A LOW COST VIDEO AND STILL IMAGING CONSTELLATION FOR HIGH TEMPORAL COVERAGE

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ABSTRACT: Small satellite technology has matured to the point where demanding operational missions can now be implemented routinely and reliably. This has driven demand for groups and constellations of such small low-cost spacecraft, in order to provide high temporal resolution capabilities on a global scale. Examples include the Orbcomm communications constellation, and the RapidEye and Planet Labs Earth Observation constellations. As the cost of ownership for space systems has come down, an increasing number of Universities, companies and nations are also getting involved in operating their own small satellites, to get access to the data they need, and get it when they need it. Spacecraft traditionally have been very labour intensive to develop, especially where capability and reliability are important to the user. This ultimately becomes a major factor in the final cost of ownership of the spacecraft. For single spacecraft this can be justified, but for groups of spacecraft it is possible to adapt techniques used elsewhere in the consumer electronics sector. In order to address the demand for very low cost spacecraft batches, SSTL has investigated, qualified and implemented a new satellite platform production process, alongside a new set of avionics. The process makes significant use of modern automated manufacture and test techniques, and the avionics are designed taking this production process into consideration. The consequence of this is that significant savings in production costs and schedule are achieved, which are quantified in this paper. Most of the effort has been focused on qualifying the production process, to ensure it meets the strict requirements placed on equipments for long life operational space missions. Initially these techniques will be used in SSTL's smaller spacecraft platforms including cubesat, nanosatellites and microsatellites, but eventually these will be rolled out across the larger platforms as well where appropriate. The first mission which will be produced using these new avionics and processes has been contracted, and will be using a new SSTL-x50 platform. One of the reference missions using the production engineered platform is the SSTL-x50 precision mission, which provides a very high resolution imaging capability including high definition video.

1. INTRODCUTION

Over the last three decades, SSTL have delivered over 40 small satellites for a range of applications including Earth Observation, Communications, Navigation, Science and Technology Demonstration. Schedule, price and reliability are very important factors for all satellite users, and commercial spacecraft operators are increasingly considering using groups of satellites working as part of a coordinated constellation. SSTL has been involved with a number of such constellations in various capacities, including DMC/DMC3, RapidEye, KANOPUS, FORMOSAT-7, at spacecraft level, and at payload / subsystem level in ORBCOMM-SG, CYGNUS and the 22 Galileo FOC payloads. The production philosophy typically adopted for such batches of satellites to consider the closest existing product, modify this to the specific mission needs, build a proto flight unit, and then carry out a limited batch production run. As a result, the cost savings that can be achieved in batch production are often limited, as the base design was never optimised for such a batch production.

For individual spacecraft, the cost of the spacecraft production can also be prohibitive for science and technology demonstration missions, or restrict the feasibility of new business ideas in space. Increasingly, the labour costs involved in spacecraft production are dominating. SSTL has developed a concept for spacecraft manufacture which has so far not been used elsewhere in the space industry, which removes some of these limitations and cost drivers. This is targeted at improving production cost, speeding up mission delivery, and maintaining and improving reliability.

2. BATCH PRODUCTIOON FOR SPACE

Figure 1 shows the SSTL missions and their respective launch dates. Because many of the same sub-systems are used on several different spacecraft busses and mission, there is regular and significant opportunity in SSTL to batch build spacecraft equipment and so make economy of scale cost savings - even across different spacecraft for different customers, providing they are produced at roughly the same time. There are then also some cost savings in sharing staff and facilities. For instance in the AIT/EVT phase spacecraft can be processed at around the same time using the same test setup, for instance sharing a Thermal Vacuum chamber. For most missions SSTL already gains these benefits. Nevertheless there is a fundamental limit on the amount of savings that can be achieved without a significant investment in building equipment for stock and permanent test setups, due to the fact that the avionics were designed considering conventional 20th century space industry practices, namely hand-crafted production, human inspection, one-off and bespoke setup and test, and manual harness integration.

