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Breaking the Smallsat Barriers to Sub-50cm Imaging

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ABSTRACT

New cutting-edge imaging sensors can now reduce instrument size and mass, leading to mission cost savings, and bring sub-50cm imaging capability into the realm of small satellites. Whilst aperture is essential to achieving resolution, half-pixel shifted sensor architectures decouple achievable Ground Sampling Distance (GSD) from the native ground projected pixel. This facilitates the deployment of Very High Resolution (VHR) small satellite constellations featuring improved Signal-to-Noise performance and increased area collection rates compared to push-frame systems.

A fundamental limitation to the theoretical performance of an optical system is imposed by its aperture diameter; hence, for a given aperture, the aim is to maximize the information content resolved up to this limit. This is achieved by minimizing losses caused by aberrations in the optical system and enhancing platform stability on-orbit. Further information is lost due to aliasing at higher spatial frequencies; however, the recovery of such information is unlocked through the novel sensor technology and processing techniques proposed.

Funded under the European Space Agency (ESA) “Investing in Industrial Innovation” (InCubed) program, this paper reports on the build and verification campaign of a sub-50cm capable instrument Proto-Flight Model (PFM), the beneficial properties of half-pixel offset sensors, and the platform supporting such a payload.

INTRODUCTION

The clear aperture size of an optical system imposes a fundamental limitation to theoretical resolution performance that can be achieved. For any given aperture, the aim is therefore to maximize the information content resolved up to this theoretical limit. The information content transmitted through an optic can be partially evaluated by the system’s Modulation Transfer Function (MTF), which describes the contrast transmitted through the system at various spatial frequencies. The theoretical highest spatial frequency that may be transmitted, the optical cut-off frequency, is dictated by the aperture diameter of the system. Hence, larger apertures may transfer higher spatial frequencies from the object space to the image space.

However, larger apertures also drive increased telescope costs. It has been demonstrated[1] that the cost of an optical telescope assembly is proportional to the primary mirror diameter to the power of 1.7. Furthermore, unless complex and costly deployable optics are used, small spacecraft place an inherent limit on the maximum payload size and therefore aperture diameter. If a larger platform is used to host a larger payload, with increased size and mass, this typically leads to compounding effect on cost. Furthermore, larger spacecraft with greater launch masses impose increased launch costs and are less well suited to the deployment of constellations that facilitate revisit.

These factors of aperture diameter and spacecraft size/mass create the common conflict of performance versus cost. If we are to maximize the ratio of performance-to-cost, we must maximize the information content resolved from smaller aperture systems hosted on small low-cost spacecraft. This may be achieved by minimizing losses caused by aberrations; which can arise from the manufacture of optics, imager alignment and thermoelastic effects on-orbit. Additionally, platform affects such as pointing stability and the vibrations transmitted to the optical system must be appropriately controlled. Finally, useful information lost due to aliasing at higher spatial frequencies should be made accessible. Hence a system level approach must be taken to realize high performance at a lower cost than has been traditionally viable.

SSTL’s vertically integrated low-cost production techniques, alongside advances in imaging sensor technology to reduce aliasing, provide an opportunity to overcome the cost barriers to high resolution imaging. Low mass and cost small spacecraft are well suited to deployment at scale, establishing constellations that achieve detailed high quality earth observation and a high temporal resolution.

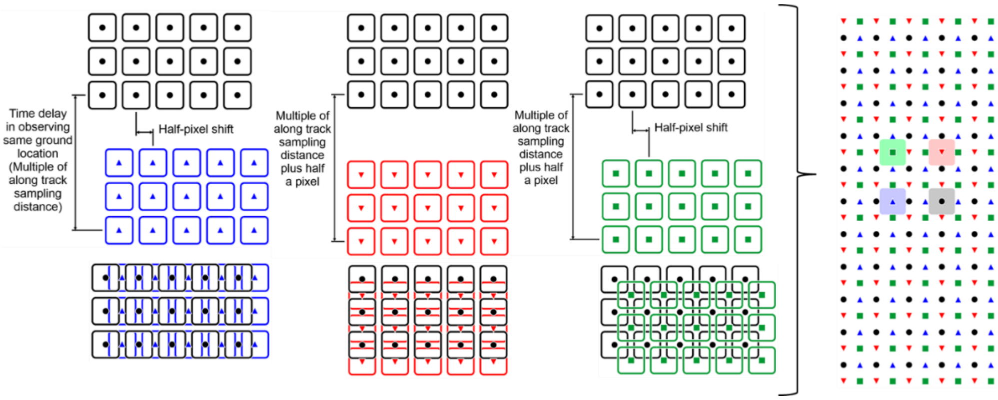

Figure 1. The linear sensor employed in the SSTL Precision payload features 4 banks of PAN pixels, each separated in the along-track direction with a half-pixel offset to one another, facilitating double the sampling.

