

Design of a Compact Diffraction-Limited Imaging Payload Based on the Monolithic Tiny Telescope Architecture

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ABSTRACT

The growing demand for high-resolution Earth observation from small satellite platforms requires optical payloads that combine high imaging performance with reduced volume, mass, and mechanical complexity. Conventional space telescopes rely on multi-element optical assemblies requiring precise alignment and complex mechanical structures, limiting their scalability for CubeSat and other small satellite applications.

This paper presents the design and development of a compact imaging payload based on the monolithic Tiny Telescope architecture. The proposed system TT-245-40 combines a monolithic telescope design with a dedicated imaging sensor and mechanical housing concept to enable high-performance Earth observation from small satellite platforms. The monolithic optical architecture integrates reflective and refractive surfaces, internal baffling, and structural features within a single optical element, providing a compact and mechanically robust solution while maintaining diffraction-limited optical performance.

The optical design and payload architecture are presented, including the selection and integration approach of the imaging sensor and the mechanical design required to support a compact and stable instrument configuration. In addition, an image contrast enhancement algorithm is being developed to improve the quality and interpretability of the acquired imagery, complementing the optical performance of the payload.

The presented design demonstrates the potential of the monolithic Tiny Telescope architecture as an enabling technology for compact Earth observation payloads, combining high optical performance with reduced system complexity. Future activities will focus on the fabrication of the complete payload, environmental testing, and space qualification in preparation for future in-orbit demonstration missions.

Keywords: Monolithic telescope, Earth observation, CubeSat, Compact optical payload, Diffraction-limited imaging, Space optics, Image contrast enhancement.

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1. INTRODUCTION

In recent years, there has been a growing trend towards the development and deployment of small satellite platforms for a wide range of space applications. Advances in miniaturized technologies, together with reduced development and launch costs, have enabled small satellites to evolve from primarily educational and technology-demonstration platforms into increasingly capable systems for scientific, commercial, and Earth observation missions. Earth observation represents an important application area for small satellites, where their reduced size and cost enable the development of dedicated missions and satellite constellations with increased observation frequency. At the same time, advances in optical and detector technologies have enabled increasingly capable imaging payloads to be accommodated within the constrained dimensions of small satellite platforms. Recent developments have demonstrated optical payloads targeting metre-scale ground sampling distances within CubeSat-class platforms, highlighting the increasing potential of small satellites for high-resolution Earth observation [1] [2] [3].

Despite these developments, designing high-performance optical payloads for small satellites remains challenging. The achievable spatial resolution is fundamentally linked to the optical aperture, while the limited volume of small satellite platforms constrains the size and configuration of the telescope [2] [3]. At the same time, conventional optical systems rely on multiple components that require precise alignment and mechanical stability. Maintaining this alignment under launch loads and temperature variations becomes increasingly challenging as the payload is miniaturized. Therefore, compact optical payloads require architectures that combine high optical performance with mechanical and thermal stability.

Monolithic optical architectures offer a potential approach to addressing these challenges by integrating multiple optical surfaces within a single substrate. By defining the relative position of the optical surfaces within the same optical element, the number of mechanical interfaces and alignment requirements can be reduced, while providing a compact and mechanically robust configuration. Fused silica is particularly suitable for this approach due to its low coefficient of thermal expansion and favourable optical properties. The Tiny Telescope architecture [4] [5] exploits these characteristics through a monolithic catadioptric design, in which reflective and refractive surfaces, together with internal baffling features, are integrated within a single fused-silica optical element. This enables a folded optical path within a compact physical envelope while maintaining the optical alignment and stability required for high-performance space imaging.

Building on this monolithic optical architecture, this work presents its evolution towards a complete compact diffraction-limited imaging payload for small-satellite Earth observation. The telescope is integrated with an imaging sensor and a dedicated mechanical structure, with the overall design considering the optical, mechanical, and thermal requirements of the payload. The expected optical performance and sensor integration approach are presented, together with the resulting mass and volume considerations. In addition, a computational image-enhancement approach is investigated to complement the optical performance and improve the quality and interpretability of the acquired imagery. The presented payload concept provides a basis for the future fabrication, environmental testing, and space qualification of the system for potential in-orbit demonstration missions.

2. MONOLITHIC TINY TELESCOPE ARCHITECTURE

2.1 Optical Architecture

The Tiny Telescope is a monolithic catadioptric telescope in which the complete optical system is integrated within a single fused-silica optical element. The architecture is derived from a Schmidt-Cassegrain configuration and combines two refractive and two reflective surfaces. The entrance surface acts as a Schmidt-type corrector, while the primary and secondary mirrors provide the main optical power. The exit surface provides additional field correction and defines a flat focal plane suitable for integration with a semiconductor detector [4].

