

# Tiny Telescope: Monolithic Diffraction-Limited Imaging

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**Abstract**— The Tiny Telescope is a compact, fully integrated monolithic telescope, designed to address the stringent volume, mass, and alignment constraints of small satellite missions. By integrating refractive and reflective optical surfaces, internal baffles, and structural features within a single optical element, the Tiny Telescope eliminates the need for complex multi-element assemblies and post-integration alignment. This architecture results in a highly compact imaging payload, with increased mechanical robustness and improved thermal stability.

Recent advances in optical fabrication technologies make it now possible to manufacture such monolithic telescopes with the precision required for space applications and with a scalability compatible with series production. This capability enables new mission concepts for Earth observation from Low Earth Orbit, where compact payloads integrated on CubeSat (or even picosat) platforms can achieve ground spatial resolutions on the order of several meters, consistent with diffraction-limited optical performance. The same architecture is applicable to airborne platforms, with unmanned aerial vehicle deployments enabling millimeter-range spatial resolution imaging at distances of several hundred meters.

Optical simulations show that the diffraction-limited performance can be achieved across the ultraviolet, visible, and infrared spectral ranges, enabling the Tiny Telescope to be integrated with multispectral and hyperspectral instruments on small satellite missions.

**Keywords**—monolithic telescope, CubeSat payloads, diffraction-limited imaging, Earth observation, precision optical fabrication, compact space optics

## I. INTRODUCTION

The first 'Solid State Telescope' was crafted by Rik ter Horst in 1994, primarily driven by curiosity regarding the potential alteration of an optical mold, produced for the ophthalmology industry, into a super small catadioptric telescope. 25 years later, postings on social media platforms resulted in a spike of renewed attention: 2M views on YouTube. This resulted in the start of a NOVA spin-off company: Tiny Telescope Development B.V. (Ref 1), pursuing to make the monolithic telescope concept a commercial success.

The design of the tiny telescope combines all optical surfaces of a Schmidt-Cassegrain system in a single block of glass: the Schmidt-type corrector, the primary concave mirror, and the secondary aspheric convex mirror. The exit surface is used as a field flattener lens, ensuring that the focal plane

coincides with a flat semiconductor CCD or CMOS device. This combination has resulted in achieving a high image quality, reaching the diffraction limit. Integrated baffles ensure that spurious light cannot reach the detector.

## II. DESIGN

### A. Optics

The Tiny Telescope is a catadioptric design with two refractive surfaces: the Schmidt-surface (entrance) at the front surface, where the spherical aberration of the primary mirror is corrected, and the curved exit surface at the back of the telescope, which can have a variety of shapes, depending on the application. And then there are two reflective surfaces: M1, the primary mirror surface at the back side of the telescope that reflects light onto mirror M2, the smaller secondary mirror at the front side of the telescope. These mirrors are often aspherical for performance optimization for specific applications.

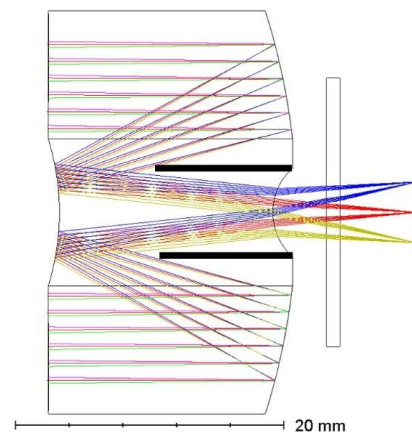


Fig 1. Layout of a 25 mm aperture diameter Tiny Telescope, light enters from the left through the aspherical front surface, the Schmidt-corrector. Mirror surface M1 reflects the light on mirror M2. Finally the light exits the Tiny Telescope at a concave surface acting as a field lens. Baffles ensure that parasitic light cannot reach the detector.

Virtually all optical power of the Tiny Telescope is created by the reflective surfaces, with only minor corrections in the refractive surfaces. This makes the system inherently athermal and suitable for very wide wavelength bands. Schmidt-type systems suffer from spherochromatism, which is the variation of spherical aberration with wavelength, causing different colors to suffer different amounts of spherical aberration. A severely reduced space envelope

results in a shortened design with shorter radii and consequently stronger aspherical profiles, adding to the amount of spherochromatism. By integral system design, the amount of spherochromatism can be controlled quite well. Tiny Telescopes have been designed with diffraction limited image quality over a wide wavelength range from 2200nm down to 200nm in some cases. This demonstrates that, despite inherent challenges, the solid Schmidt-Cassegrain design can, deliver high-performance optical results across a wide spectral bandwidth. In fact, the diffraction limit is achieved in this design, as the spot diagrams are smaller than the Airy disc.

