 s	400ms or 1s or 2s
Optional interference bandpass in front of sensor	NA	Edmund Optics 1550 – 1" (1540-1560nm)

ADC quantization, effective	8 bit up to 16 bit	8 bit up to 16 bit
Cam interface	GigE	GigE

Table-2: Camera and lens combinations used for our All-Sky-Monitor

To calculate the optical signal intensity from pixel values on the camera sensor (and further parameters like exposure time), the sensitivity of the whole system sensor – filter – lens - signal power was tested in lab, over a range of signal elevation angles. While the effective aperture opening of a fish-eye / all-sky camera lens is effectively extremely small (albeit its huge apparent lens diameter), only few millimeters diameter have to be expected here.

In figure 2 the integrated pixel values over elevation and for different frame exposure times are shown. While up to 600ms the curves show expected behavior (near constant sensitivity over elevation, with a slight decrease towards higher elevations), for longer exposure the irregular run below 30° hints at nonlinearities which should be avoided. Together with image noise quality considerations, an exposure time of 1/2s to 1s appeared most promising for any elevation. No camera-internal amplification was employed, since this showed increased image noise.

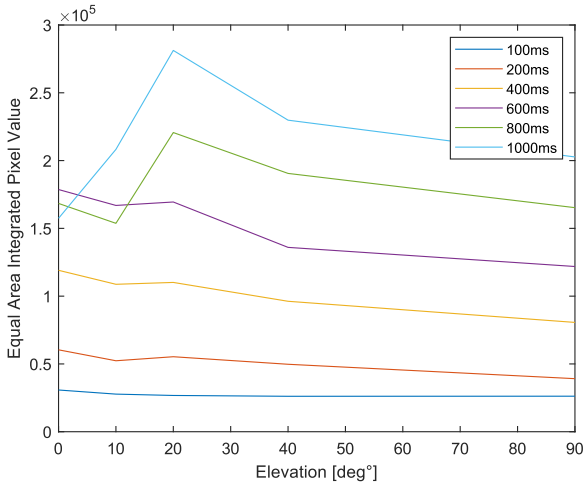


Fig. 2 :Sum of pixels digital numbers vs elevation and exposure time.

These parameters refer to an absolute camera intensity sensitivity of

$$\sim 8E-6 \mu W s / m^2 \text{ per DN}$$

Where DN indicates the sum of the spot-pixels digital numbers from TIFF-images.

Since the fish-eye lens itself is already measured in the lab setup, its actual effective aperture area and attenuation is not required to calculate this conversion factor.

An optical bandpass interference filter can also be inserted to reduce background light offset and noise, and thus enhancing system sensitivity. We tested system responsivity similar to figure 2 but with a filter between the lens and the sensor (SWIR 1550nm C-Mount Bandpass Filter with 35nm FWHM).

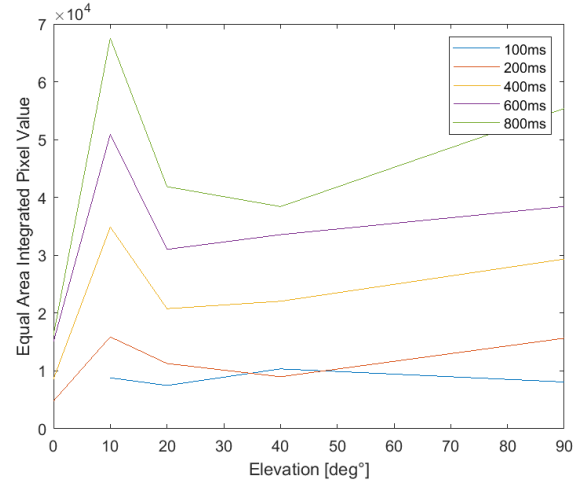


Fig. 3: Similar as fig. 2 but with opt. bandpass filter in front of sensor

The system sensitivity with bandpass filter showed to be reduced to about one fifth, and also due to further strong angular dependencies this filter was not used in the downlink tests (Fig. 3). Although the use of an optical bandpass filter theoretically appears beneficial to increase the images' SNR, it would practically require much more consideration in the post-processing than was possible in this project.