The folded optical path allows a relatively long effective focal length to be achieved within a compact physical envelope. Since the optical surfaces are defined within the same substrate, their relative positions are inherently constrained by the monolithic structure, reducing the number of mechanical interfaces and alignment requirements compared with conventional multi-element telescope assemblies. Internal baffles are also integrated into the optical element to suppress stray light reaching the detector [4].

Fused silica is used as the optical substrate for space applications due to its low coefficient of thermal expansion, radiation resistance, and broad spectral transmission range. The predominantly reflective nature of the optical power also contributes to the broadband capability of the design. Previous work has demonstrated diffraction-limited performance over a wide spectral range, with the optical design and manufacturing process enabling spot sizes below the corresponding Airy disc [4].

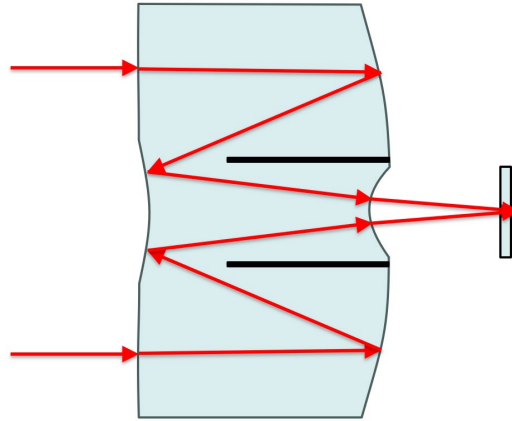


Figure 1. Light path in the monolithic catadioptric telescope, made from a single piece of fused silica. All optical powered surfaces are included in this part, including baffles. A multi zone filter is placed just before the detector.

The monolithic architecture therefore provides the basis for a compact and mechanically robust optical system suitable for integration into small-satellite platforms. In the present work, this telescope is used as the optical element of a complete Earth observation payload, with the detector and mechanical architecture designed around its optical characteristics.

2.2 Optical Performance

The optical design of the Tiny Telescope is optimized to achieve diffraction-limited imaging over the field of view and spectral range considered for the Earth observation payload. The diffraction-limited performance of the monolithic architecture has been demonstrated in previous work [4], including through spot-diagram analysis and measured wavefront error.

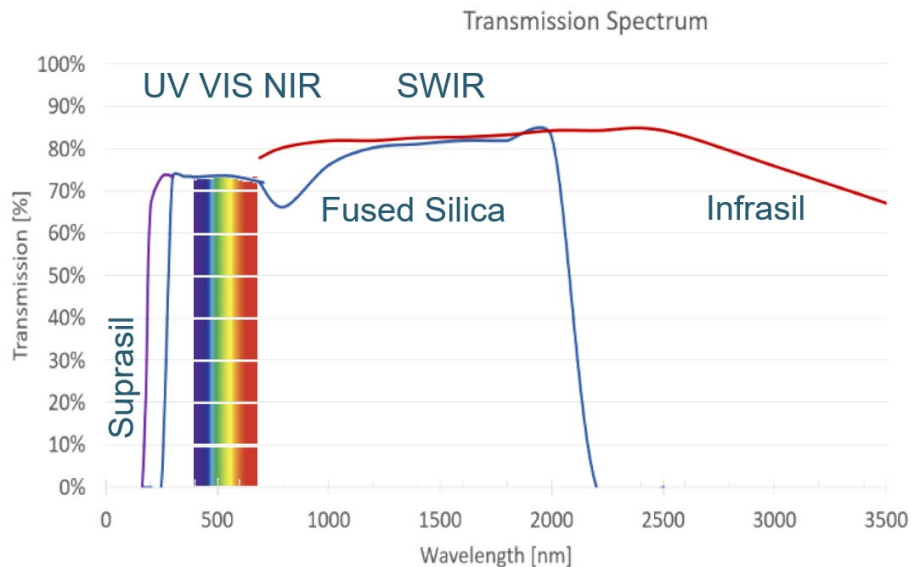


Figure 2. Calculated total optical transmission of the Tiny Telescope as a function of wavelength. The throughput is obtained by sequentially accounting for central obscuration, transmission losses in the fused-silica optical element, wavelength-dependent reflectivity of the primary and secondary mirrors, and transmission losses at the field-flattening and window/field-lens surfaces.

In addition to image quality, the total optical transmission was evaluated to determine the optical power available at the detector. The calculation accounts for central obscuration, transmission through the optical substrate, reflection losses at the primary and secondary mirrors, and transmission losses at the field-flattening and window/field-lens surfaces. Figure 2 compares the resulting transmission for fused silica with aluminium mirrors, Suprasil with aluminium coated mirrors, and Infrasil with gold coated mirrors.