THE BARRIERS TO HIGH-RESOLUTION IMAGING FROM SMALL SATELLITES

A line or array of rectangular pixels are often employed to sample an optical image produced at the focal plane. Fine spatial sampling, through a small pixel size, is beneficial as it facilitates a high Nyquist limit for the spatial frequencies that can be accurately sampled. Beyond this Nyquist limit spatial frequencies transmitted by the optical system are aliased, generating unwanted artifacts such as Moiré patterns. Whilst desirable for a high Nyquist frequency, small pixels often limit Signal-to-Noise Ratio (SNR). Ideally therefore, finer sampling would somehow be achieved whilst using larger pixels, which appears to be a contradicting aim.

The sensor pixel size and the focal length of the optical system traditionally describe the Ground Sample Distance (GSD). For a given sensor pixel size, aperture size and platform stability, it is possible to achieve a small GSD using a long focal length. However, such a system could still produce poor quality imagery if the optical system or platform stability result in a blurred or distorted image that is sampled. It can also be challenging to accommodate a payload with a long focal length within a small platform.

Some spacecraft or payload providers may try to avoid the uncomfortable truth of aperture limited performance from small satellites and propose solutions that employ “super resolution processing” to achieve “beyond diffraction limited” performance. Such statements do not conform with fundamental physical laws and are sometimes applied to solutions which simply employ sharpening filters or up-sampling to improve the visible nature of the image product. Alternatively, there are proven methods that facilitate real improvements to information content. These rely on collecting additional information; either through careful characterization of the imager, or through additional samples.

MAXIMISING OPTICAL PERFORMANCE FROM A SMALL SATELLITE

To improve the spatial sampling of an of Earth observation spacecraft operating in pushbroom mode, additional overlapping samples of the same object on the ground may be collected at very small time intervals and processed together. This breaks the traditional view that sampling is dictated by the size of the sensor pixel projected on the ground. Whilst relevant, it also depends on the arrangement of the pixels on the focal plane.

Collecting additional samples through half-pixel offset sensors to reduce aliasing is a method proven on the CNES SPOT5 satellite[2]. The SPOT5 “supermode” employs a single shifted line of pixels. This additional line is shifted by half a pixel in both the horizontal and vertical directions, providing an improvement in sampling equivalent to the square root of 2 when synchronized to the ground rate. The proposed “hipermode” takes this further to effectively double sampling with double the sensor line rate. This is not compatible with sensors that employ Time Delay Integration (TDI), as the line speed of the sensor is required to match the ground rate.

The Precision imager has been developed by SSTL through the European Space Agency (ESA) Investing in Industrial Innovation (Incubed) program[3] to develop a very high-resolution multi-spectral (MS) Earth observation system. It features a 420mm clear aperture primary mirror and a 4200mm focal length. This has included the development of a new linear detector that facilitates double the sampling of a conventional sensor. Four banks of pixels, each offset to one another by half a pixel, successively image the ground to obtain additional samples (Figure 1). There is a datum bank, illustrated by black circles, a bank shifted in the horizontal direction (blue upright triangles), the vertical direction (red upside-down triangles) and the both the horizontal and vertical directions (green squares).

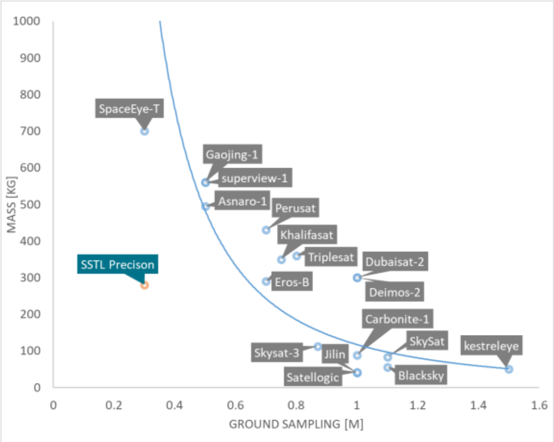

Figure 2 Ground sampling against mass for selected public high resolution spacecraft

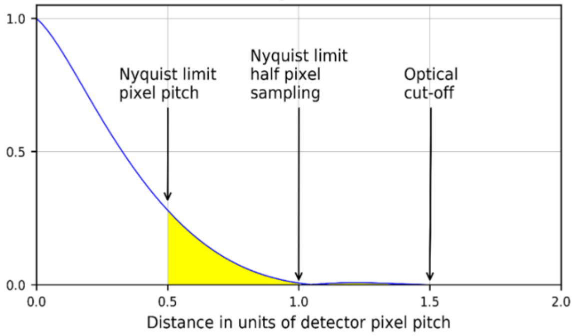

Figure 3 Illustrative example of a 420mm aperture diameter optical system MTF performance. The region in yellow would be aliased without half-pixel sampling and becomes accessible with additional samples.

