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Reading the Fine print from Orbit: Its not just about the resolution

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ABSTRACT

Is it possible to offer sub metre imaging from a small satellite, in this case defined as having a total mass under 500 kg, while still staying within the boundaries of a 'low cost space mission'? If so, can a constellation of such spacecraft offer an operationally unbeatable combination of imaging resolution, area coverage and timeliness for less than the cost of a single, large, high resolution spacecraft?

Government and a growing number of commercial customers have recognised the utility and price-performance benefits of small spacecraft. Sub-1m imaging opens up a huge range of applications to the user of Earth Observation (EO) data, however targeting improved imaging payload resolution does not make a system more useful, unless a number of other parameters are improved. The paper firstly summarises the options for building a sub-metre resolution camera in a low cost, small satellite mission context, since this is currently the metric used to compare small satellites against the state-of-the-art. An analysis is then presented of the complex trade-offs between orbit height, image resolution & quality, lifetime, and spacecraft configuration. This initial trade-off is required to identify the most appropriate operational altitudes associated with different orbit maintenance strategies. A comparison is made with other high resolution commercial EO missions.

The paper will cover the engineering challenges of flying a sophisticated optical bench into orbit, considering in particular the propulsion, structure, thermal and Attitude control; and the modes of operation that can be supported with a spacecraft designed to deliver very high resolution from orbit.

Some of the trade-offs associated with detector design will also be addressed, including the potential need for active attitude control during imaging to control the read-out rate required from the sensor.

The paper concludes with a short section on the estimated performance of a constellation of small, low cost very high resolution imaging spacecraft, which has the potential to offer an operationally unbeatable combination of imaging resolution, area coverage and timeliness for less than the cost of a single, large, high resolution spacecraft.

INTRODUCTION

The first five satellites of the Disaster Monitoring Constellation (DMC-1), launched in 2002-2005, confirmed the humanitarian, political and technological value of Earth imaging using cost effective small satellites. SSTL and many other companies have extended this capability and continue to demonstrate the utility of small satellites for a range of Earth observation applications. SSTL is has now greatly improved the SSTL-100 and SSTL-150 designs used for the first generation DMC and is integrating the SSTL-300, which is significantly more capable but is still a small, low cost spacecraft. The SSTL-300, due to

launch in 2009 will offer 2.5m GSD imagery in a panchromatic waveband along with 5m and 32m imagery in four multi-spectral channels. This spacecraft will be the most advanced spacecraft of its class to be built and will deliver high data throughput from an agile platform, whilst still maintaining high levels of pointing and geolocation accuracy. The SSTL-300 is the starting point for the design of a small (<500kg) satellite capable of delivering sub 1-metre GSD imagery. Experience gained in previous missions presented at this conference, including DMC+4, TOPSAT and RapidEye has been used to overcome a host of engineering challenges associated with increasing the resolution, but also to offer a range of high quality image products delivered in a timely fashion, covering areas of specific interest to the satellite operator.

OPTICAL SYSTEM DESIGN TRADE

This section covers the range of imaging camera designs which have been considered to enable a system design capable of sub-1m Ground Sampling Distance, (GSD) or resolution. However, selection of a telescope capable of meeting this fundamental resolution criteria poses other trade-offs which affect the value of image products and system utility as a whole. This changes the relative weighting assigned to each type of camera configuration. Two key issues to bear in mind are the envelope in which the imaging device must fit with its associated system mass impact (which must be matched to the launcher selected); and the ability to manufacture the optics within the customer's price and time constraints.

Table 1 shows four options for a small satellite Very High Resolution Imager, VHRI:

Imager type	Advantages	Disadvantages	
Cassegrain- derived	Comparatively simple and cheap spherical mirrors. Easy to build and align.	Secondary mirror limits light gathering capacity. Large diameters needed for sub-1m resolution.	
Three-Mirror Anastigmatic (TMA)	No aperture obscuration. Relatively compact & lightweight format.	Off-axis aspherical, expensive mirrors. Complex alignment.	
Korsch	Smaller hole in primary mirror	Complex to manufacture. High mounting sensitivities	
Newtonian- derived	Comparatively simple mirror shapes. Very small obscuration.	Long. Relatively complex relay lens needed.	