In order to provide further significant improvements in price and schedule for constellations of spacecraft, as well as on individual satellites, it is necessary to consider alternative approaches. An SSTL internal R&D programme was started in 2011, with its main objective to improve performance to cost ratios even further, by exploiting new commercially developed technologies, protocols and processes in order to offer improved performance of current SSTL small satellite platforms at a similar or lower mass, but with significantly reduced schedule and price. This internal development programme heavily leverages the investment made in other industries in batch manufacture of highly reliable products, and has resulted in the “X-Series” spacecraft.

The SSTL-X50 series of spacecraft are the first mission products. The series were released in 2013, and the first spacecraft using this class bus is already under contract and in production for launch in 2016.

Figure 1. SSTL Historical Parallel Spacecraft Production

3. X-SERIES PLATFORM

3.1. Platform Design for Low Cost Production

The X-Series avionics and core platform elements are designed with maximum production efficiency as a driver. Hence the design takes advantage of automated batch manufacture and test processes space qualified by SSTL. This entails management of a controlled preferred parts list, use of pick and place machines, reflow soldering process, press fit connectors and comprehensive test coverage via automatic test equipment and built-in self-test.

The process has been quantified in terms of cost and time in comparison with the traditional space industry approach, and the traditional SSTL approach. There are dramatic saving in production time and cost (Bradford, 2013) with the X-Series approach. The automated test theme is carried in to the platform and spacecraft Assembly Integration and Test (AIT) phases also, with a platform level Automated Test Equipment (ATE) setup employed to run representative (‘test as you fly’) scripts and scenarios on the platform. This also contributes to the reduction the costs and durations associated with the AIT phase of X-Series implementations.

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The low cost, batch build philosophy allows for a module level rather than component level stores inventory, drastically reducing the period from customer order to spacecraft delivery. Coupled with the low cost of the recurrent parts, this results in extremely low recurrent costs for the core X-Series elements.

In recent years SSTL have invested heavily in mass production facilities and processes. These in-house capabilities (examples shown in figure 2) are now installed and qualified, and are being leveraged to drastically reduce the production costs of the next generation X-Series elements. The key capabilities are:

- Pick & Place of Components
- Automated soldering (re-flow)
- Automatic Inspection, including X-ray inspection of re-flowed electronics
- Automated Test

These factors result in a step change in production approach: Typically when producing space hardware, significant costs are expended both on the raw materials and parts ('Space Qualified' parts being extremely expensive with associated long lead times), and the skilled labour associated with largely manual assembly and test activities. Even if lower cost (e.g. COTS) parts are used, the significant labour elements results in a high cost investment in any space equipment produced in this way. A secondary effect is that the resulting hardware is typically extensively analysed, tested and repaired if it develops a fault – due to the high value, discarding the equipment at the point where the fault is discovered is not a realistic option. This pattern is broken by the production approach for the X-Series; low cost parts are procured, automated process are used extensively to manufacture, inspect and test the hardware. Therefore if a fault is detected, during test, for example, the option to simply discard the element in question becomes an easier and more attractive option in the cases where faults can be shown not to be systematic and/or design related.

The following table illustrates in broad labour cost terms (man hours/weeks/days/months) the differences between three production approaches:

1. A traditional space industry approach, where Space Qualified Parts are employed and the manufacture and test phases are largely bespoke and manual
2. SSTL's historical approach, where COTs low cost parts are utilised, but the remaining production phases remain labour intensive,
3. The X-Series approach, where COTs parts are used and the remaining production activities are all automated and therefore shortened in duration.

Figure 2. Automated Production Line

Table 1. Comparison of production of equipment between traditional labour intensive methods and SSTL X-Series automated techniques

	Approach Scenario	*Traditional/ Bespoke*	*COTs Manual*	*COTS Automated*
Production Phase Durations	Procurement	Weeks	Days	Days
	Assembly	Weeks	Weeks	Hours
	Inspection	Days	Days	Hours
	Test	Weeks	Weeks	Hours
	Overall	Months	Weeks/ Months	Days

It can clearly be seen that a dramatic saving in production time and therefore cost is attained with the X-Series approach. This is further illustrated in the graph below, which illustrates broadly how the proportion of costs associated with each production phase and activity changes with the different approaches adopted.