The resulting optical performance and transmission characteristics provide the main optical inputs for the detector and payload design described in the following sections.

3. SENSOR SELECTION

The sensors need to match the telescope architecture in a number of parameters. Detectors with a high quantum efficiency over a large wavelength range are desired. The pixels need to match the resolution achieved by the telescope and the number of pixels needs to match the field of view of the telescope. Finally there is a choice for radiation hard electronics, radiation tolerant versions, or Commercial Off the Shelf Items (COTS). For new space applications the COTS versions are the most common, as satellites are launched in swarms, and it is more important to keep the cost down, than to lose one satellite in a larger swarm.

We have selected the Sony IMX541 sensor for the visible and NIR wavelength range. This is a 20.4-megapixel industrial CMOS image sensor featuring a 1.1-inch optical format, a 1:1 square aspect ratio, and a stacked backside-illuminated (BSI) structure from the Pregius S 4th Generation family. It utilizes a hardware global shutter to eliminate geometric distortion, capturing images via tiny $2.74 \mu\text{m} \times 2.74 \mu\text{m}$ pixels at up to 42 fps at full resolution of 4512×4512 pixels.

The Tiny Telescope TT-245-40 in combination with the Sony IMX541 VIS + NIR sensor achieves the following performance from a 500km Low Earth Orbit: Ground Sample Distance (GSD) 5.5m, Field of view 25x25km, Resolution for different wavelengths as indicated in the graph below.

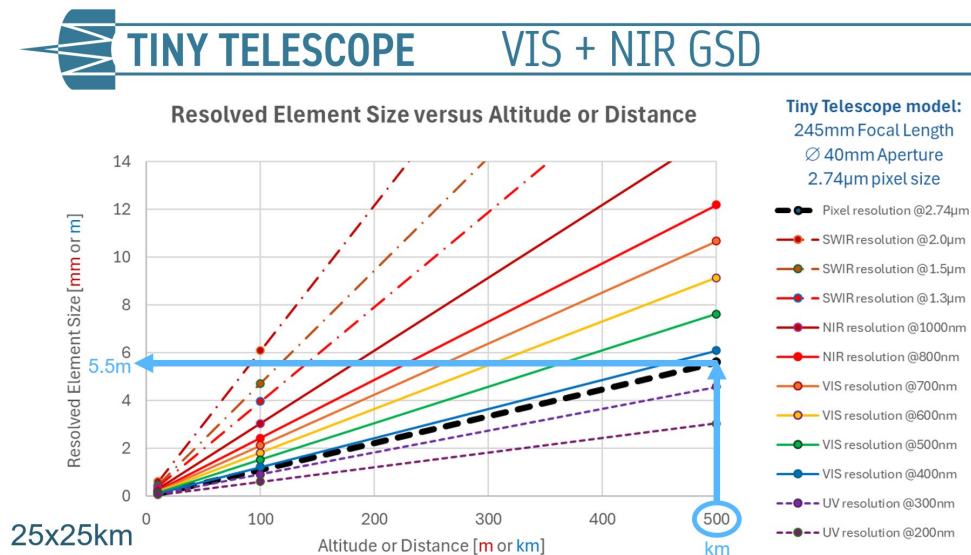


Figure 3. The Tiny Telescope TT-245-40 in combination with the Sony IMX541 VIS + NIR sensor achieves the following performance from a 500km Low Earth Orbit: GSD 5.5m, Field of view 25x25km, Resolution for different wavelengths as indicated in the graph.

We have selected the Sony IMX992 sensor for the visible and SWIR wavelength range. This is a high-performance 5.32-megapixel short-wavelength infrared (SWIR) image sensor featuring a 1/1.4-inch optical format built on Sony's specialized SenSWIR technology. It utilizes an Indium Gallium Arsenide (InGaAs) stacked structure with an ultra-compact pixel size of $3.45 \mu\text{m} \times 3.45 \mu\text{m}$, delivering the industry's highest SWIR resolution while maintaining a hardware global

shutter to eliminate motion distortion. The sensor outputs digital data via high-speed SLVS and MIPI interfaces, achieving frame rates up to 131 fps (at 8-bit readout) and supporting highly flexible integration times that scale from broad industrial exposures down to microsecond-level speeds. This broad spectral response (400 nm to 1700 nm) enables seamless imaging across both visible and invisible light spectrums.

The Tiny Telescope TT-245-40 in combination with the Sony IMX992 VIS + SWIR sensor achieves the following performance from a 500km Low Earth Orbit: GSD 7m, Field of view 14x18km, Resolution for different wavelengths as indicated in the graph below.