Table 1: Small satellite VHRI options

Other systems can be considered e.g. an off-axis three mirror system differing somewhat from a classical TMA, as used in Quickbird. However, these alternative design forms have similar advantages and disadvantages as discussed for the four options above . Furthermore, although the satellite systems they are used on can be considered as small compared with classical EO satellites (Quickbird-2 had a wet mass slightly in excess of 1000kg), they have absorbed significantly greater budgets than the typical small satellite as defined by SSTL, priced well below \$100M.



Figure 1: SSTL 4m GSD camera and SSTL-150 spacecraft

The Cassegrain-derived design for Earth observation cameras is typified by the SSTL-built optical payloads for the DMC+4 (SSTL-150) and SSTL-300 satellites. The former is a 4m resolution / 24km swath width panchromatic camera for mapping purposes and which has been operated successfully since 2005. The latter is a multispectral camera with 2.5m resolution in the panchromatic channel and 5m resolution in four Landsat-type bands, R, G, B and NIR in a swath width of 20km. This represents state of the art for 300kg class satellites with fast (~2-3 yr) project turnaround. The

first SSTL-300 and camera is currently being built and is due for launch in 2009.

Both instruments are designed to achieve the stated resolutions from an orbital altitude of 700km. The Cassegrain-derived design form is demonstrated by the SSTL design shown in Figure 2. The diameter of the primary mirror is 385mm, and the length around 1000mm. It is a scaled up version of the SSTL-150 camera (Figure 1) which has an aperture of 310mm and a length around 800mm.



Figure 2: 4m GSD camera and focal plane CCD configuration

The Cassegrain design form is relatively simple to build and camera delivery times (including non-recurring design) on the order of 20 months (SSTL-150) and 27 months (SSTL-300) are reasonable. The designs are implemented in low expansion materials – carbon fibre composite for the structure, Zerodur and fused silica for the optics and low expansion alloys for optical mounts. The cameras are designed in this way to operate over large temperature ranges, to avoid imposing tight temperature control which is an undesirable complication on low-cost satellite projects.

The focal plane design is relatively simple, using long linear CCD arrays and in-field separation of colour channels to avoid complex beam-splitting focal plane assemblies (Figure 2). Focus control is implemented by moving one of the corrector lenses located near the centre of the primary mirror, in order to compensate for moisture release of the carbon fibre composite in orbit which, experience has shown, cannot be easily predicted. Isostatic mounting arrangements take up any differential expansion between the telescope and the satellite, again simplifying satellite design and thermal control.

This design form reaches its limit of viability at parameters around those for the first SSTL-300. For further reductions in ground resolution, the first problem is that adequate signal-to-noise ratios cannot be maintained, due to the smaller pixel area on the ground and the shorter dwell time on each of these. Although this problem can be solved by using TDI (Time Delay Integration) CCD detectors to restore signal-to-noise ratios. Once the transition to TDI CCDs is made, the optics diameter is limited by the diffraction Modulation Transfer Function, MTF and not by lightgathering power. An SSTL-300 with TDI detectors could be flown in orbits down to 400km to give around 1.5m resolution. However, remote sensing customers are beginning to require resolutions down to 0.6m, coupled with swath widths in the region of 16km, even from relatively low-cost smallsats. This requires large focal plane dimensions, since the TDI CCDs cannot be made with pixel sizes below about 0.01mm. The limit of viability of Cassegrain-type designs comes from the fact that the large focal planes require very large holes in the middle of the primary mirror, driving the primary diameter up much higher than simplistic diffractionlimit calculations might suggest, to around 500 to 600mm. For conventional, affordable mirror materials such as glass, the telescope becomes too large and heavy to be practically hosted on a small satellite.

