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A novel deployable telescope to facilitate a low-cost <1m GSD video rapid-revisit small satellite constellation

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ABSTRACT

The multi-billion dollar Earth observation applications market continues to demand better spatial and temporal resolution; simply put, this means bigger apertures and more satellites. This paper describes a novel deployable telescope that addresses the market needs for a <1m GSD imager in a small launch volume. This system will allow many identical satellites to be launched into a constellation from a single launch vehicle, providing a low-cost solution to rapid-revisit high resolution imaging requirements. Alternatively, two or three satellites could be launched in a dedicated small satellite launch vehicle, where previously only one would have fit.

Surrey Satellite Technology Ltd. (SSTL) has already demonstrated low-cost 1m GSD imagery from the Carbonite-2 platform, but the deployable telescope solution presented here provides the opportunity to build on this capability by significantly improving revisit time, without the typical increase in cost.

SSTL is developing, alongside the Surrey Space Centre (SSC) and the Dynamic Optics and Photonics Group at the University of Oxford, a telescopic deployable structure and a fine alignment system to align the Cassegrain-type telescope in-orbit. The three-concentric barrel deployable structure and mechanisms are discussed including the associated requirements and trade-off study that led to this design.

The dynamic nature of this system exacerbates traditional optical challenges such as alignment and stray light control; solutions to these are proposed, the optical design rationale is explained and predicted imaging performance shown. The novel autonomous fine alignment system, both algorithms and mechanisms, is presented. The last section deals with the spacecraft level implications and accommodation. Then finally the constellation level system design is shown with regards to the launch vehicle options and orbit configuration for coverage optimization; both global and target-specific.

Keywords: Deployable, telescope, small satellite, constellation

1. INTRODUCTION

1.1 The market

Not long ago, earth imagery from space was a rare commodity with just a few key players in the industry, but the advent of the excellent Copernicus program [1] has brought large amounts of high quality data for everyone to use. Whilst providing a lot of opportunity for the scientific community, it has meant that the market for earth imagery has changed. Copernicus, through its Sentinel series of satellites, provides a wide range of very high quality data of medium/high resolution but with a limitation on temporal resolution. Now the focus in the commercial sector has shifted to improving revisit time, something Copernicus cannot do without significant additional expense.

The emerging demand for low cost, high resolution, regular imagery and the arrival of the ‘NewSpace’ or ‘Space 2.0’ era has spurred the development of a number of different nano/micro/small satellites all aiming to quench the thirst for data. There are some companies proposing vast constellations of CubeSats, others aiming at more capable >100kg platforms, and everything in between. The customer base has a strong knowledge and influence on performance and is interested, not just in low GSD numbers, but also in high MTF across the range of spatial frequencies. Therefore the challenge set to the satellite manufacturers, fledgling and experienced, is that of quality and quantity.

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1.2 Carbonite-2

Surrey Satellite Technology Ltd. (SSTL) has a long heritage of earth observation satellite systems [2] making it a market leader in the design, build and operation of optical imaging systems and their respective platforms. These have included push-broom, multi-spectral, hyper-spectral, wide-swath systems and more recently high resolution video.

Carbonite-2, launched in January 2018 [3], demonstrated the world’s first commercial high-resolution full color video from space; it achieved a GSD of 1m with good MTF. This mission was a follow-on from Carbonite-1 which was a rapid build, very low cost system using a COTS telescope. Some modifications and improvements to this have resulted in some very impressive imagery, a frame of one such video is shown in Figure **1**. A sample of the videos from orbit can be accessed from SSTL’s YouTube channel, SSTLTV [4].

Figure 1: Dubai airport acquired by Carbonite-2, 2018. Credit: SSTL.

2. DEPLOYABLE TELESCOPE DESIGN

2.1 Design philosophy

A traditional Cassegrain-type telescope has a large amount of unused volume between the primary mirror and the secondary mirror; the principal aim of this telescope is to reduce this volume during launch. The secondary mirror can be held in a stowed configuration near the primary mirror and then deployed to a near-nominal position once in orbit; further fine alignment can then be performed.