The offset pixel banks double the sampling compared to a conventional detector, providing 0.3m sampling on the ground rather than 0.6m natively from a 500km orbit, a 9.5km swath is also achieved. This effectively doubles the Nyquist limit and significantly reduces aliasing. Figure 2 highlights how spatial sampling at this granularity within the compact ~280kg SSTL-Mini platform provides a solution that breaks the traditional barriers and trends of very high-resolution space missions. It facilitates a higher ground sample distance than would traditionally be expected for a spacecraft of the mass specified. Additional details on the platform design philosophy are discussed further within this paper.

Advancing beyond the SPOT5 hipermode, each off-set bank within the SSTL Precision's sensor is also capable of Time Delay and Integration (TDI) to enhance SNR. This is particularly beneficial for very high resolution systems where the small projected pixels necessitate a small integration time for a pushbroom sensor, TDI allows for high performance under challenging lighting conditions. Using TDI an SNR of 100:1 is readily achieved for all bands at 30% albedo, 45° Solar Zenith Angle (SZA), whilst simultaneously avoiding saturation on all but the brightest of targets (~95% albedo SZA45). Anti-blooming technology additionally prevents saturation from affecting neighboring unsaturated pixels.

Figure 3 shows an illustrative MTF for an optical payload that has been simulated. The area in yellow highlights the spatial frequencies which would be aliased using conventional sampling with a 5um pixel. With 4 samples half-pixel offset to each other the frequencies in yellow become accessible and unambiguous. The following conditions are applied to the generation of this MTF:

- Diffraction limited aperture diameter: 420mm.
- $\lambda/4$ wave front error applied.
- Representative 5um detector function.
- Note platform stability is not included.

The aperture diameter establishes the diffraction limited performance of a circular aperture equal to the Precision imager's diameter. A wavefront error of $\lambda/4$ is applied to degrade optical performance away from the theoretical diffraction limit and more closely represent manufactured performance. Based on SSTL's experience with measured image sensor data, a representative detector function for a 5um pixel has also been generated.

The improvement in aliasing performance from such a system is also intuitively demonstrated in simulated imagery generated by SSTL. This is designed to represent the Precision payload resolution performance from a 500km altitude. Figure 4 shows the base image chip, at a 7.63cm GSD, which is generated by aerial photography. This base imagery is convolved with the diffraction limited optical system point spread function, including the impact of the secondary mirror central obscuration, and sampled at 0.6m. This represents the performance with a half-pixel shift sensor (Figure 5), where each image chip represents the half-pixel shift in each direction. Finally, the samples can be interleaved to produce the final image. Note platform stability effects are not included, no noise model was applied besides that of the base imagery and for these simulated images a wavefront error has not been applied.

Such simulated imagery clearly outlines the benefits that can be achieved using a half-pixel offset sensor. Additionally, they have supported the design process for the specification of the overall value of wavefront error that would be acceptable from the Precision payload optics. As discussed later within this section, the optical tube assembly has now been manufactured (Figure 7) and is undergoing testing. After testing has concluded, the assumptions within the simulated model can be retired and replaced with measured data.

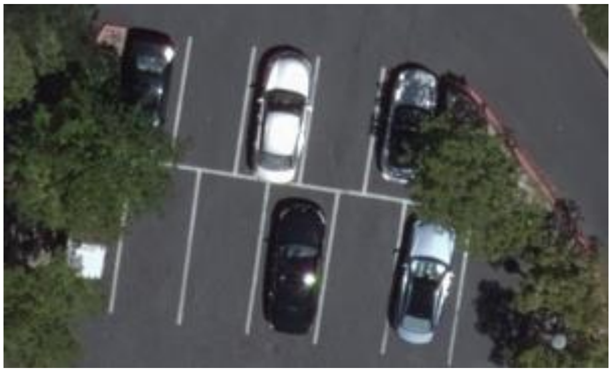

Figure 4: Base imagery used for simulation – 7.63cm GSD.

