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Enabling cost-effective high-resolution Earth observation with deployable space telescopes

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Abstract

Abstract: This paper shows the roadmap of the development of a deployable space telescope at Delft University of Technology and explores its applications, key innovations and the design of a small demonstrator. Deployable space telescopes allow for smaller stowed dimensions during launch and it is expected that increasing demand for Earth observation at a high temporal resolution enables large constellations for which the reduction in launch cost per telescope will eventually break even with the required investment. The long term development of deployable space telescopes at TU Delft foresees a primary mirror of up to 1.5 m and the measurements in the visual spectrum, the thermal infrared spectrum and specific spectral lines for trace gasses. The near term objective is to develop a small demonstrator performing wide-band monitoring in the thermal infrared spectrum. This demonstrator comprises of a fixed 30 cm primary mirror and a deployed secondary mirror and baffle. The stowed instrument has roughly half the volume of its deployed configuration. Currently, critical technologies are being designed and proto-typed. The M2 is deployed and suspended by three carbon-fiber booms with custom-designed hinges and actuators at its root. Different configurations have been tested on their correct and accurate deployment.

1 Introduction

The development and launch of the James Webb Space Telescope (JWST) is a milestone in terms of deployable optics for space telescopes. A deployable primary and secondary mirror, as well as a sun-shield, was required to overcome the fairing constraints of a launch vehicle [1]. Developments continue for even larger deployable space telescopes, such as the Advanced Larger Aperture Space Telescope [2]. If the development of deployable optics is not intended to overcome the launch vehicle fairing constraints, such as for the JWST, the need or incentive for deployable optics is less straightforward and is mainly associated with financial cost. The JWST costed over 10 B$ due to complexity of the design, which could be seen as a contra-indicator for saving cost using deployable optics. This is, however, a single satellite high-end mission with very demanding requirements. Its development started 30 years before launch and it thus could not make use from the latest technical developments in terms of optics, sensors and mechatronics.

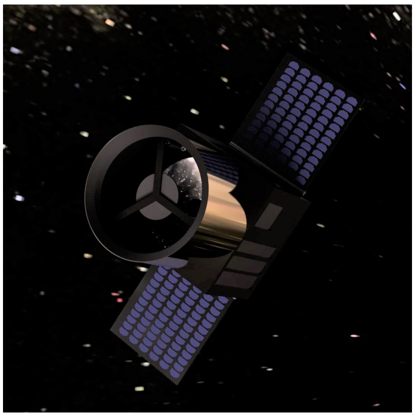

Figure 1: Artist impression of a 30 *cm* aperture DST.

A relatively high fraction of the volume of an optical telescope is empty which can be reduced in stowed configuration when using deployable optics. However, launch cost is often associated with mass, which does not directly justify a saving in volume. Moreover, the gross launch cost per mass and volume unit has recently dropped significantly by a approximately a factor 20 in the last decade [3]. The emergence of CubeSats provides a different perspective. This form factor enforces volume constraints due to the containerization of the satellite during launch. This container adds significantly to the effective launch and volume due to its own dimensions as well as its placement within and interfaces with the launch vehicle. While the nominal figure for CubeSats is one kilogram per unit, the maximum allowed mass is often two kilogram per CubeSat unit [4]. Below this limit, there is no (linear) relation between mass and launch cost and a higher density thus pays off.

Figure 2: Impression of a 1.5m aperture DST (baffle not shown).

The high investment cost and technical risk of deployable space optics have thus far prevented its implementation in optical payloads for Earth observation. It is expected that increasing demand for Earth observation at a high temporal resolution enables large constellations for which the reduction in launch cost per deployable telescope will eventually break even with the investment. Moreover, using active techniques to align the optical elements will reduce the required effort for on-ground optical alignment, saving cost in the Assembly, Integration and Testing (AIT) phase compared to traditional telescopes. It also allows light-weight construction and materials as opposed to relatively heavy thermo-mechanically rigid materials (e.g. Silicon Carbide) often applied in non-deployable space telescopes. This would yield not only saving of (stowed) volume, but also mass. The development of cost-effective high accuracy active optical path control will also provide cornerstone technology for (larger) segmented space telescopes in the future. Still, the development risks are high and the long term gains unknown, so the development of deployable space telescopes is mostly taking place at research institutes and different concepts are being explored at for example KU Leuven [5] and Surrey Space Center [6]. At TU Delft, the development of a Deployable Space Telescope (DST) is currently focusing on a first demonstrator with a primary mirror diameter of 30 cm (see Figure 1) and measurements in the Thermal InfraRed (TIR, 8-12 μm) spectrum. The developments, however, started in 2017 are also plans and high-level designs for future developments of a 1.5 m aperture DST in the TIR and visual spectrum (see Figure 2) [7].