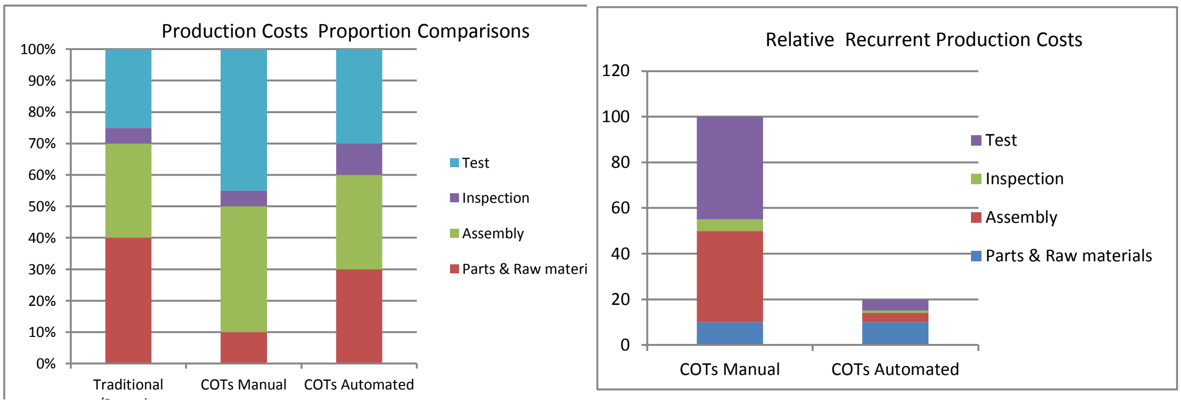

Figure 3. Breakdown of Production of Equipment Between Traditional Labour Intensive Methods and SSTL X-Series Automated Techniques

A second graph illustrates the expected absolute production costs of SSTL's historical labour based approach compared to the forecasted total costs for the automated production X-Series elements. As can be seen from the graph in figure 3, the recurrent average production costs of X-Series modules is expected to be in the region of 20% of the historical, previous generation SSTL equipments.

The automated test theme is carried in to the platform and spacecraft AIT phases also, with a platform level ATE setup employed to run representative ('test as you fly') scripts and scenarios on the platform. This also contributes to the reduction the costs and durations associated with the AIT phase of X-Series implementations.

2.2 The SSTL-X50 – The First X-Series Platform

This spacecraft provides the basis for a number of possible Low Earth Orbit missions for science, technology, and Earth Observation. It also provides a useful basis for SSTL's development projects with training or co-development partners, allowing such projects to focus on spacecraft configuration, payload design and mission applications.

Over the coming years, result in all SSTL developed equipments being evolved in line with core principles of robustness, standardisation, modularity and design for production efficiency. This transition is managed via the generation and maintenance of roadmaps for each major satellite functional element. Automated production and test is at the center of all of these developments, and avionics are designed to be scalable across a wide range of different size spacecraft, in order to end up with robust systems with short lead-time and at low cost.

Different size platforms can employ the new avionics mostly through duplication of modules to increase storage, computer and power capability. The first of these to be realised is KazSTSAT for Ghalam LLP, which is an "SSTL-X50" - 50 kg class platform with a launch planned for 2016.

2.3 Platform Modularity and Flexibility

The Card Frame based architecture at the heart of all of the X-Series platforms has been developed with maximum flexibility and modularity in mind. A number of standard building block "cards" deliver the main platform functions such as power conditioning, TT&C, on-board processing and storage. The card-frame can be configured in an expandable arrangement to deliver the platform performance required by different payloads and associated mission classes. This is illustrated in the figure 4.

The platform subsystems and payloads are accommodated in two levels separated horizontally by an aluminium panel that isolates them physically and electromagnetically from each other, shown by the red dotted line in figure 4. The proposed platform structure allows access to all equipment at any time without the necessity of removing other equipment.