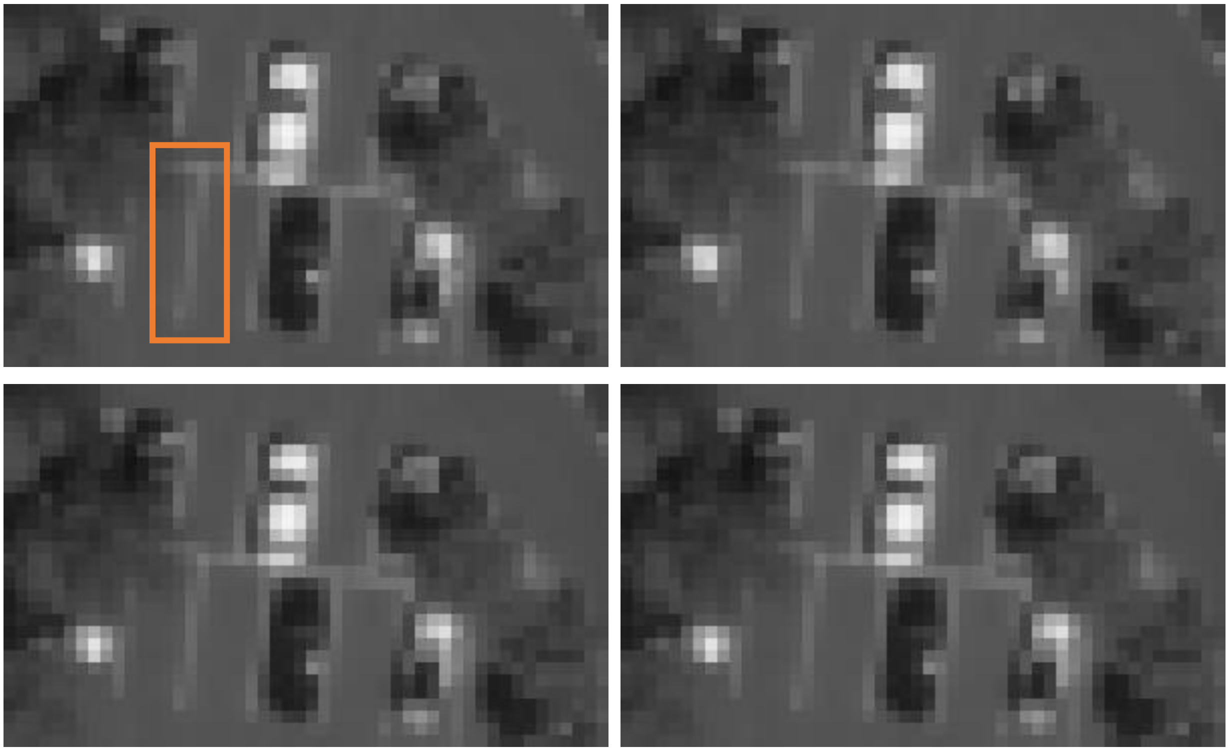

Figure 5: Base imagery convolved with imager PSF and sampled at 0.6m GSD. Illustrating the performance of conventional imaging payloads without half-pixel shift technology. In these images aliasing can be seen on parking bay lines. Each panel represents one of the shifted banks of pixels in the Precision optical system.

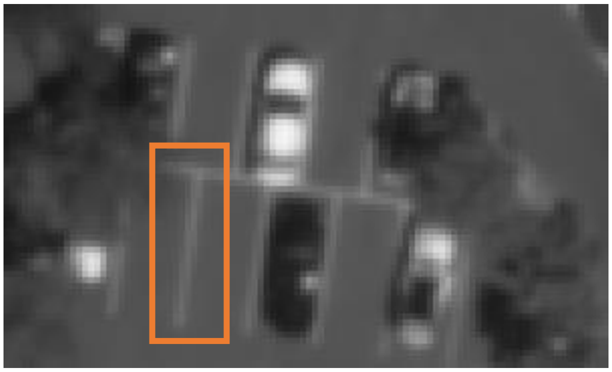

Figure 6: Base imagery convolved with imager PSF and sampled at 0.3m GSD. Representing half-pixel shifted performance and visibly reducing aliasing.