Section 2 provides a comparison of the potential of a DST, combined with a innovative design philosophy at satellite level. This is followed by the development roadmap of a DST at TU Delft in Section 3 and the key technology development results in Section 4.

2 DST High Level Performance

At TU Delft, the development of a DST for small satellites is embedded in a larger system perspective which aims to optimize the architecture of the spacecraft bus for payload volume [8] and to fly the satellite at low altitudes [9]. Saving mass and volume with a DST will only pay off if the satellite has the majority of its volume and mass available for the payload. Flying optical Earth Observation instruments in a low orbit improves the achievable spatial resolution, which could decrease the gap between existing large Earth observation satellites with non-deployable telescopes and a small satellite with DST. Flying at Very Low Earth Orbit (VLEO) comes at the cost of increased aerodynamic drag, which requires (significantly more) propulsion for orbit maintenance compared to orbits from 500 *km* upwards. Also attitude stabilization becomes more challenging at VLEO due to increased aerodynamic disturbance torques. For this reason, the majority of Earth observation satellites fly in orbits between 500 *km* and 800 *km* altitude. Pending key technology developments [9], a reference orbit of 300 *km* is considered feasible in terms of attitude control and delta-V budget. Furthermore, the aim is to develop a diffraction limited DST. In Table 1 the achievable ground resolution from a typical reference orbit of 600 *km* and 300 *km* for a 0.3 *m* and 1.5 *m* aperture is provided.

Table 1: Diffraction limit from different altitudes at center wavelength λ_c.

aperture	alt.=300 *km*, λ_c=10 μm	alt.=600 *km*, λ_c=10 μm	alt.=300 *km*, λ_c=0.6 μm	alt.=600 *km* λ_c=0.6 μm
30 *cm*	12 *m*	24 *m*	0.75 *m*	1.5 *m*
1.5 *m*	2.4 *m*	4.9 *m*	0.15 *m*	0.30 *m*

A comparison is made between a diffraction limited DST to existing Earth Observation missions. In Figure 3, it can be seen that the GSD for the diffraction limited DST of 1.5 *m* aperture, operated from 300 *km* altitude outperforms existing Earth observation capabilities in the visual and TIR spectrum. For the 30 *cm* aperture DST, this is only for the TIR spectrum. It should be noted that this input from Figure 3 only contains data from the public domain and the GSD is not normalized for the same orbit. When normalized for the orbital altitude, as shown in Figure 4, it can be seen that the DST is still competitive with a 30 *cm* aperture, especially in the TIR spectrum, and stands out with a 1.5 *m* aperture. The DST designs at TUD have a stowed to deployed volume ratio of 46% for the 30 *cm* aperture and 25% for the 1.5 *m* aperture. Including the spacecraft bus of a micro-satellite platform for the 30 *cm* DST and a optimized small satellite bus architecture for the 1.5 *m* DST, the total stowed satellite volume is estimated to be 45 *l* and 2400 *l* respectively. Figure 5 shows that the DST outperforms existing capabilities in all cases.