OLEODLs were monitored semi-automatically with a Python-GUI (Fig. 4). On the left the current image is visible, while on the right the static background was subtracted, leaving only the signal-under-test.

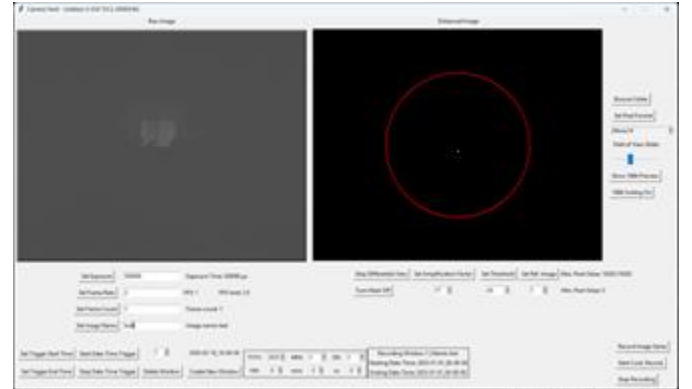


Fig. 4: Python-GUI for automated (scheduled) ASM operation, during sensitivity tests in lab with a weak test source.

The whole camera setup consisted of two different InGaAs-cameras from Allied Vision, and two types of fish-eye lenses, mounted in parallel looking towards zenith (Fig. 5). The capturing and processing software ran on two separated notebooks. This whole setup can also be operated remotely (via remote-desktop), or even time-scheduled, so no local personal is required during operation.



Fig. 5: Setup of the two near infrared InGaAs cameras with their fish-eye lenses, establishing the ASM hardware.

Figure 6 shows the typical scene observed by the ASM during an optical satellite downlink, where image contrast enhancement was applied to show the details.

III. POST-PROCESSING OF ASM-IMAGES

One typical raw camera image (after applying contrast enhancement) with the signal spot from the laser terminal on the QUBE-satellite, and the backscatter of the two OGS uplink-beacons in figure 6.

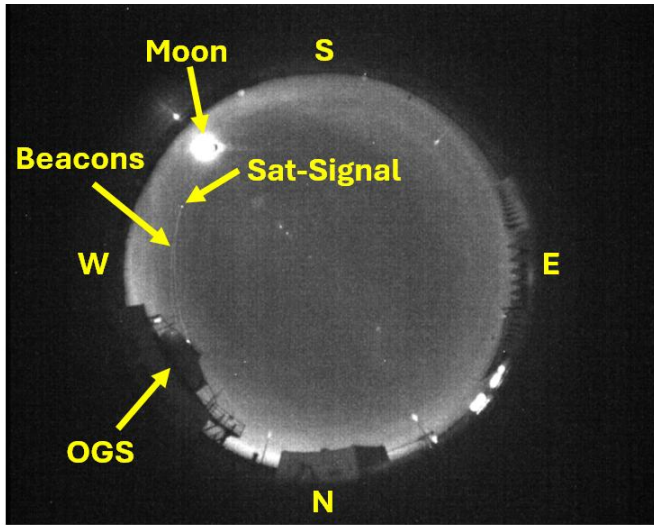


Fig. 6: ASM-Frame (NIR-image from the InGaAs-Sensor, at enhanced contrast), showing the satellite signal spot, and backscatter from the two OGS-beacons pointing towards the satellite. Some OGS-structure at the horizon can be seen, as well as the bright moon in the upper left corner. Image taken Friday 03.10.2025 at 00:19:32 local time.

The ASM processing algorithm identifies the satellite's track across the night sky and discerns it from other signal tracks (other satellites, or planes) that are potentially identified but disregarded if their path does not correlate with the expected track in terms of length or velocity.

The track is also simulated from TLE data available from public sources before the actual OLEODL. The discrepancy of the track from

TLEs vs. the respective orbit trajectory found from the ASM images is obvious in figure 7 and confirms that the algorithm cannot rely open-loop on TLE data.