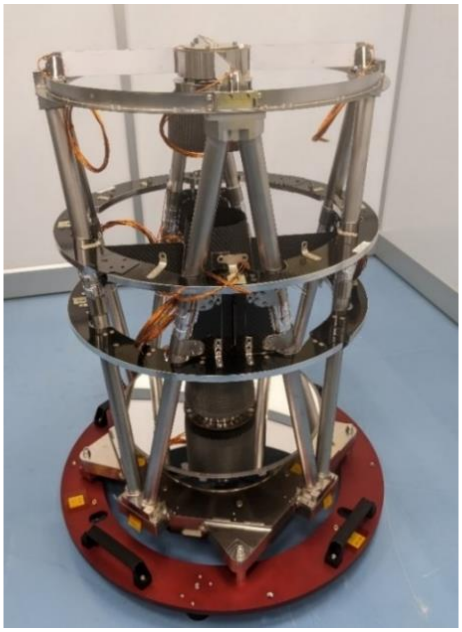

Figure 7. The Precision imager optical tube assembly

To further enhance the performance-to-cost ratio, the payload design has been optimized for low-cost manufacturing techniques which also maintain high stability and performance of the optical system. Thermoelastic stability of the opto-mechanical design may be achieved through active thermal control, however this leads to increased power demands which are particularly undesirable for small spacecraft featuring limited solar array areas. Hence, for the Precision payload, a passive athermal approach has been pursued; This includes the prevention of excess thermoelastic stress in the mirrors and minimizes bowing of the detector during operation.

Through the ESA Incubed program a Proto-Flight Model of the Precision optical tube assembly has been manufactured (Figure 7) and is currently undergoing testing. The majority of the structural components are metallic, such as the truss metering structure, while straylight components are made from light-weight carbon composites.

While SSTL has significant heritage in imager designs employing high-performance carbon composites, such as on the N-2 *(Nigeriasat-2)* and S-1 *(DMC-3/TripleSat)* payloads, a metallic truss structure has been selected to enable the use of readily available and machinable materials (Figure 8). These can be procured on shorter timescales and avoid issues associated with high performance resins such as minimum order quantities, long lead times and limited shelf life, ultimately driving down the payload cost. The metallic truss approach is also a common design feature within the latest SSTL carbonite-class of smaller imagers. Allowing lessons learnt to be shared from the similar manufacturing processes used, facilitating improved efficiency on the Precision payload manufacture. The Precision payload advances on the composite N-2 and S-1 imagers to produce a compact system, <1.25m in length and <55kg mass, at a lower cost and with higher performance. This results in a spacecraft better suited to rideshare opportunities and constellation deployment. Further detail on the Precision payload design and specification can be found in [4].

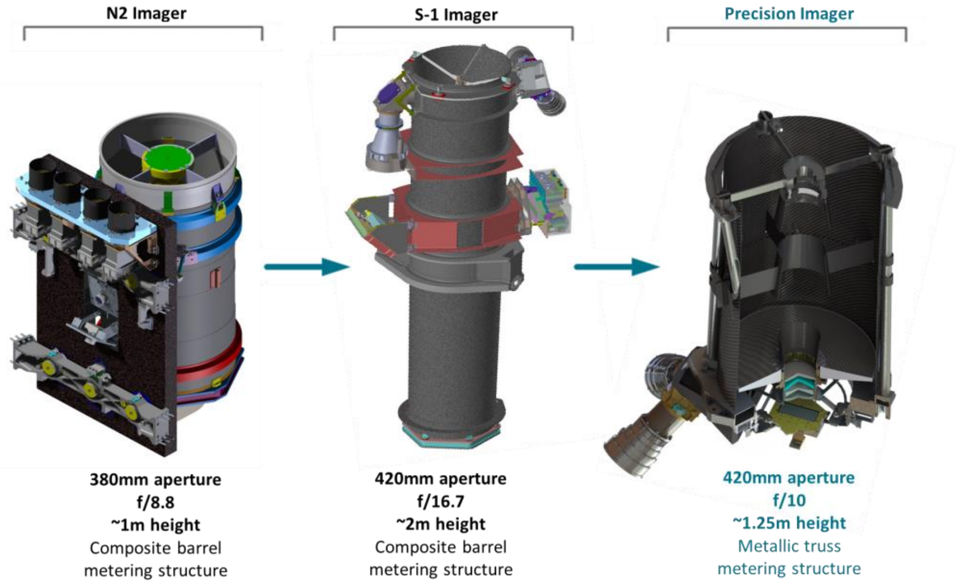

Figure 8 The evolution of the SSTL's high performance imagers, to improve performance whilst simultaneously constraining size and mass (Note: not to scale)