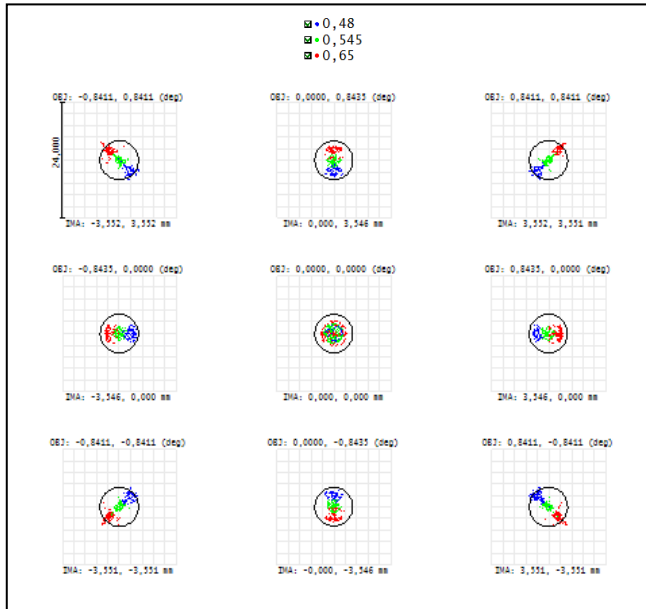


Fig 2. Typical spot diagram for a 40 mm F/6 Tiny Telescope with additional Field corrector lens. The black circle represents the Airy disc. The spots are given for a 1.7 x 1.7 degrees flat FOV.

### B. Baffles

One eye-catching aspect of the Tiny Telescope is that the design includes baffles, which are structures used to prevent stray light from affecting the optical path. These are crucial for enhancing the image contrast and quality. These primary- and optionally secondary baffles are manufactured inside the monolithic body. They are blackened using a proprietary method.

### C. Manufacturing

The material of choice for Tiny Telescopes in a space environment is Fused Silica. This material has a long heritage in space optics and a high radiation damage threshold. It is robust against large temperature swings, has a very low CTE, and can be used over a wide wavelength range. Fused Silica also has exceptional optical polishing capabilities.

The tolerances on especially the reflective surfaces of the Tiny Telescope need to be significantly more accurate than for comparable aspherical surfaces in lenses. This is because in a lens, 1 nanometer surface shape irregularity results in only half a nanometer wave front error, based on the difference in refractive index between the glass and the surrounding vacuum/air. For the immersed reflection inside a Tiny Telescope this is six times worse. In this case 1 nanometer

surface shape irregularity results in 3 nanometer wave front error, based on the refractive index of the glass, times 2 for the reflection. Achieving such high tolerances by hand for prototypes took a lot of patience and was not economically feasible. This process by hand has now been replaced by an industrial process that is ready to be scaled-up, as the yield in the first pilot series proved to be sufficient to start series production. The measured wave front error in most systems supports the statement that diffraction limited image quality can be achieved.

### D. Product range

The non-recurring cost for manufacturing Tiny Telescopes, are higher than for typical other optics. This is due to the fact that all optical surfaces need to be well aligned during the manufacturing process, as there is no way to realign the surfaces later. In smaller series a number of products does not yield, while searching for optimal process window parameters. The price per piece lowers relatively quickly in a series production. This is why we limit the number of clear aperture diameters at the moment to 25mm, 40mm and soon extended with 60mm. Still optimizations are possible for your application, think of spectral range, Field of View (FoV), illumination conditions, detector size and pixel size.

## III. PERFORMANCE

The Tiny Telescope design has significant advantages over traditional optical systems.

- 1) The focal length is much longer than alternative systems of similar size. This results in a larger magnifications. Depending on the application this can be translated to:
  - improved resolution for earth observation, with smaller ground pixels.
  - increased position accuracy for star trackers.
  - higher signal strength for laser satellite communications.
- 2) The high purity Fused Silica used is radiation resistant, both in darkening and refractive index change, even under an extreme radiation dose.
- 3) In Fused Silica it delivers excellent image quality in an extreme wide wavelength range: from Ultra Violet (UV), throughout the visible spectrum and the Short Wave InfraRed (SWIR). Multispectral and hyperspectral remote sensing is possible in push-broom and snapshot imaging mode.
- 4) The design is compact and lightweight, making it ideal for small satellites and space-constrained applications. It easily fits in a nano-satellite or even a pico-satellite.
- 5) The design consists of only a single a-thermal optical component. This makes it robust against large temperature swings, with minimal to no focus variations in a range from cryogenic temperatures to elevated temperatures. Even under extreme shocks and vibrations, optical alignment and collimation are maintained without compromising the optical integrity.
- 6) The reflective surfaces in the Tiny Telescope are well protected, preventing contamination from accumulating on these surfaces. This is beneficial for a range of

applications, from high-contrast imaging to high-power laser applications.