The processed trace of the whole overflight shows the color-coded intensity, where the offsets were individually subtracted and background light sources were temporally masked out.

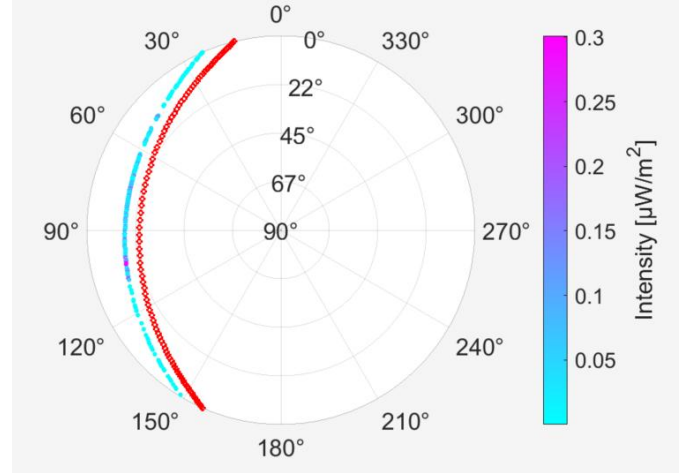


Fig. 7: Track and signal intensity derived from ASM images (blue-magenta), compared with the track predicted from TLEs from SpaceTrak.org (red), on Fri 3 Oct 2025 from 00:14:28 to 00:24:50 local time (for UTC subtract 2h).

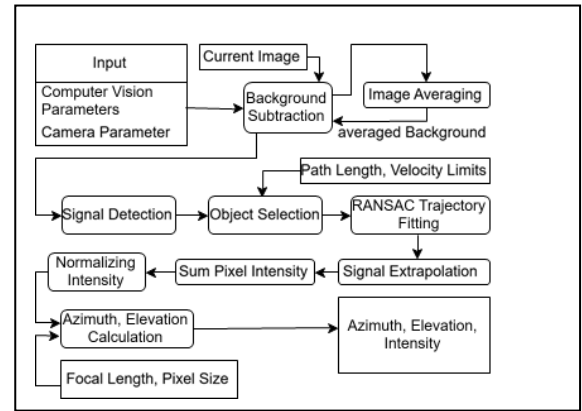


Fig. 8: Functional diagram of ASM post-processing

Intensity-offset from electronic noise and background light is a major issue that needs detailed treatment in post-processing.

Image processing description: Since severe offset from noise and background light is present on the ASM images, the signal detection algorithm is based on differential images, obtained by subtracting an average of past images. This differential is then multiplied by a gain factor and filtered for connected regions of bright pixels. These regions are compared against size constraints, and their positions evaluated across the entire image series to identify connected paths of bright regions with spatial proximity over time. The resulting paths are checked for their total length and pseudo velocity in pixel space. The most promising path is used to fit an RANSAC (random sample consensus) function over the data points. This estimated trajectory is then used to predict the satellite's position over time. For a 2-to 5-pixel-wide square, all pixel values are summed to obtain an integrated pixel brightness. To isolate the satellite signal, the background

brightness is subtracted by summing over the same region for a past image. By regarding the exposure time, this leads to a value of signal-intensity. Finally, the coordinates are converted from pixel space to elevation and azimuth using fisheye mapping functions. The resulting position-pixel value vector is the result of the post-processing algorithm. With the help of the transmission factor this allows the estimation of signal intensity on ground.

IV. RESULTS FROM ASM INTENSITY MEASUREMENTS

We investigated in more detail the downlink on Fri 3 Oct 2025 from 00:14:28 to 00:24:50 local time. Fig 9 shows the measured signal intensity over frame (in this case with 1 frame per second exposure) for the time span where the satellite was more than 10° over the horizon. This plot required detailed analysis over time and image structure with the above algorithm. We identify the influence of the strong moon background around frame 220, which could not be masked completely by the algorithm. Also, we find the received intensity rather unstable, which was but not due to scintillation from atmospheric index-of-refraction turbulence, since the averaging over 1s per exposure would have smoothed these out [19].