One obvious design form to solve this problem would be an off-axis mirror system such as the Three-Mirror Anastigmat (TMA). TMA designs have been flown in space on microsatellites such as TOPSAT, achieving 2.7m GSD on a 110kg bus, Figure 3. A TMA design meeting the specification of 0.6m resolution, 16km swath at around 400km altitude will require a fourth flat fold mirror, which also can be used for focusing. The main problems with this type of TMA design are the difficulties of manufacturing and aligning the three offaxis aspheric mirrors, which tends to militate against fast and cost-effective programmes. In the last few years, two Earth observation satellite programmes using SSTL platforms suffered severe delays in payload deliveries from subcontractors using TMA designs (including one which was started two years before the SSTL-150 shown in Figure 1, but launched on the same rocket) and these had relatively small apertures compared to that necessary for the 0.6m specification. Another issue is thermal control. One TMA with relatively modest 6.5m resolution supplied for an SSTL platform demanded thermal control of around $\pm 1^{\circ}$ C, which can become a significant system complexity and cost driver. Such requirement is not well suited to a small satellite programme, or indeed for a design that is

intended to be used for a range of different mission scenarios.



Figure 3: TOPSAT, camera design and CAD model of imager (primary mirror shown in green)

Despite previous difficulties, the TMA design form has tremendous attractions. It has an unobscured aperture, giving a good diffraction limit from a relatively small aperture; it is shorter than conventional optical form; and relatively lightweight. This type of design is already being used in major satellite programmes with larger budgets and longer timescales than available to many customers. Modern techniques such as free-form optical grinding and polishing, alignment with large coordinate measuring machines, and the use of structuraloptical materials like silicon carbide may bring the TMA within the cost and timescale constraints of the smallsat manufacturer.

The Korsch design form resembles a focusing TMA used close to axis, with the front-end appearing like a Cassegrain system with a focused image close to the centre of the first mirror. This image is relayed with magnification by the third mirror and folding mirror behind. The primary image is smaller than the final image so the hole in the first mirror is not as large as in the Cassegrain option. However, the Korsch design form (Figure 4) still has a central obscuration, is quite complex to manufacture and some of the mounting sensitivities are high.



Figure 4 Korsch camera design

One on-axis design which is almost unobscured and overcomes the need for large mirrors is derived from the Newtonian form, utilising only one large curved mirror. The image is collected by a prism or mirror at the primary mirror focus, which can be relatively small and therefore provides only a very small obscuration of the aperture. The image is then re-imaged by a relay lens on to the focal plane. A mirror diameter of around 350mm is sufficient to give a resolution around 0.6m on the ground from an altitude of 400km. A multi-CCD focal plane using a combination of TDI CCDs for the panchromatic channel and linear CCDs for the colour channels (where the pixel size is larger) gives adequate signal-to-noise ratios. The disadvantages of this design form are that the relay lens is relatively complex, and the telescope is the longest in its class, making the satellite cross-section high in the direction of travel unless additional optical folds are applied. A high cross section is undesirable since drag, a major consideration at low orbit altitudes, increases dramatically with cross section. The section on Mission design trades discusses the impact of atmospheric drag on spacecraft and propulsion system design in further detail.



Figure 5: Design MTF estimates for unobscured and Cassegrain design forms for 0.6m in 16km swath

Figure 5 shows the design MTF for the optics alone, for Cassegrain-derived (2-mirror) and unobscured design forms. The effects of optics manufacturing and assembly tolerances are not included in this figure, and will worsen the MTF. Considering that the detector MTF will be typically 50%, these figures will typically be halved for the complete assembly. The advantage of unobscured apertures (e.g. the TMA) over the Cassegrain form is clear, in terms of MTF per a given aperture size.

In conclusion, departure from Cassegrain-derived systems may offer significant performance enhancements without involving the complexities, time constraints, and associated higher costs, of aspherical, off-axis mirror designs such as the TMA. However non conventional optics (e.g. Korsch and Newtonian) pose their own unique challenges, so further examination of the merits of TMA systems is underway at SSTL in its Optical Payload Group.

MISSION DESIGN TRADES

The introduction to this paper points out that resolution is not the only important metric in a cost effective, very high resolution Earth observation system. However to deliver this primary metric of performance, which is a key customer buying factor, an initial trade must be made between orbit altitude (the 'see it better if you move closer') and camera aperture ('see it better with a bigger lens – or mirror'). The previous section looked at different camera designs, which are dominated by the size, cost and manufacturing complexity of the primary optic. This section looks at how a given camera performance can be traded against orbit parameters to derive the best resolution. Orbit parameters, notably altitude have the most impact on either lifetime, hence the value for money of the satellite system, or the propulsion system sizing for orbit maintenance. Lifetime and / or propulsion system size, and system mass, complexity and size will impact price and delivery time, which are critical in the small satellite world.