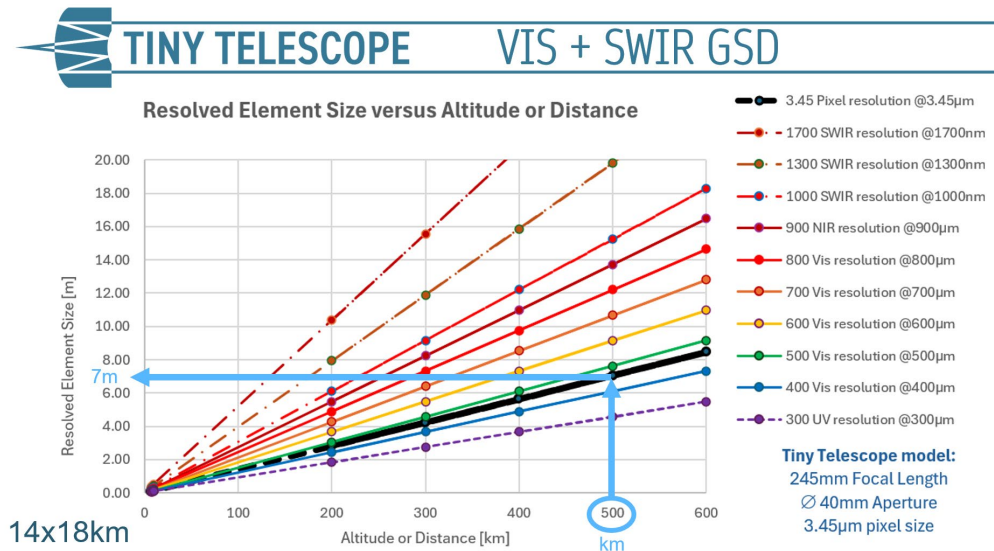


Figure 4. The Tiny Telescope TT-245-40 in combination with the Sony IMX992 VIS + SWIR sensor achieves the following performance from a 500km Low Earth Orbit: GSD 7m, Field of view 14x18km, Resolution for different wavelengths as indicated in the graph.

4. EARTH OBSERVATION PAYLOAD ARCHITECTURE

The Tiny Telescope enables frequent Earth observations in an economic feasible configuration. These low-SWaP (Size Weight and Power) telescopes can be mounted in satellite constellations, serving both defense and civil applications. This market is currently growing quickly due to demand for higher-resolution VIS/NIR/SWIR imaging and shorter revisit times.

This is illustrated by the Canary Islands provincial government, which is deploying its own 3x medium sized satellite constellation for daily high-resolution VIS-NIR-SWIR observation. Combining VIS and SWIR increases detection and classification capability by combining high-resolution scene information with material identification and spectral anomaly detection. This provides a more robust solution for Earth observation and defence applications under varying illumination and environmental conditions, including wildfire prevention and rapid-response disaster management. This is directly relevant to an island region with recurring wildfire and volcanic risk. Secondary use cases supported by the same constellation include:

- Volcano monitoring
- Flood detection and response
- Marine surveillance and spill detection
- Coastline security
- Climate change and desertification tracking
- Soil moisture monitoring
- Resource optimization

Tiny Telescope can achieve comparable performance in a CubeSat form factor. Each application requires trade-offs in orbit and resolution: aperture, altitude, ground sampling distance, revisit time, constellation size, and detectable target velocity, to balance performance against mission cost.

Depending on the specific use case for Earth observations, a combination with spectral filters is essential. The combination of visible and SWIR data is especially powerful, as it delivers complementary spectral information for improved target detection and classification. The VIS channel (400–700 nm) relies mainly on reflected solar or artificial illumination and provides high-resolution imagery and colour information. The SWIR channel (0.9–1.7 μm) adds material-specific spectral signatures and increased sensitivity to hot objects. In particular, the thermal radiation from forest fires and lava flows is observable in the SWIR wavelength range; including through smoke plumes, which obscure these events in visible light. The afterglow of such events also remains visible in SWIR for some time after the visible flame or flow front has died down, extending the window in which they can be detected and monitored.

SWIR enables detection of features that are difficult to identify in visible imagery by exploiting differences in material reflectance, moisture content, and temperature. Examples include:

- Vegetation monitoring: spectral changes in the 1400–1700 nm range enable detection of vegetation stress and fire-prone areas.
- Snow, ice, and water discrimination: differences around 1180–1310 nm improve surface classification.
- Object detection: artificial materials can exhibit distinct SWIR signatures compared with natural backgrounds, improving target discrimination.