There are a number of potential benefits that this technique can provide to a mission. Firstly, the volume savings in the launch vehicle can allow the use of different launch slots or vehicles, this is discussed in some detail in Section 4. Secondly, the deployment of an optical system can minimize the design restrictions on the opto-mechanical structure as the alignment of the optical elements isn’t required to be maintained during the launch event which has the potential to save mass. Thirdly, the design has been developed with scalability in mind, and so it could be used in the future with a much larger system for higher resolution EO imagery or astronomy.

A loose goal of this payload development is to improve on the imagery provided by Carbonite-2 at one third of the volume at launch. The technique proposed here might not be the optimal or most elegant solution to a deployable telescope, but it designed to be rugged, low-cost and to meet the technical requirements.

2.2 Optical design

The optical design is a modified Dall-Kirkham variation of a Cassegrain-type telescope, with an elliptical primary and spherical secondary mirror, a series of COTS lenses are used to minimize off-axis image degradation. A novel baffling system has been designed which deploys with the telescope and manages stray light, but is purposefully omitted from Figure **2**.

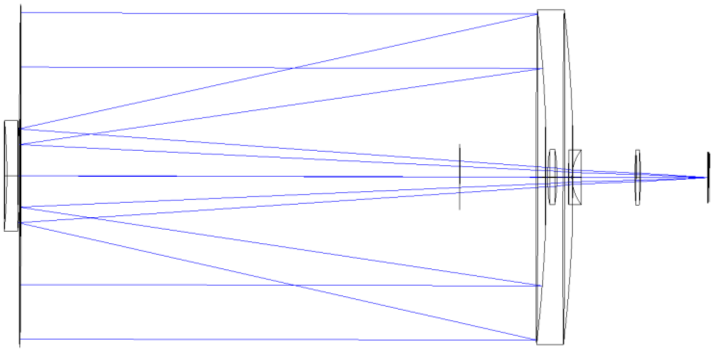

Figure 2: Optical design of telescope

This design was chosen for its performance, simplicity, compactness potential, and ease of alignment. The spherical secondary mirror is the optical element which needs to be manipulated in-orbit to achieve alignment. Typically a rotationally symmetric mirror requires five degrees of freedom to be aligned, but with a spherical reflective surface, this can be reduced to three. Tip and tilt about its center of curvature can be traded off for decenter, thus removing two degrees of freedom. This trade-off can introduce some clipping of the beam by moving the secondary away from its nominal position in the optical axis, but with deployment induced misalignments expected to be small, the impact of clipping is likely to be negligible.

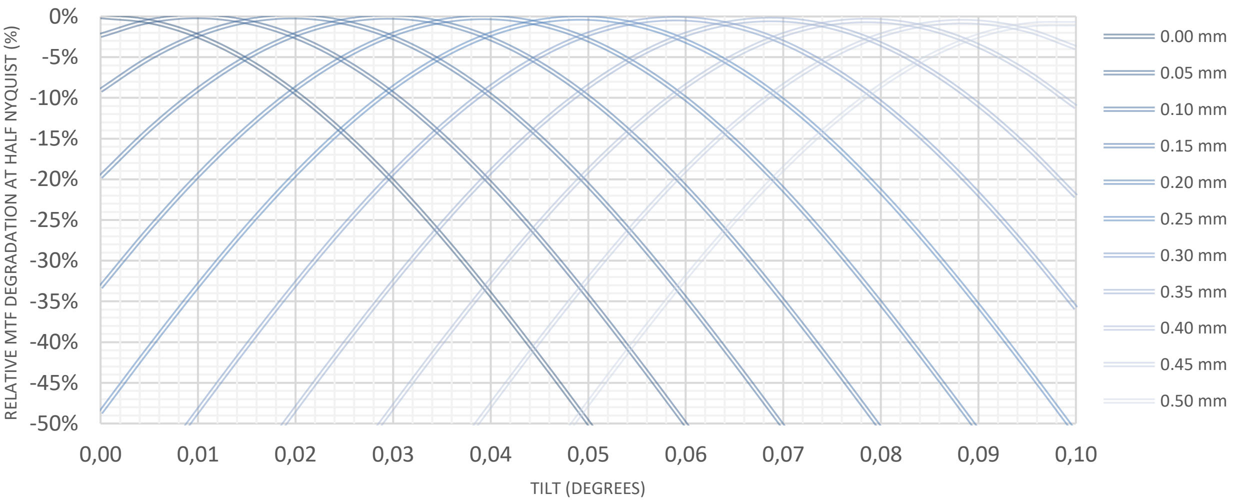

Figure 3: Relative MTF degradation from nominal at half Nyquist against tilt of secondary mirror for a range of mirror decenters