Subsequently a complex trade-off between image quality and modes, area coverage, spacecraft lifetime (hence value), and spacecraft configuration must be made.

Orbit altitude

This initial trade-off is required to identify the most appropriate operational altitudes associated with different orbit maintenance strategies.

Despite the potential resolution advantages of operating in low orbits, surveillance satellites have historically tended to operate at altitudes well above 500 km. Exceptions have chiefly comprised relatively shortlived Russian surveillance systems operating in circular orbits at about 400 km, and a limited number of US surveillance assets which occupy comparatively elliptical 200 x 1000 km orbits. The reason for high operating altitudes, is that most LEO surveillance satellites have typically been treated as grand strategic assets, which has driven up their costs significantly, and this has acted as an incentive for system designers to try to maximise the lifetime of their assets by operating at an altitude sufficient to avoid the worst of the drag from the Earth's atmosphere.

Recently a number of specific trends have eroded the rationale for this 'build it big (& expensive), make it last longer' approach. Of these, perhaps the most significant development is the increasing capability that is being delivered by small satellites using high capability modern electronic components. It has now been conclusively demonstrated that mass produced, cost terrestrial components can be used low successfully in the LEO radiation environment that is encountered by surveillance satellites close to the Earth. As a result of the reduction in costs, it is now far more feasible to envisage relatively short lifetime, (e.g. 5year or less) missions which have far more relaxed propulsion design drivers, since the velocity change required to counteract drag for a mission of this duration is clearly far less than for traditional missions.

The following table shows a trade off between operating orbit altitude, and propellant mass to reach operating orbit and maintain that orbit, for a fixed overall spacecraft mass (assumptions being a starting 200km circular 'parking orbit', mission lifetime of 2 years, an Isp of 1000s for a relatively simple electric

propulsion system, and a mid-range¹ satellite ballistic coefficient:

	Operational imaging altitude (km)					
	200	400	500	600	800	
Orbit raising	0	33.5	49.5	65.1	95.1	
propellant						
mass (kg)						
Orbit	1714	29.0	4.9	1.2	0.1	
maintenance						
propellant						
mass (kg)						
Total	1714	62.5	54.4	66.3	95.2	
propellant						
mass (kg)						
Total	2850	2850	2850	2850	2850	
satellite						
mass (kg)						

Table 2: Impact of operating remote sensing operating altitude on orbit maintenance propellant

At lower altitudes the effects of atmospheric drag dominate the design of the spacecraft (if the propulsion system is allowed to grow to meet the increasing deltaV need from atmospheric drag). In the case of a fixed satellite and propellant mass (not shown), drag dominates the mission lifetime achievable. At higher altitudes the orbit raising propellant mass also becomes less attractive. However, when a more sophisticated metric (taking into account the effective surveillance areas accessed by the satellite) are wrapped into the assessment, the answer is clearly biased downwards to lower altitudes. This metric is explained thus:

SSTL has a philosophy of re-using existing designs wherever possible, to shorten development timescales and lower costs. This is consistent with the "realworld" situation for the Operationally Responsive Space community, where operational constraints will dictate that there is insufficient time to fundamentally redesign the satellite. For example, the SSTL-300 spacecraft is designed to operate, i.e. maintain orbit for 7-years at an altitude of 700km. At this altitude a nadir GSD of 2.5m is achieved, which increases towards 3.8m as the spacecraft off-points to 45°. (The assumption here is that the resolution figure corresponds to the resolved distance perpendicular to the line of sight to the satellite. This is seen as a reasonable assumption, since at least some of the potential targets for such a system could be buildings, where the resolution projected perpendicular to the line of sight is arguably more relevant to vertical structures than the resolution value when projected onto the ground).