Heritage from Landsat and Sentinel missions can be used in the selection of the filter bands, which are implemented as a multi zone filter, just in front of the detector. This provides decades of heritage as well as cross correlation options. Tiny Telescope enables an affordable constellation that can achieve a much higher revisit time for the areas you care about most. Table 1 shows that a global revisit every 2 hours is achievable and affordable.

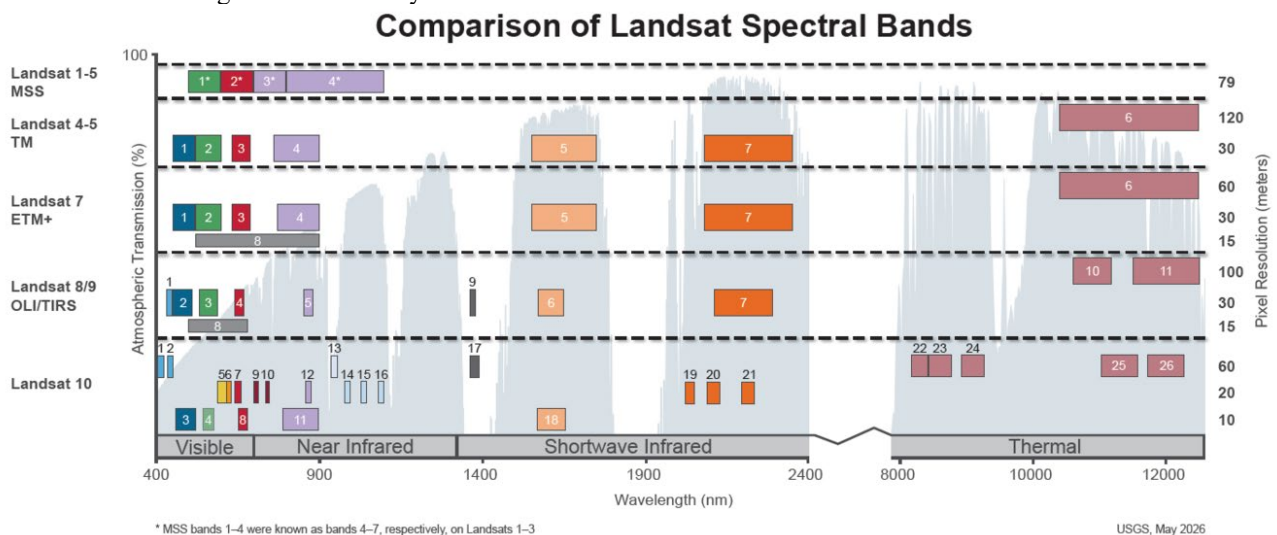


Figure 5. As an example the spectral bands and Pixel Resolution in the NASA Landsat program are shown.

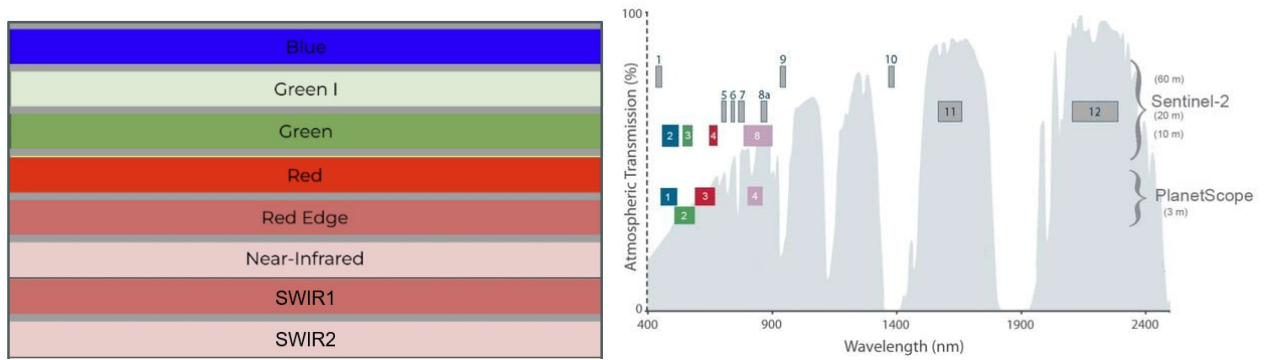


Figure 6. Integration of a Multi Zone Spectral Filter with up to 8 bands is possible, in the wavelength range between 300nm and 1700nm. Left: example of the layout for such a Multi Zone Filter, composed of slices from individual filter blanks. Right: As an example the spectral bands and pixel resolution in ESA Sentinel 2 program and PlanetScope are shown.