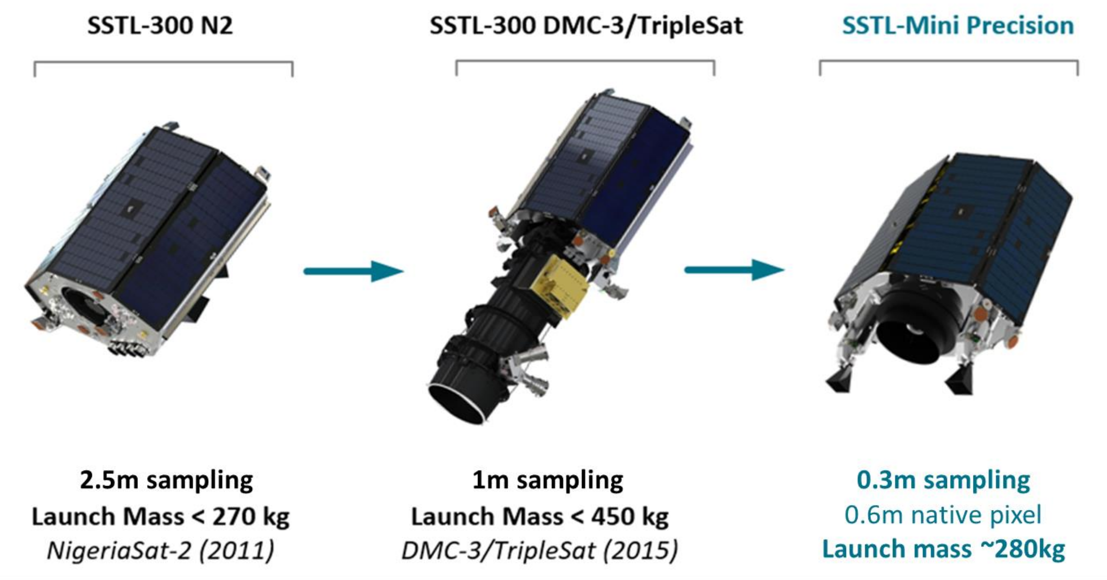

Figure 9 SSTL Mini Structural Heritage

SSTL-MINI PRECISION MISSION CAPABILITES

SSTL have developed the ~280kg *SSTL-Mini Precision* to host the payload outlined. This builds upon SSTL's extensive small satellite heritage and presents the latest iteration of the high performance SSTL-300 platform (Figure 4). Through these iterations several improvements have been made; SSTL's core avionics suite has been upgraded, improving payload data throughput and additionally platform agility and stability performance has been enhanced.

The SSTL developed XTx-800 transmitter is selected for the *SSTL-Mini Precision* and builds upon SSTL's heritage X-band transmitter for increased throughput. Using advanced modulation protocols the XTx-800 can support up to ~1200Mbps over-the-air data rate. The spacecraft is equipped with two XTx-800s which may be used in conjunction to effectively double this data rate (note some losses are expected due to interference). This improvement allows a *SSTL-Mini Precision* mission to maximize the volume of high-resolution imagery collected over its 7-year design life, further enhancing the value proposition.

Furthermore, the AOCS system has been revised to improve agility from the *DMC-3* heritage baseline. This required a considered assessment of the potential negative vibrational impacts of using additional, or larger, reaction wheels. Ultimately, the selection of 6 SSTL developed SSW-110 reaction wheels met the specification required; an increase on the 4 wheels employed on the *DMC-3* mission. This facilitates improved acceleration and rates for retargeting, even in the event of a reaction wheel failure. Due to its heritage, the SSW-110 vibrational performance is well characterized by SSTL and can be successfully isolated from the payload through anti-vibrational mounts, mitigating the impact on final image quality. In addition to the improved reaction wheel configuration, the AOCS guidance and control law algorithms have been advanced to improve settling time for rapid retargeting. A field of regard of 45° in pitch and roll is achieved and the agility performance allows targets separated by 60 degrees to be imaged within 60s.

This increased agility enables a range of novel imaging modes such as Spot, Strip, Inclined Strip (for covering coastlines or borders), Across-Track Stereo, Along-Track Stereo, and 2 x 2 Mosaic Mode (Figure 10). High resolution imaging with these modes would enable applications including disaster monitoring, risk assessment, reconnaissance, and urban planning.