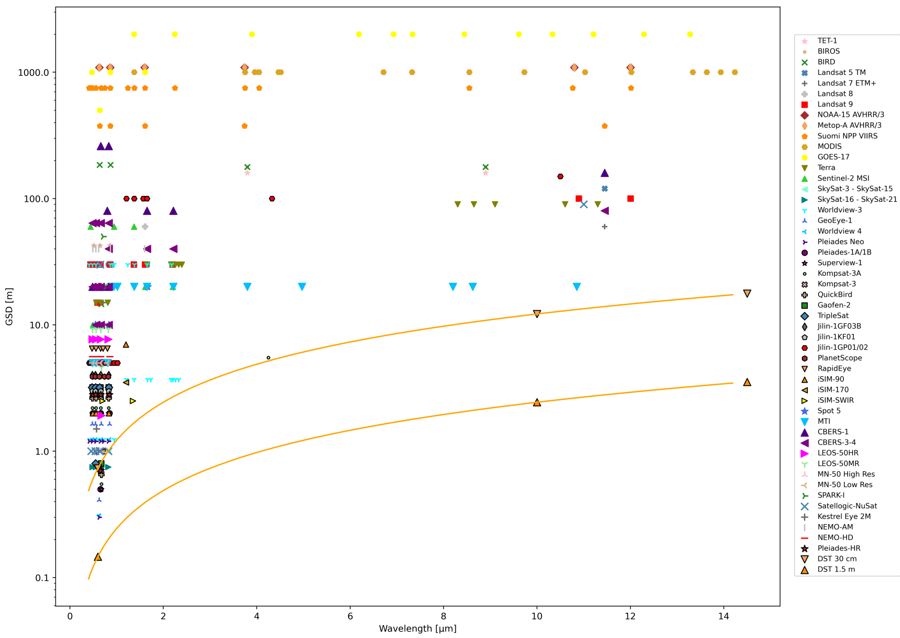

Figure 3: Satellite GSD vs wavelength, with DST at 300 km altitude

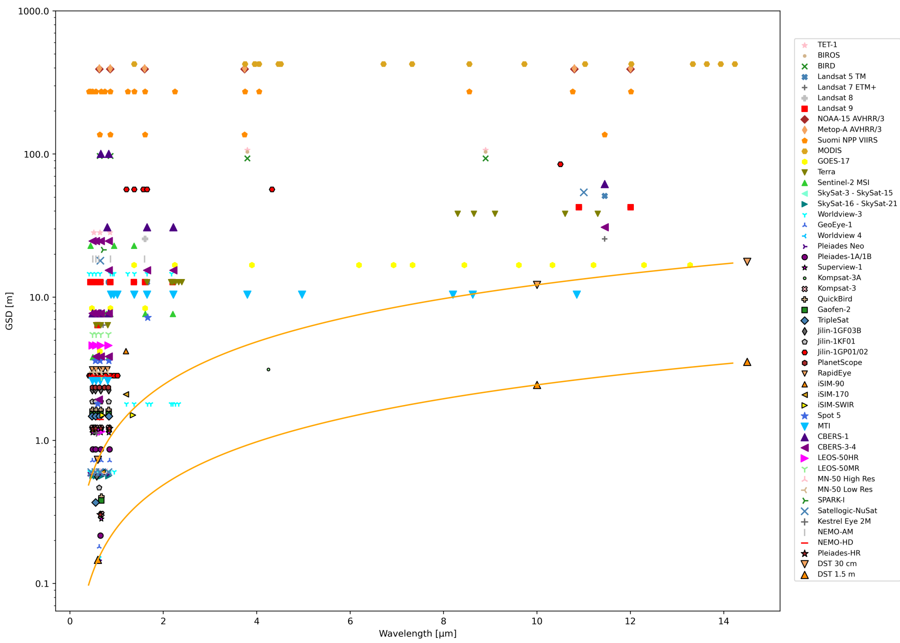

Figure 4: Satellite GSD vs wavelength, all data normalized to 300 *km* altitude.