The same spacecraft can be flown at lower altitudes to improve the resolution at the expense of lifetime, but, also to improve the potential field of regard. In addition, small changes to the focal plane assembly can improve this further. Replacing the existing sensor with a TDI version allows resolutions of 1.5m to be achieved at 400km. In our trade-off a minimum acceptable resolution can be defined. This resolution requirement then defines the maximum slant-range from the satellite to a target region on the curved surface of the Earth. The maximum slant-range dictates the potential field of regard, and (assuming that the satellite sensor's field of view can be directed anywhere within that field of regard), also constrains its coverage performance. Clearly the size of the potential field of regard will depend not only on the maximum slant range but also on the altitude of the satellite. Somewhat counter intuitively, a much larger field of regard could potentially be accessed by a satellite operating at 200km, if very low elevation imaging angles (a possibility for wide-area operations over maritime areas, although not realistic for most terrestrial applications) are allowed. A higher orbiting satellite will actually obtain a narrower field of regard, limited by slant range / resolution as defined above, rather than the projection onto the ground of the range of satellite viewing angles, which is the conventionally definition. This drives the trade-off back to a lower, 400-500km orbit.

The trade-off on altitude needs to encompass many more parameters than the orbit maintenance / drag / propulsion system and altitude / resolution / field of regard to optimise for a specific mission. However lower altitudes around 4-500km, as shown in Table 2 can offer significant advantages over higher orbits in many operational scenarios. This is particularly advantageous when combined with the idea of taking an existing design, offering attractive cost and schedule benefits..

DETECTOR DESIGN TRADES

Cameras with sub-meter resolution and operating at or near the diffraction limit for the primary optic need signal enhancement to ensure sufficient signal-to-noise ratio and contrast (modulation transfer function). One way to achieve this is to use Time Delay Integration, TDI. CCDs within the region of 128 TDI lines give enough signal enhancement for a 0.6m resolution instrument flying at 400km. It is possible to design the CCDs to be used with variable numbers of TDI lines, typically 8, 16, 32 and 64 as well. This allows the sensitivity to be adjusted to the average scene brightness for instruments which are to be used over a wide range of latitudes and seasons, so that bright scenes do not saturate the CCD whilst useful signal-tonoise ratios are achieved on dim scenes.

The pixel size is a major factor to be considered in design trade-offs for the detector. Small pixels are desirable to keep the focal plane size as small as possible, otherwise the opto-mechanical design of the telescope becomes difficult for common configurations. However, small pixels allow only a small full-well signal capacity, reducing the dynamic range of the sensor. If the TDI length is adjusted to avoid saturation on bright parts of the scene, dim parts of the scene may not have adequate signal-to-noise ratios. Another issue to be traded against signal capacity is anti-blooming. Anti-blooming structures on the CCD take up real estate, and whether these are used or not depends on the application - can the customer tolerate a percentage of images containing flares from specular surfaces like greenhouses and vehicle windscreens, and is it more important to optimise full-well capacity?

The colour channels of a multispectral imager can often have a coarser resolution than the panchromatic channel, especially if the application is mapping or surveillance rather than scientific analysis of surface properties. Typical for pan-sharpened image processing is a 4:1 ratio. This gives 64x more light gathering power for the colour pixels than for the panchromatic, and obviates the need for TDI in the colour channels. If in-field separation of the colour channels is used, a hybrid CCD chip is possible with one TDI CCD and three coarse linear CCDs on the same silicon die. A number of CCD dice is needed to cover the whole swath width, either in a staggered pattern or with the use of beamsplitters.

IMAGING MODES

There are a number of inherent differences between small satellites and larger ones that result in advantages when it comes to possible imaging modes. The compact nature of small satellites, their lack of appendages, such deployable solar arrays, and fewer as large requirements for large quantities of propellant mean that the resulting small satellites can be much more agile. SSTL is currently building the first of its SSTL-300 missions capable of delivering 2.5m GSD imagery. Work is progressing on the design of a sub 1-metre SSTL-300. In addition to resolution, other satellite parameters must be matched to camera data output to ensure data bottlenecks do not compromise expected system performance. The SSTL-300 is designed to ensure high data throughput, high agility and high levels of pointing accuracy.

The design orbit for the first SSTL-300 is 700km altitude sun-synchronous, with a mid-morning orbit node. This provides a good compromise between strong lighting conditions and discernible ground features. Coupled with the accessible field of regard, this orbit also provides revisit opportunities to anywhere in the world at least every two days. The first SSTI-300 mission and its imaging modes and intended applications are discussed further in another paper².