5. MECHANICAL DESIGN

Both configurations were assessed for mechanical fit within a PocketQube 2P envelope ($50 \times 50 \times 100$ mm). The TT-245-40 telescope; 40 mm clear aperture, 45 mm physical lens diameter; fits within this volume using an aluminium housing that also serves as the mechanical interface to the satellite structure. The monolithic design enables a long focal length of 245mm in a housing that is three times smaller than usual.

The TT-245-40 comprises of the following elements: housing with mechanical interfaces for mounting on the satellite, the monolithic telescope, a field lens in order to increase its field of view, a multi-zone spectral filter, the camera, with a mounting to keep it in focus over a large temperature range, passive cooling elements and temperature control sensors and features such as optional Multi-Layer Insulation. A data cable delivers the observations to the onboard for further processing and analysis. The mass of the entire TT-245-40 payload unit is 384 grams. It is possible to fit 4 such units in a single 1U nanosat module.



Figure 7. The TT-245-40 telescope & camera unit and its internal components. A single unit measures $50 \times 50 \times 100$ mm, thus 2P units in the pocket qube standard. This fits perfectly as the main payload in a Alba Orbital Unicorn 2 platform. The mass is 384 grams.

The thermal performance has been assessed by simulations and testing. The monolithic telescope works at any temperature, however it is essential to keep temperature gradients at acceptable level and the detector must stay in focus at any temperature. The system is designed to keep the detector plane in focus in the temperature range from -200°C to +200°C. This is achieved using passive components and a combination of materials such as: Fused Silica, Aluminium, Titanium and Copper. The practical temperature limits are driven by the electronics operational temperature, which is from -20°C to +65°C for the particular detector and electronics here. We have conducted temperature performance tests with and without an MLI cover. The results will be published later.

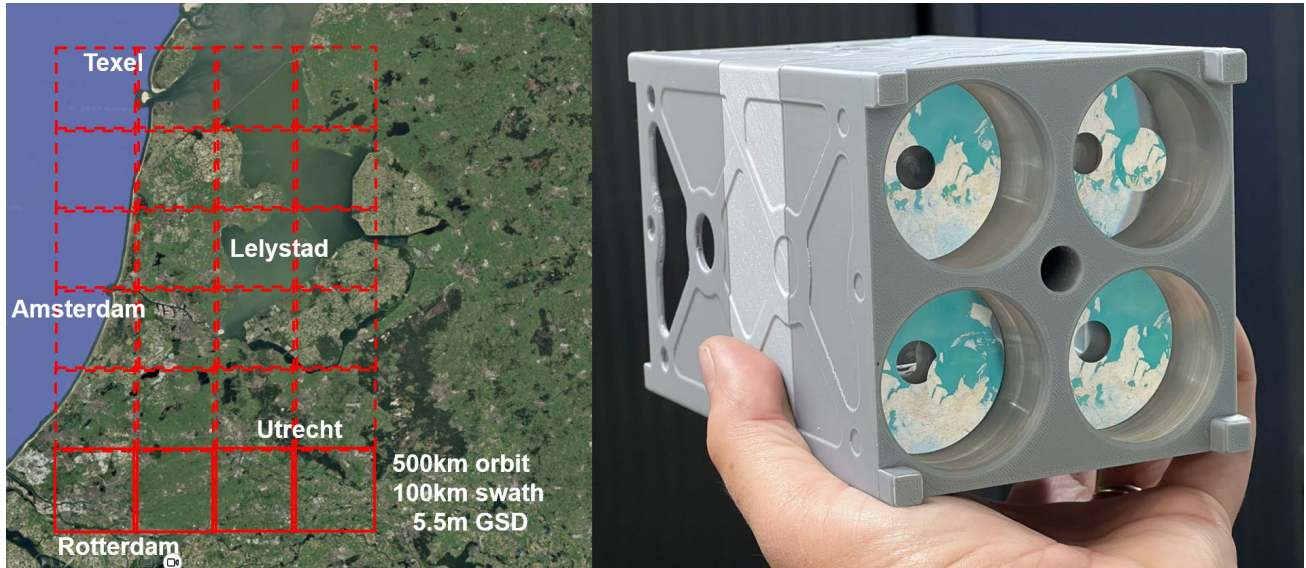


Figure 8. A single 1U satellite building block, measuring 100x100x100mm, can house 4 telescopes and cameras, with a different pointing in order to increase the swath width.

Using the selected Sony IMX992 (7 m GSD, 18 km swath per telescope): a 1U nanosat carrying 4 telescopes achieves a 72 km total swath width. Two such units combined give a 144 km swath. At the equator, Earth rotates 40,075 km per day, which corresponds to 140 km every 5 minutes. So full global coverage requires a satellite crossing the equator every 5 minutes. This can be achieved by a small constellation of 18 satellites, launched into a single sun-synchronous orbit, therefore achieves daily global imaging at 7 m resolution in VIS+NIR+SWIR.