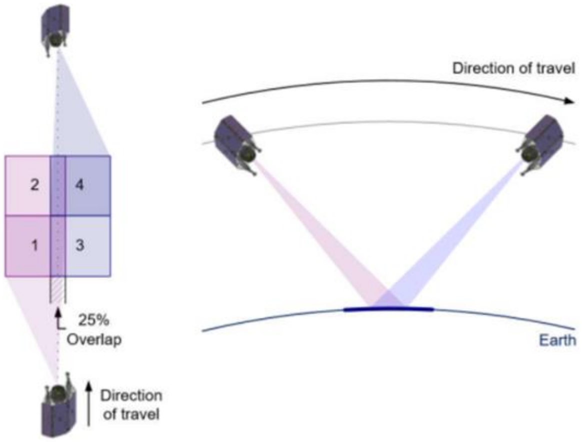

Figure 10 Example high-agility mosaic mode

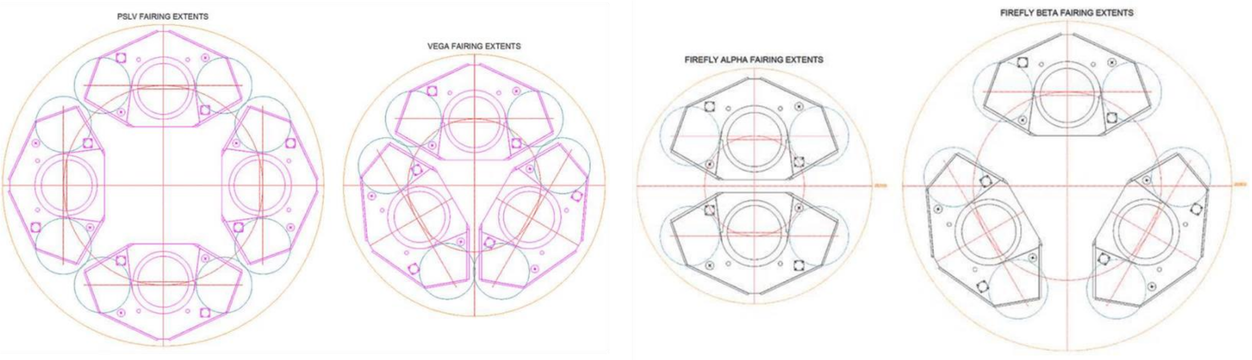

Figure 11. Accommodation of multiple SSTL Mini Precision spacecraft within PSLV, VEGA, and Firefly launch vehicles

Figure 12 Three *DMC-3/TripleSat* spacecraft within the PSLV-XL launch vehicle, 2015 (orange box)

DESIGNED FOR MISSIONS AT SCALE

The shape of the platform structure for the first SSTL-300 mission, Nigeriasat-2, was designed for natural accommodation within launch vehicles, particularly alongside other SSTL-300 spacecraft for constellation deployment (Figure 11). The outer perimeter of the spacecraft is designed to align with the curved payload fairing diameters of medium sized launch vehicles. In July 2015 this was demonstrated via the launch of the three *DMC-3/TripleSat* spacecraft onboard a PSLV-XL launch vehicle (Figure 12).

Furthermore, when the spacecraft is in sunlight, the shape of the body mounted solar arrays are beneficial for power generation when compared to a flat surface of the same area in a 10:30am LTAN Sun-Synchronous Orbit typical for optical Earth observation missions.

A scenario modelling the optical imager swath of 9.5km and a spacecraft roll of +/-30 deg (of a maximum possible +/-45deg roll) has been developed to examine the system's revisit time. For an optical sensor in the visible waveband the revisit time is defined as the time it takes for the satellite to image the same point on the Earth's surface, during direct sun. The analysis has been performed for spacecraft in a reference orbit of 500km altitude with an LTAN of 10:30am, studied over a duration of one year starting January 1st. As presented in Figure 13, the worst-case revisit time for a target located at 0 deg latitude is found to be 5 days (120 hrs) for most of the year, with a window of lower revisit times that range from 24 hours to 4 days.

A constellation of three precision satellites was also explored. These were separated by 120deg in True Anomaly, a configuration proven on the SSTL *DMC-3/TripleSat* mission. Employing the same 500 km 10:30 LTAN orbit, the frequency of access to a target point located at 0 deg latitude is greatly improved, with a revisit time that fluctuates between 2 days and 1 day, with a worst-case maximum revisit time of 2 days.

As can be expected from economies of scale, deployment of a constellation has additional commercial benefits. Efficiencies in manufacturing processes are enabled and non-recurring engineering costs are reduced through the use of common parts, driving down the cost per spacecraft.