The relationship between decenter and tilt is displayed in Figure 3; it shows for a given starting decenter of the secondary mirror induced by the deployment and launch events, the tilt about the opposing axis that is required to compensate for it. The extreme case is a 0.5 mm decenter, for which a 0.1 degree tilt will be required. This helps confine the requirements of the alignment mechanisms, and supports the decision to use a Dall-Kirkham design.

2.3 Mechanisms

The dynamic nature of this telescope means that there are a number of different mechanisms that need to be employed in order to ensure that the telescope can be safe during launch, deployed accurately and then aligned. The first is the deployable telescopic barrel as it is essentially one large mechanism in itself. Secondly, there are three identical fine alignment mechanisms that interface between the barrel and the secondary mirror. Finally there is a hold down and release mechanism (HDRM) designed to ensure that the other parts are secure during the launch event.

2.3.1 Deployment

This component provides the critical distance member between the primary and secondary mirrors. The main goal of the deployment mechanism is to minimize this distance when stowed, and then return to the nominal distance in an accurate, repeatable and low shock fashion.

A number of different concepts have been investigated, including trusses, telescopic tubes and barrels, and then a trade-off study was performed to identify the preferred solution. The criteria were: mass, length reduction, thermoelastic stability, complexity, scalability, stray light management, cost and repeatability.

The selected approach consists of three concentric carbon-fibre barrels; the lower most and narrowest is mounted to a bulkhead which interfaces to the spacecraft. The middle and upper barrel are deployed post-launch simultaneously by lead screws spaced at 120° around the circumference, driven by a ring gear and redundant motor arrangement in the base. They are driven into V-blocks which provide high positional repeatability.

Figure 4: The deployable telescopic barrel, stowed (left) and deployed (right)

The chosen concept exhibits a high tolerance to launch loads when stowed and to micro-vibration when deployed, therefore enabling the imager to perform well during operation.

2.3.2 Alignment and focus

Once the barrel is deployed and the secondary mirror has been moved from a stowed configuration to near-nominal position, some adjustment of the secondary mirror alignment will be required. The deployable barrel will have a repeatability of less than 1mm in each axis and so the required travel range of the mechanisms will be short. A three-armed spider will hold the secondary mirror, with each arm having a linear actuator driving it in the z-direction (piston). When operated together, this provides piston of the secondary mirror, and when driven individually, it provides tip and tilt; it is therefore a 3-axis system.

The alignment mechanisms also double up as a focus mechanism. Traditionally the focal plane array would be actuated along the optical axis in order to perform small focus adjustments in-orbit, however in this design the focusing is done by translating the secondary mirror along the optical axis with the primary mirror and focal plane fixed in place. The nature of the optical configuration of this telescope means that small movements at the secondary mirror mean large movements at the focal plane. The chosen optical design has a ratio of 1:12, so that a 1um movement of the secondary mirror causes a 12um shift at focus, this means that the step size requirements of the linear mechanisms are driven by the focus step size requirements.

2.3.3 *Hold down and release*

A single-shot shape memory alloy device, based on extensive heritage, holds down the secondary mirror assembly and telescopic barrel during the launch event and then can be commanded to release once the spacecraft is stabilized in orbit. There is one mechanism on each of the three spider arms around the secondary mirror and so will be activated simultaneously. The mechanism is low-shock and will allow the mirror back onto its flexures for alignment.

2.4 Alignment system

In partnership with the Dynamic Optics and Photonics Group at the University of Oxford, utilizing their experience in adaptive optics systems [5], novel autonomous alignment algorithms have been developed to improve the on-ground build procedure of space based telescopes. Now the partnership has been extended to develop algorithms for autonomous alignment in-orbit, and a different approach is taken due to the change in operating conditions in space compared to the lab.