Table 1. trade-off between the number of payload modules and the number of satellites for daily global coverage from LEO (500km) with the provided GSD.

Orbit	Detector	Number of telescopes	GSD (m)	Swath width (km)	Number of satellites	Revisit time
LEO 500 km	Sony IMX992	4 in 1U	7	72	35	Daily
LEO 500 km	Sony IMX992	8 in 2U	7	144	18	Daily
LEO 500 km	Sony IMX541	4 in 1U	5.5	99	26	Daily
LEO 500 km	Sony IMX541	4 in 1U	5.5	99	152	Every 2 hours

6. COMPUTATIONAL IMAGE ENHANCEMENT

The performance of the Tiny Telescope TT-245-40 can be assessed before launching it into space. This is achieved using 30cm high resolution earth observation images from the Dutch Satelliet Data Portaal as a starting point. Knowledge of the pixel size and telescope Modulation Transfer Function MTF and Point Spread Function PSF is used for each wavelength band to mathematically simulate (convolve) what the performance is.

There are ways to increase contrast and resolution. The PSF of each telescope is measured and can be used to deconvolve the observed scene and increase the resolution, even achieving super resolution when using dithering. There is potential for implementation of these techniques in both onboard or ground processing.

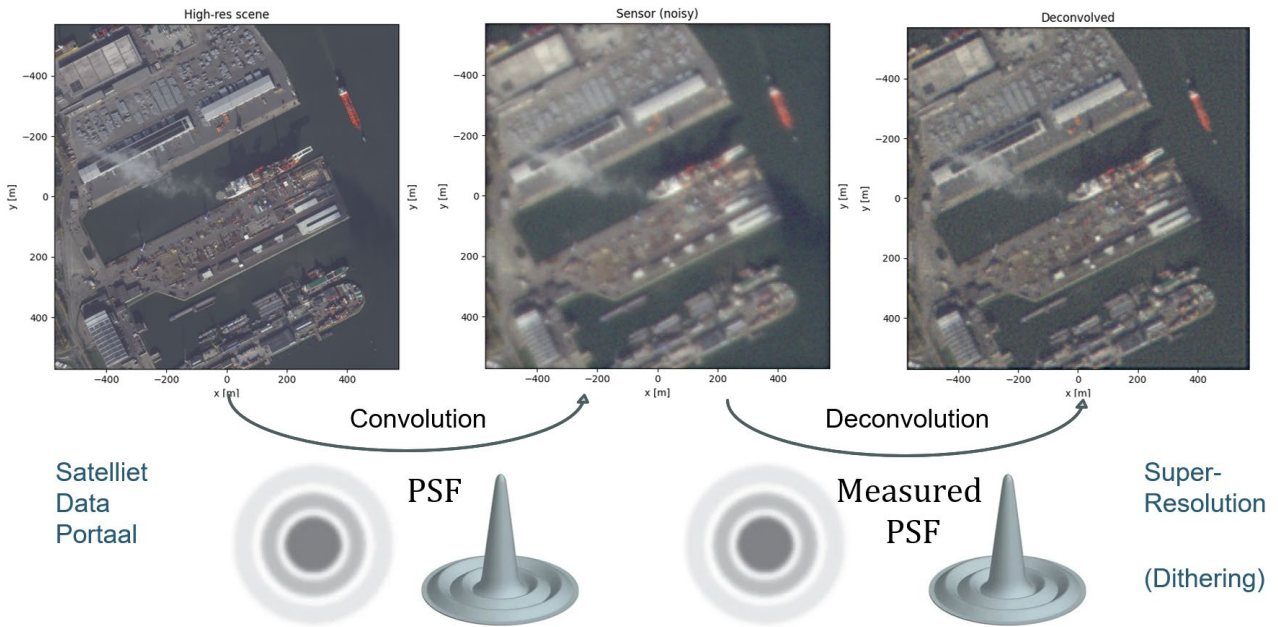


Figure 9. Simulated performance, using 30cm high resolution earth observation images from the Dutch Satelliet Data Portaal. Knowledge of the Modulation Transfer Function MTF and Point Spread Function PSF is used for each wavelength band to to mathematically simulate (convolve) what the performance is of the Tiny Telescope TT-245-40. The PSF of each telescope is measured and can be used to deconvolve the observed scene and increase the resolution, even achieving super resolution when using dithering.