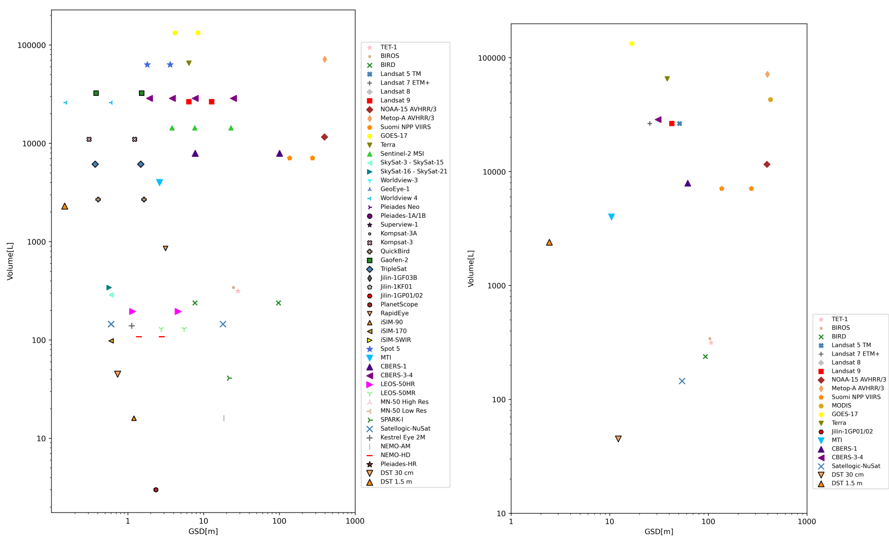

Figure 5: GSD vs sat. volume (left 0.4-0.75 μm, right 8-12 μm), normalized to 300 *km* altitude.

3 DST Development Roadmap

The development at TUD is now focused on a DST for the TIR spectrum using a fixed 0.3 *m* primary mirror and deploying the secondary mirror and the baffle. This has been chosen as a compromise between complexity and utility as first step to demonstrate the potential of a DST. With an achievable GSD of 12 *m* (see section 2, main applications can be found in monitoring of large groups of humans, movement of vehicles and ships, fires and military actions. After successful demonstration of a 30 *cm* aperture single-axis DST, the developments can continue in several directions. One of these directions is increasing the aperture. This can be done by up-scaling the dimensions, but a more advanced approach would be to go towards a three-dimensional deployment. This concept uses a 1.5 *m* deployable primary mirror of four segments which are folded along the body and deployed under a angle of approximately 90° [7]. The secondary mirror is deployed along the optical axis, similar to the single-axis concept. The baffle needs to deploy in three dimensions. The aforementioned applications will be enhanced by the improved GSD and detection of smaller fires, vehicles and groups of humans will become possible. Another direction in which the DST development can evolve is towards the visual spectrum. With a spectrum of 380 *nm*-750 *nm*, the alignment and drift error budgets become more than an order of magnitude smaller than for TIR. Although thermal self-imaging is no longer an issue, the thermal range to comply to the error budget as well as the requirements on active compensation techniques are expected to become more challenging. Another potential interesting application may be in the monitoring of trace-gasses. By using the relatively large aperture of a DST, the spatial resolution can be greatly enhanced compared to large scientific instruments in this field such as the Tropomi instrument on Sentinel-5P. It would be too simplistic to compare such a high-end instrument simply on the size of its aperture, as for the example of Tropomi the spectral measurements cover a wide spectrum from UV to TIR and it uses multiple apertures. To exploit a single large aperture for this purpose, most likely compromises need to be made. For example, monitoring spectral lines not too far apart such as for methane at 760 *nm* and 2340 *nm* which is measured at 5.5 km resolution for Tropomi [10]. For a 30 cm aperture DST flying at 300 km, a GSD of several meters should be possible. This allows monitoring and enforcement of emissions at the level of individual industrial factories and farms.

4 Key Technology Development

At present, the development focus at TU Delft is on a 30 *cm* aperture TIR DST. Its optical lay-out is provided in Figure 6. The observed light enters the deployable baffle and is reflected from the 30 *cm* primary mirror (M1) towards the deployable secondary mirror (M2). The rays enter through a hole in the M1 and is reflected 90° towards the remaining optics. The key technology developments are the secondary mirror deployment and actuation system, a deployable baffle and thermal control for TIR operation.

4.1 Secondary Mirror Deployment System

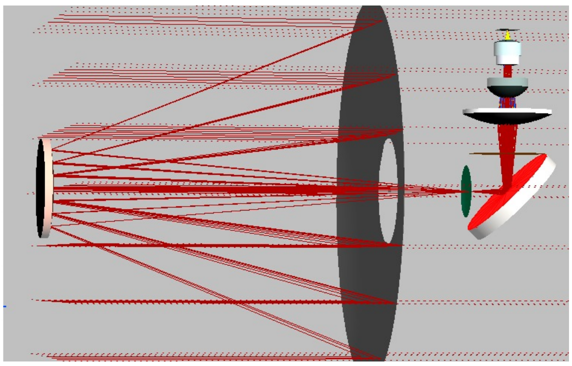

Figure 6: Optical lay-out of the 30 cm TIR DST.