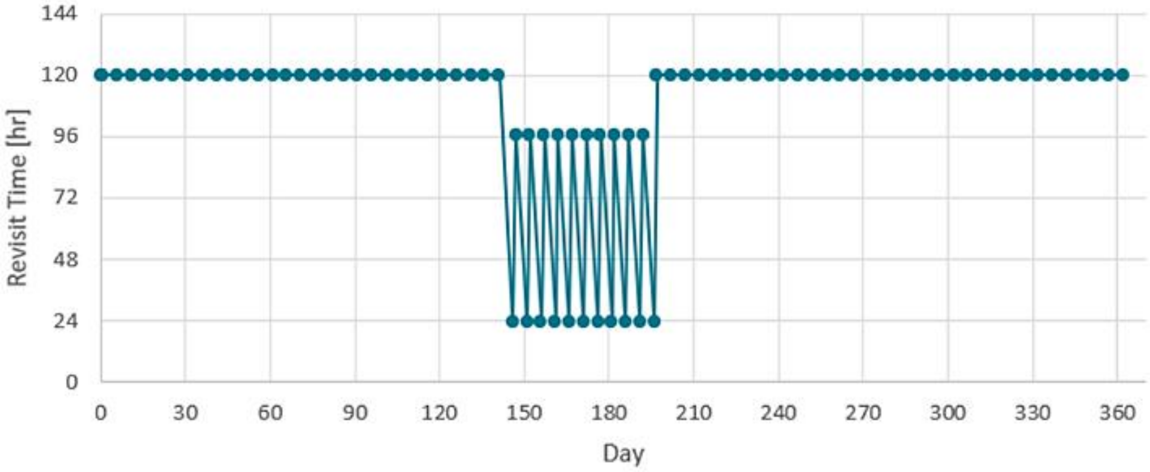

Figure 13 Worst case revisit times for a 0deg latitude target, for a single spacecraft

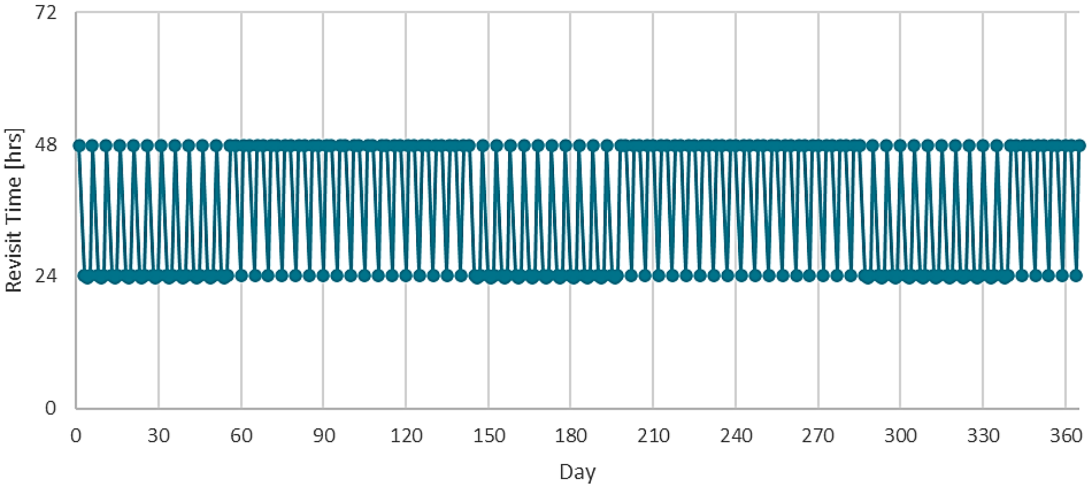

Figure 14 Worst case revisit times for a 0deg latitude target, for three spacecraft

CONCLUSION

Within the constraints of a low-cost, small satellite form factor, SSTL have developed the ~280kg SSTL-Mini Precision spacecraft to deliver very high-resolution imaging with a multi-spectral capability. Through the use of an innovative optical system and cutting-edge developments in half pixel offset sensor technology, higher resolution is achieved from a small payload. A native ground pixel size of 0.6m and a sampling of 0.3m is enabled from an orbital altitude of 500km. This improvement in sampling realizes a reduction in aliasing in the resultant image products; allowing the higher spatial frequencies transferred through the optical system to be accessible and unambiguous, producing additional information content.

The spacecraft has been developed with updated avionics to provide increased agility whilst maintaining pointing accuracy. It also facilitates a range of beneficial imaging modes including Spot, Strip, Inclined Strip, Across-Track Stereo, Along-Track Stereo and 2 x 2 Mosaic Mode. Additionally, improvements to SSTL's X-band payload downlink allows for increased data rates to maximize image throughput over the craft's 7-year life.

The SSTL-Mini Precision builds upon the heritage SSTL-300 platform structure, designed for the deployment of missions at scale, to facilitate natural accommodation within a launch vehicle fairings. Previously proven in the three spacecraft *DMC-3/TripleSat* constellation, the structure readily enables the deployment of constellations of very high-resolution spacecraft, allowing the capture of targets at an increased temporal resolution. Through SSTL's established use of COTS components and updated manufacturing techniques, this system is possible at the reduced cost of a small satellite produced at scale.

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