Fig 10 shows this intensity mapped to elevation, comparing with the theoretical plot from a link budget calculation. Although there remains ambiguity about the absolute sensitivity of the ASM over elevation, we find here strong variations of the measured samples. This was later identified as a pointing constraint in the terminal's PAT controller, to be resolved in a future firmware update [20].

This specific pointing issue with QUBE could convincingly be identified through the ASM, and exemplifies impressively the benefit of employing such all-sky intensity monitor.

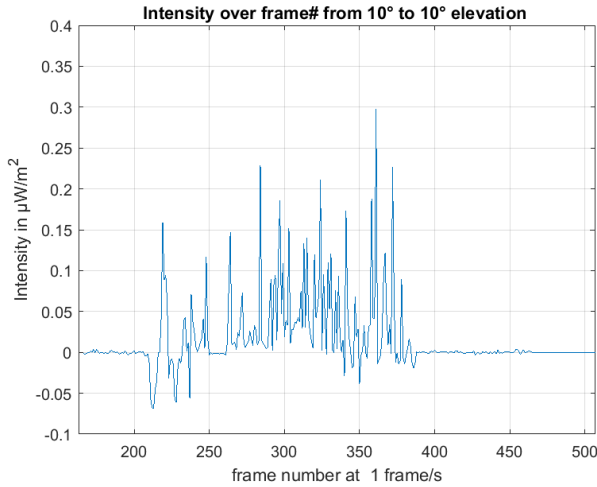


Fig. 9: Signal intensity received on ground by the ASM, showing the time-window from 10° to 10° of satellite elevation.

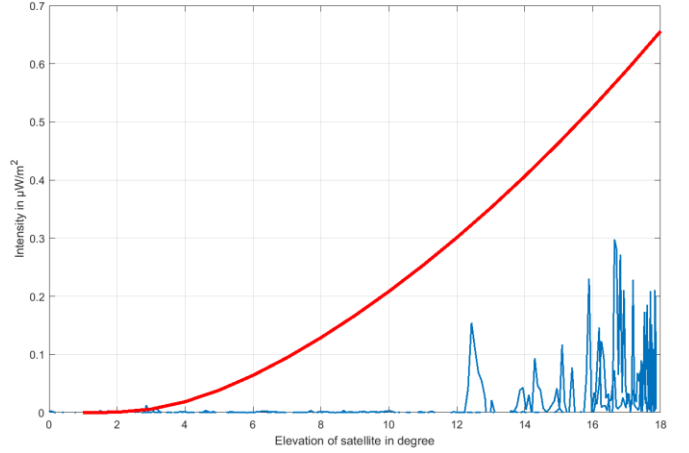


Fig. 10: Comparing the ground-intensity over elevation, from the ASM measurements (blue), vs. the ideal axial intensity from link budget (red).

V. SUMMARY AND OUTLOOK

The ASM allows verification of the absolute signal stability, pointing quality, and functioning of the whole optical downlink signal chain, without imposing additional constraints (like requiring decent active tracking of a ground telescope system). The radial pointing error of the satellite's coarse- and fine-pointing assembly as well as Tx-source stability can be assessed, leading to according adoptions of controller algorithms during commissioning phase. This ASM setup has already shown its valuable results in the QUBE-satellite operational verification, where it was able to capture the optical signal even at severely reduced intensity and strong background offset from the full moon and a strong pointing offset of the laser beam.

Further improvements of the ASM-setup will include: The fish-eye lens needs further calibration of the intensity-to-pixel-value conversion especially at the low elevations, and the implementation of optimized optical bandpass filters shall be pursued.

An advanced setup will include a robust housing, to enable fast relocation of the ASM and to secure the protection of camera and controller plus the necessary networking hardware.

A major challenge is to immunize the evaluation against celestial and terrestrial background light and noise, since both appear much stronger than the weak signal-under-test.

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AUTHORS' STATEMENT:

The authors declare that no "generative AI / LLM" was involved in generating any part of this document.

CONFLICTS OF INTEREST:

The authors declare no conflicts of interest.

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