A trade-off between several deployment options and configurations has been performed, with inwards articulating arms as winning concept as sketched in Figure 7. The arms comprises Carbon fibre tubes with hinges at the top, bottom and in the middle. At the bottom, where the hinge interfaces with the main DST structure, an actuation system will be placed to perform post-deployment optical alignment and in-orbit thermo-mechanical drift compensation.

The key development results thus far are in the field of the hinges. Non-compliant hinges, such as simple pin-slot hinges, ball-socket hinges or ball-bearing hinges, typically suffer from tolerances and hysteresis effects when they undergo the thermal variation as expected in space and are thus discarded. The compliant rolling hinge is designed to provide agility during and after deployment while minimizing thermo-mechanical hysteresis [11], [12] and are allocated at the top and bottom of the carbon-fibre tube.

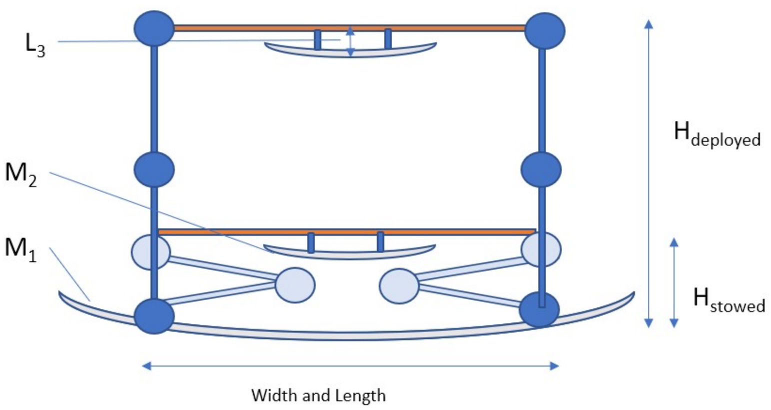

Figure 7: Sketch of the secondary mirror deployment configuration.

Figure 8: Hinge prototype.

A prototype is shown in Figure 8. They can still rotate after deployment to absorb torques due to asymmetric thermal variations in the booms such they do not create undesired warping of the system.

The middle hinge should provide locking or stiffness after deployment, to make the system determined and improve the vibration response. Experiments with a slot in the carbon fibre tubes to make a compliant middle hinge failed due to rupture of the material. Two type of hinges are currently under investigation: a (compliant) strip hinge and a magnetic-locking hinge [13]. The strip hinge is slightly curved, such as applied to rolling measurement tape. This way, the hinge is resilient and has a mild form of self-locking. A hinge using a magnetic clamp has a strong form of self-locking, which makes the carbon tube act as a a single rigid piece. An proposed alternative deployable space telescope design comprises self-locking mechanisms for all hinges using mechanical latching [14]. Future analysis and experimentation should provide insight into the trade-off between a fully locking, significantly over-determined system or a system which only provides locking of the middle hinge. For the DST defined by TU Delft, the deployment accuracy of a compliant rolling hinge at the top and bottom and a magnetically locking as well as a curved strip hinge have been tested. The setup is shown in Figure 9, where the base and secondary mirror is replaced by an aluminum truss. After repeated tests, the deployment accuracy standard deviation of 3 μm and 2 μm respectively for both options [13]. These errors are well within the actuation budgets.

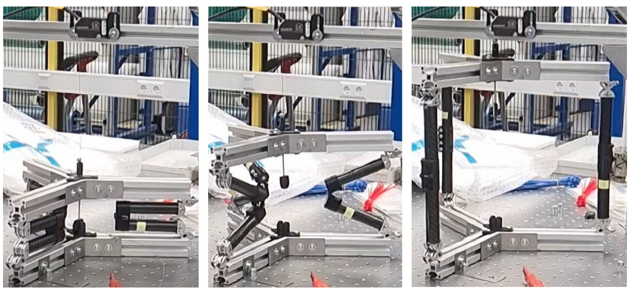

Figure 9: M2 deployment test sequence.