In-orbit alignment can be carried out using an image-based method as illustrated in Figure 5. Suppose the image is initially blurred by an aberration with a magnitude of a. This aberration could be defocus for example, owing to an incorrect z-position of the secondary mirror. The amount of blur in the image can be characterized using an image quality metric M, such as the magnitude of the high frequency components of the image power spectrum. By measuring the image quality metric when applying three bias magnitudes 0, $+b$, and $–b$, by adjusting the z-position of the mirror, the required correction can be determined. This procedure can be repeated to account for tip and tilt errors. This can be done quickly, on the fly, whilst staring at a target.

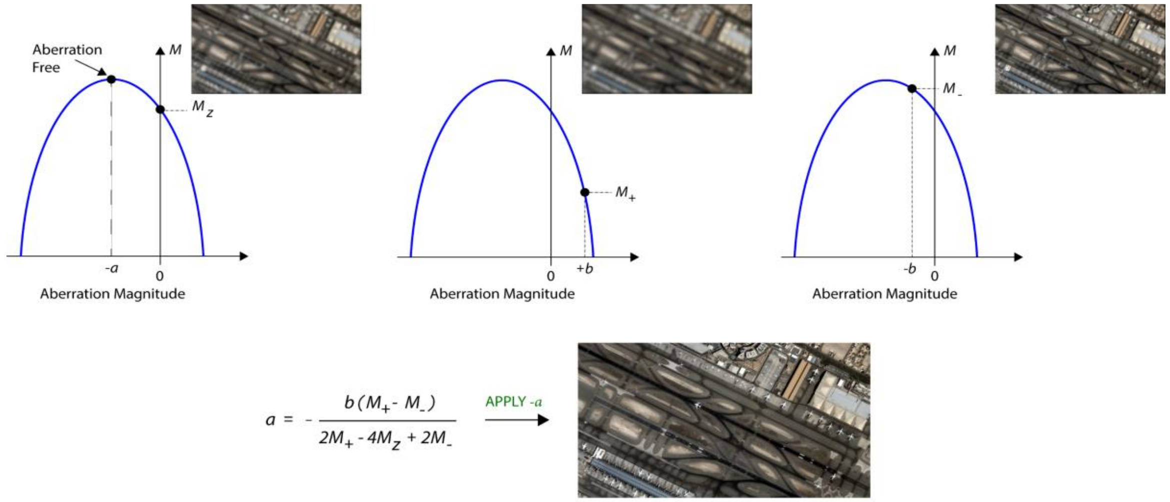

Figure 5: Proposed image based alignment technique

2.5 Detector and FEE

Carbonite-1 and 2 used a COTS CMOS detector, a large area array with an RGB Bayer pattern, the same sensor has been baselined for the deployable telescope. Read-out electronics are developed in-house, including a processor on which the alignment algorithms are run.

3. SPACECRAFT LEVEL DESIGN

In order to utilize the technology of a deployable telescope, it needs a compact and highly capable platform to suit. SSTL has a strong track record of developing small satellite platforms for a range of applications; and its latest creation is the SSTL-42.

One of the key challenges with launching small spacecraft into orbit is finding the right balance between system performance and system cost. The SSTL–42 has been designed as a highly capable system, offering excellent payload power, mass carrying capability and redundancy. It offers the performance of a significantly larger system in a small, auxiliary launch-compatible form factor. In particular, the system provides excellent power provision with a high capacity battery enabling continuous payload operation.

The SSTL-42 elegantly combines heritage and innovation to ensure optimised performance and reliability. The platform is customisable with two proposed variations; standard and high power variants. There a wide range of potential applications and additional downlink capacity is possible for imaging payloads.