7. SPACE QUALIFICATION AND FUTURE APPLICATIONS

Although all technologies presented here have a Technology Readiness Level of TRL9 and have been used frequently in space, by the authors and by others, the TT-245-40 payload has not flown yet in space and thus has not reached the status of TRL9. Tiny Telescope aims to execute an In Orbit Demonstration mission soon.

Alternative applications for the Tiny Telescope TT-245-40 include the use as a star tracker for larger missions. The high magnification enables high accuracy determination of the attitude of the spacecraft, achieving sub arcsecond performance. Star trackers require higher contrast, compared to Earth observation, requiring external baffles to decrease the sun avoidance angle.

With the relatively small field of view of the Tiny Telescope, it observes faint stars and has an extensive catalogue of a few hundred thousand objects. Some pointings of the star tracker can be close to (or looking directly into) the sun, where even a hint of stray light can ruin the entire observation of faint stars. An external baffle solves this issue and the performance of several designs has been assessed. The results of these tests are published in a future publication.

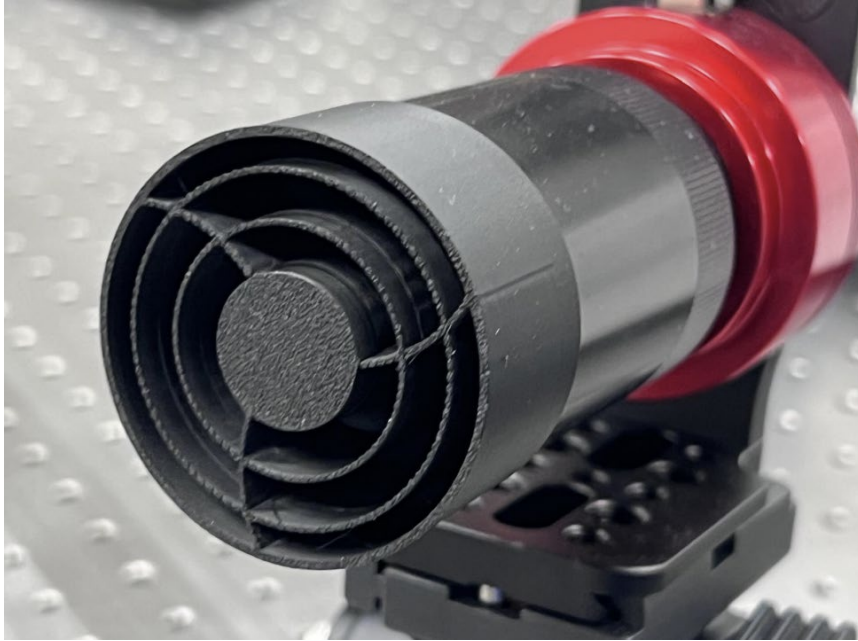


Figure 10. Star trackers require higher contrast, compared to Earth observation, requiring external baffles to decrease the sun avoidance angle.

8. CONCLUSION

This paper has presented the design of the TT-245-40, a compact Earth observation payload built around the monolithic Tiny Telescope architecture. By integrating all optically powered surfaces and internal baffling into a single fused-silica element, the design achieves diffraction-limited performance while substantially reducing the mechanical complexity, mass, and volume associated with conventional multi-element telescopes. The complete payload, including sensor, housing, and thermal management, fits within a $50 \times 50 \times 100$ mm envelope at 384 g, enabling multiple units per CubeSat or PocketQube platform.

Two sensor configurations were evaluated: a Sony IMX541-based VIS/NIR channel achieving 5.5 m GSD, and a Sony IMX992-based VIS/SWIR channel achieving 7 m GSD, each compatible with a multi-zone spectral filter for Landsat/Sentinel-heritage band selection. System-level trade-offs show that constellations of 18-35 satellites can achieve daily global revisit at metre-scale resolution, with higher-frequency revisit (down to 2 hours) achievable at increased constellation size. This demonstrates that the low SWaP of the Tiny Telescope makes dedicated, high-revisit constellations economically feasible. A computational image-enhancement approach, using measured PSF data for deconvolution and super-resolution, was outlined as a complementary means of improving effective resolution beyond the optical baseline.

Beyond Earth observation, the same monolithic architecture shows promise as a compact, high-accuracy star tracker, subject to the addition of external baffling to manage stray light near the Sun.

The results presented here establish the TT-245-40 as a mechanically robust, diffraction-limited payload concept ready for the next development phase. Future work will focus on fabrication of the complete payload, environmental and thermal-vacuum testing, and space qualification, in preparation for an In-Orbit Demonstration (IOD) mission.

ACKNOWLEDGEMENTS

The authors are grateful for the Innovation Impact Challenge (IIC) grant by the Netherlands Space Agency (NLSA).

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