Laser-displacement sensors will be used to detect the deployment error and thermal drift. For the actuation system, different component types have been traded off with an amplified piezo actuator as winner. The selected component has sufficient range and accuracy to account for deployment error and in-orbit drift.

4.2 Thermal Analysis and Design

Operating in the TIR spectrum requires cooling of the detector to at least 150 K for a state-of-the-art TIR detector. Furthermore, the optics and housing in line of sight should have limited temperature to reduce thermal self-imaging.

For the 30 *cm* TIR DST, inverse ray-tracing from the detector has been performed to determine the impact of the thermal self-emission of each element. It has been found that the radiometric performance is acceptable when the internal optics are limited to a temperature of 200 *K*, while the primary and secondary mirror as well as the baffle can still be around 280 *K*. A compliant concept using a smart passive staged radiator concept with a deployable shield is currently being developed.

4.3 Deployable Baffle

A trade-off between a square and cylindrical baffle has been performed. While a square baffle allowed for additional space in the corners to place deployment mechanism and would be simpler to deploy in three dimensions, a cylindrical baffle has been selected for the best stray-light and thermal performance. At the entry, a inward slanted vane will be added to reduce stray-light further.

For the 1.5 *m* three-dimensional DST, a panto-graphic design using scissor mechanisms [15] has been chosen as best option for a deployable baffle [16]. Its octagonal shape approaches the performance of a cylindrical baffle. Not shown in Figure 10 is the multi-layer insulation shroud which is attached to a selection of outer hinge points of the structure. The panto-graphic baffle has been designed and tested on smaller scale. The main remaining development challenges are the packing of the shroud and the mechanical response due to vibration and transients when deployed, which could be negatively affected by high number of hinge points and their tolerances [16].

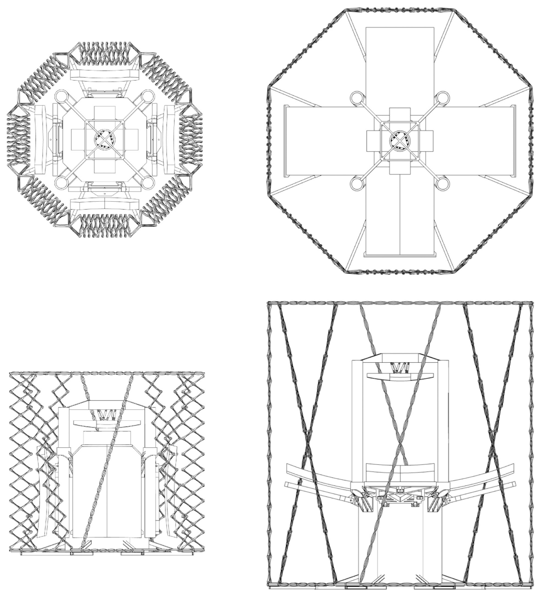

Figure 10: Design of a panto-graphic baffle (left: stowed, right: deployed).

For the 30 *cm* DST, three segmented cylindrical concentric shells will be deployed along a single axis. A DST alternative from Surrey Space Center shows a similar concept for the baffle, but integrates this directly with the deployment of M2 [6]. For the TUD DST, a separate baffle was needed to limit thermo-mechanical expansion of the M2 suspension.

5 Conclusions

A Deployable Space Telescope (DST) can push the boundaries of Earth observation from small satellites in terms of performance over mass and (stowed) volume. When embedded in a larger philosophy of miniaturization, in-orbit agility and flying in VLEO, the key characteristics are competitive or outperform high-end existing systems. The true potential of a DST will however emerge by launching them in constellations for increased temporal resolution. This way, the reduced launch and AIT cost will eventually break through the initial investment cost. Key technologies on the deployment and in-orbit actuation of optics and the baffle are currently designed and bread-boarded at TU Delft. Still, significant development steps are required towards and operational and reliable system. Due to evident advantages and the increasing number of institutes involved in the development, it is a matter of time before deployable optics and a DST for Earth Observation become common practice.

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