- 7 year mission design life
- Compatible with most auxiliary launch vehicle slots
- Fully redundant avionics
- Dedicated propulsion bay
- Up to 65 kg Payload Mass
- Up to 63 W always-on payload power
- Up to 200 W peak payload power
- Dedicated payload thermal management design
- Payload downlink options of; 4 Mbps S-Band, 160 Mbps X-Band

Figure 6: The SSTL-42 platform with proposed payload bay, high-power variant on the left

4. RAPID REVISIT CONSTELLATION

4.1 Case study

A small constellation of “Carbonite-2-like” spacecraft [6] in Sun Synchronous Orbit (SSO) would be suitable for launch from any of the new or emerging small launch sites around the world including the proposed UK launch site in Scotland.

We can consider a case study of a constellation of 6 spacecraft in a 500km altitude SSO that has 3 planes of 2 spacecraft each. This would assume the availability of a Rocket Lab “Electron” class of launch vehicle with a ~200 kg payload capacity to 500 km SSO. It is an SSO constellation so orbit planes are not evenly spread; the first plane with Local Time of Ascending Node (LTAN) = 10:00, second plane with LTAN = 13:00 and third plane with LTAN = 16:00.

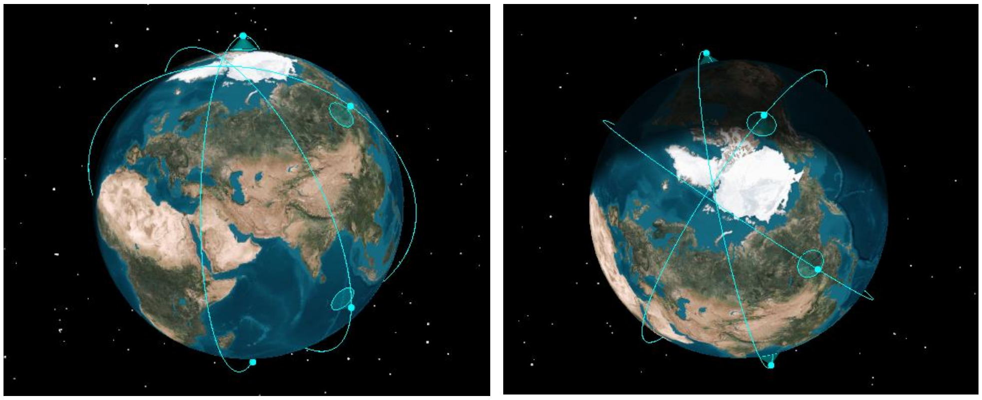

Figure 7: Constellation of 3 planes of 2 satellites each

The 3 planes are offset by 45 degrees with spacecraft separated by 180 degrees in-plane. A “normal” Carbonite-2-like spacecraft occupies all of the available volume under the fairing of an Electron class vehicle and a single Electron rocket costs ~ £4.5M.