In fact the Tiny Telescope has very few failure mechanisms, thus ensuring a very robust solution that needs little testing, making it very cost effective.

As a result, these telescopes are ideally suited for dynamic and challenging environments, where maintaining precise optical alignment and performance is critical.

#### IV. APPLICATIONS

Tiny Telescope has garnered significant interest from various companies and institutes, operating in different markets. Whether deployed in aerial or space-based platforms, the resilience of these telescopes against physical disturbances ensures consistent optical performance in dynamic and potentially disruptive conditions. This makes them ideal for a wide range of demanding applications, from scientific research to surveillance and beyond. The combination of advanced materials and engineering results in a highly effective optical system that meets the rigorous demands of modern technological applications.

##### A. Satellites

In microsattellites, the ability to integrate a high-performance optical system in a small package is crucial for effective space utilization and operational efficiency. The performance of the Tiny Telescope achieves the diffraction limit, which is the theoretical maximal performance for any optical system. This enables the largest magnification capabilities while gathering sufficient light for short exposure times and creating sharp images. Ground Sample Distance (GSD) in Nadir is 12 m for a 25 mm diameter aperture Tiny Telescope in a 500km Low Earth Orbit. For 40mm and 60mm aperture Tiny Telescopes this results in  $\sim 6\text{m}$  and  $\sim 4\text{m}$  resolution respectively. The TT240-40 model even fits in the smallest satellite form factor, the 50 mm by 50 mm PocketQube satellite, such as the Alborbital Unicorn2.



Fig 3. The Field of View from Low Earth Orbit is 25 x 25km at 500km altitude. The achievable resolution of the Tiny Telescope Model TT240-40 is 6 meters in green and 5 meters in blue wavelengths, allowing basically to observe even small boats in the harbor.

Mass limitations and robustness are important parameter in science exploration missions to other planets and moons within our solar system. Tiny Telescope provides both, and we would be thrilled to collaborate on such deep space missions. In star trackers, the larger magnification of the Tiny Telescope results in increased attitude accuracy performance by a factor  $\sim 5$ , without the need for a large size and mass as other high performance star trackers have. The relative large aperture of the Tiny Telescope enables moderate slew rates.

Robustness and price effectiveness are key parameters in laser satellite communication terminals. With networks spanning hundreds or thousands of satellites, with each having a number of optical terminals, this is a market for high volumes and plug and play technology. This fits the Tiny Telescope perfectly, because prices drop significantly with high volumes and the inherent robustness, reduces the need for testing and time consuming alignments and adjustments.

##### B. High Altitude Platform Stations

A relative new development is the HAPS, or High Altitude Platform Station. These balloons and special planes enable very long duration flights at a high altitude of about 20km. The payload mass is often very limited. With a HAPS you can monitor substantial areas continuously for extended periods of time. This is useful for situations like disaster response and for crowd monitoring during large events.

##### C. Drones

Uncrewed Vehicles such as drones, have a limited payload. Mass savings in the payload can immediately be converted into a longer flight time and a larger reach. State of the art cameras take images with tens of Megapixels, and at a minimum safe distance of 10 meter, the smallest visible features are about 1mm in size. The Tiny Telescope allows to observe 100 micrometer details at the same distance. This is a game changer for inspections, because it enables observations of e.g. cracks in windows in the façade of buildings, cracks in concrete structures such as bridges and cracks in the composite finish of modern windmill blades.

##### D. Infrared and Hyperspectral Imaging

The benefits of the Tiny Telescope stretch beyond the standard panchromatic and color imaging. Short Wave InfraRed imaging enables observations through fog and smoke. Multispectral and hyperspectral imaging with false color representations, enable many special observations, such as to identify diseased foliage of crops, soil analysis for land management, mineral prospecting for mining and to water quality management e.g. by finding oil spills contamination at sea.

#### V. CONCLUSION

The Tiny Telescope is an entire telescope, folded in a single piece of glass. Its catadioptric design with small size, low mass and extreme robustness enables new applications in the domain of uncrewed vehicles like satellites and drones. Although small in size, it offers the best theoretical diffraction limited performance for space applications like earth observation, star trackers and laser satellite communication.

The Tiny Telescope is made possible by advancements in manufacturing techniques and innovations in fabrication processes. Technological developments enable the creation of highly intricate optical components with greater accuracy and efficiency. Series production enables affordable pricing, thereby significantly expanding its potential use.

The expanding scope of applications underscores the versatility of these compact optical systems. Integrating high-performance optical instruments into small, lightweight platforms such as drones and microsattellites opens new frontiers for scientific exploration and commercial applications. This convergence of cutting-edge manufacturing

and application-driven innovation is set to unlock unprecedented opportunities for deploying miniature telescopes in diverse and demanding environments.

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