CONSTELLATIONS

The initial hypothesis of this paper was whether it is possible to offer sub metre imaging from a small satellite, in this case defined as having a total mass under 500 kg, while still staying within the boundaries of a 'low cost space mission'? At SSTL, we firmly believe the answer to this question is yes. Sub-metre resolution imaging capability within a mass of 500kg, and producing a useful balance of area coverage and image quality are possible. 'Low cost' in this context is somewhat greater than the price for SSTL missions discussed in earlier years of this conference, such as SNAP at \$1M. However it is considerably less than the \$100M estimated price for the space segment of first generation commercial high resolution imaging missions such as QuickBird-2 and Ikonos. Such a spacecraft can also be delivered in a timeframe of ~(2-3) years, potentially classifiable as 'responsive space'.

The subsequent hypothesis was whether a constellation of low cost, very high resolution imaging spacecraft could offer an operationally unbeatable combination of imaging resolution, area coverage and timeliness for less than the cost of a single, large, high resolution spacecraft?



Figure 6: Very high resolution small satellite constellation

Figure 6 shows a constellation configuration studied at SSTL and based on four SSTL-300 spacecraft carrying very high resolution imagers, operating in an inclined orbit tailored for customers with an interest in rapid repeat periods over equatorial regions.

The mission requirements this study utilised were:

- GSD 0.7 1.5m
- Delivery time between 27 and 36 months
- Constellation coverage 200,000km²/day at highest resolution
- Colour and panchromatic bands
- System lifetime 5-7 years
- Suitable for dual manifesting on low cost launchers such as Dnepr, Taurus and PSLV

The price for the capability which this constellation would offer is dependant on a number of technical options, and excludes launch and insurance, but would be competitive with quoted contract values for Nextview, delivering commercial very high resolution imaging systems such as GeoEye-1 and Worldview³. A target value-for-money metric for future very high resolution constellations, over lifetime, is considerably less than 50¢ per square km of delivered imagery. A constellation would also be considerably more robust to launch and in-orbit failures than a single large, complex spacecraft.

CONCLUSION

The paper has summarised the options for building a sub-metre resolution camera in a low cost, small satellite mission context, since resolution is currently the metric used to compare small satellites against the state-of-the-art. High-level optical system design options to deliver this resolution in small, affordable package were discussed. These options showed how a departure from traditional Cassegrain-derived systems may offer significant performance enhancements without involving the complexities, time constraints, and associated higher costs, of aspherical, off-axis mirror designs. The TMA does remain an important design form for small satellites and is under close scrutiny at SSTL. However, this paper further pointed out that high resolution in itself does not immediately result in a useful imaging mission and system. An analysis was then presented of the complex trade-offs between orbit height, image resolution & quality, area coverage, lifetime, and spacecraft configuration. This initial trade-off is required to identify the most appropriate operational altitudes associated with different orbit maintenance strategies. A comparison was made with other high resolution commercial EO missions.

Detector technologies were also covered, concluding that TDI CCDs are essential for compact imaging payload performance in the small satellite context. However CCD pixel size, anti-blooming structures, and matching coarser colour CCD sensors, with a fine pixel size panchromatic channel to optimise focal plane array area, generating pan-sharpened full colour images are further important issues.

Imaging modes were briefly mentioned in the context that high resolution, combined with high data throughput, spacecraft agility and pointing accuracy create a capable system which can open up a range of possible applications beyond that of just very high resolution imaging. A spacecraft with a high resolution camera needs to be backed up by adequate data throughput, and attitude pointing and control subsystems in order to offer real utility to the owner.

The paper concluded that high performance imaging, at an affordable cost is practical using the SSTL-300. However the real advantages of capability inherent in the first SSTL-300, due for launch in 2009, lie in using constellations of several such spacecraft for an operationally unbeatable combination of imaging resolution, system robustness, area coverage and timeliness. This constellation can be offered for a cost which is highly competitive with that of single, large, state-of-the-art high resolution spacecraft.

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- 3. See <u>http://earsc.eu/news/transformation-of-the-</u> <u>earth-observation-sector</u>, for example. Accessed May 19, 2008.