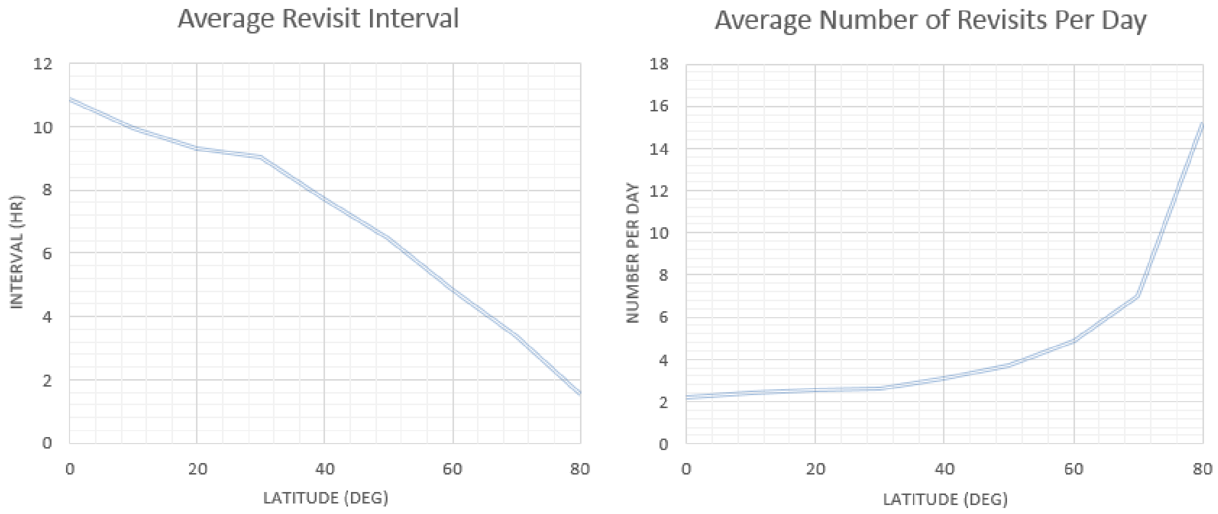

Figure 8: Basic constellation performance

4.2 Benefits of a deployable telescope

The constellation is attractive from a customer point of view as it samples at different local times rather than a fixed time, as is the case with a single larger spacecraft. It can be very useful for many economic, business, security and military applications. However, to do this kind of mission with launching all 6 spacecraft at the same time on a single rocket is impossible. All 6 satellites would need to be launched into the same orbit plane and there is no rocket available today that can provide a 90-degree node shift to deploy into three separate orbit planes directly. The constellation needs to separate into 3 separate orbit planes which could be achieved by a small manoeuvre to shift the relative altitude of the satellites so they experience a differential node precession rate (the “J2 Effect”).

However at SSO inclinations the rate of separation that can be achieved within the ΔV budget of a Carbonite-2-like spacecraft is very low, even spending 100 m/s to do the drift would only “reduce” the drifting time needed to ~10 years. The only really feasible option is to envisage a launch directly into each of the three orbital planes, it is worth noting that piggyback opportunities are also very rare into afternoon LTAN SSO orbits.

With a spacecraft that occupies all of the volume but only a half of the lift mass of the rocket, then 6 separate launches would be needed. Very basically, a deployable payload allowing 2 spacecraft under the fairing of the rocket reduces this to 3 launches, halving the launch cost. There is also the potential for a quicker constellation deployment (starts to make money earlier) and it reduces significant other costs to the user (e.g. reduction in launch campaign, shipping etc.).

4.3 Launch campaign case study

A pragmatic assumption on actual launch cadence that will be feasible, would be for a launch facility to provide a launch service roughly every 60 days, which is about 6 launches per year.

For the case when a single spacecraft is on a single rocket (6-off launches), each satellite goes directly to its assigned slot in its orbit plane and the total time between first and last launch is 300 days. The total launch cost is £27 M and there are 6-off launch campaigns to run.

For the case when deployable optics allows 3-off launches of 2 satellites, each pair of satellites is launched together into the assigned orbit plane then the satellites have to separate by 180 degrees in-plane. Each one can move 90 degrees away from its nominal injection location (one goes "forward", one goes "backwards"). This would take about 40 days in 500 km SSO if ΔV of 2 m/s is used on each spacecraft (which is compatible with a Carbonite-2-like gas propulsion). In-plane drifting can take place whilst other launches are happening and so total time between first launch and last satellite arriving at its assigned location = 160 days. The total launch cost is £13.5 M and there are 3-off launch campaigns to run.

In this case the deployable optics allows a nominal cost saving of approximately £13 M in terms of launch cost and there are additional potential savings in shipping, insurance, launch campaigns etc., which is not quantified but will be non-negligible. There is also a decrease in constellation deployment time of ~140 days (~4.5 months).

5. CONCLUSION

A deployable telescope has been designed that has the potential to improve upon the performance of Carbonite-2 and, alongside the SSTL-42 platform development, will be available in a smaller package which can drastically reduce the cost of deploying a constellation of small imaging satellites. An optical design optimized for the system has been identified and the deployment and alignment concept has been decided.

During Q4 of 2018, a working breadboard of the deployable barrel mechanism is being developed, with a series of verification tests planned to ensure deployment repeatability and thermal stability. In 2019, the goal is to develop a telescope PFM, and identify a launch opportunity for a demonstration mission. This would pave the way to an operational constellation providing low-cost rapid-revisit high resolution imagery all over the world.

Beyond that, the scalability of the design could be put to the test, perhaps with a CubeSat mission or a much larger aperture telescope. There is also the ambition that this technology development will be an enabling step to in-orbit assembly of larger structures [7].

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