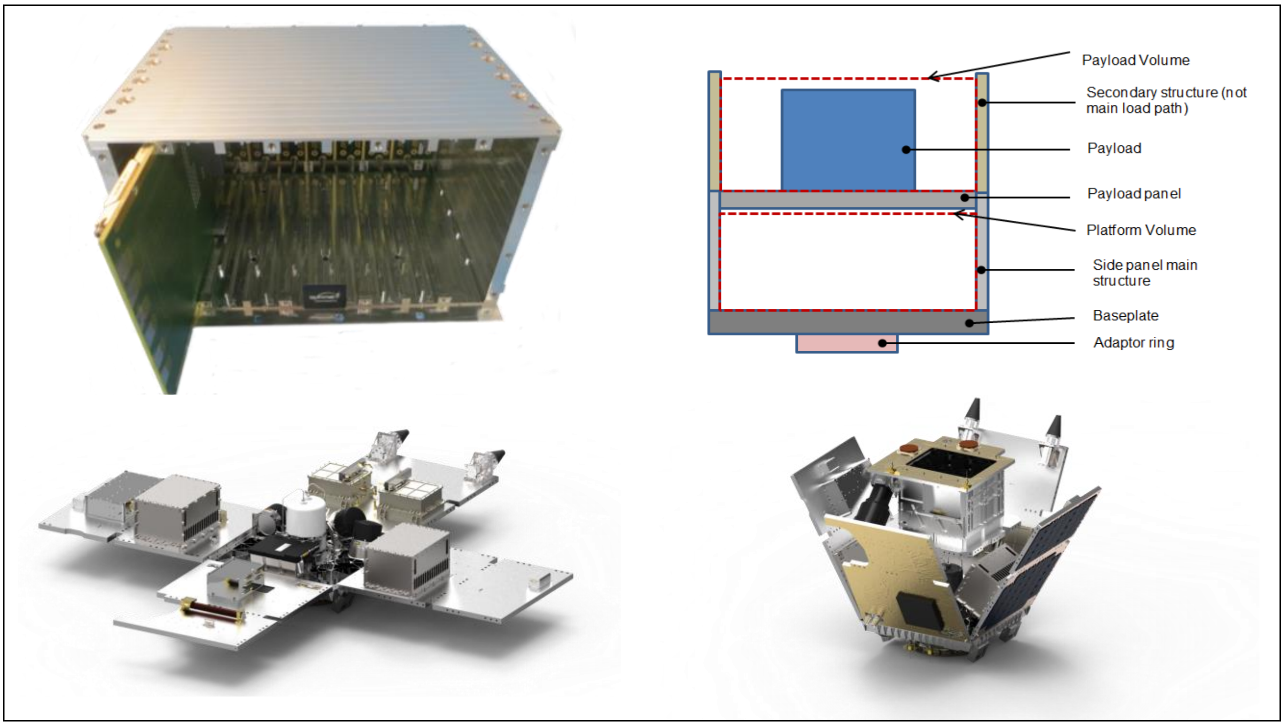

Figure 4. X-Series Avionics Card-Frame Arrangement

In the system block diagram in figure 5, the red dotted line outlines the SSTL-X50 configuration, illustrating the modularity of the X-Series avionics and the ability to build more capable and complex systems using the basic building blocks described. The same basic modules can be duplicated to provide the greater power and data handling demands of a more complex mission.

4. MISSION AND APPLICATIONS

SSTL missions have a proven track record of enabling applications previously considered not feasible. The X-Series spacecraft will continue to widen access to space applications for commercial, scientific and civil users and making them suddenly feasible due to the low price and fast delivery schedule. Three reference Earth observation mission products have been developed in the 50 kg class. These are described below along with a platform-only variant suitable for owners to supply their own payloads. These 50 kg X-Series missions are based on a common "SSTL-X50" platform, which incorporates as standard dual redundant platform systems, arc-second attitude knowledge from star cameras, data storage of a minimum of 256 Gbytes, lossless real-time image compression, high speed X-Band downlink and mission lifetime up to 7 years duration.

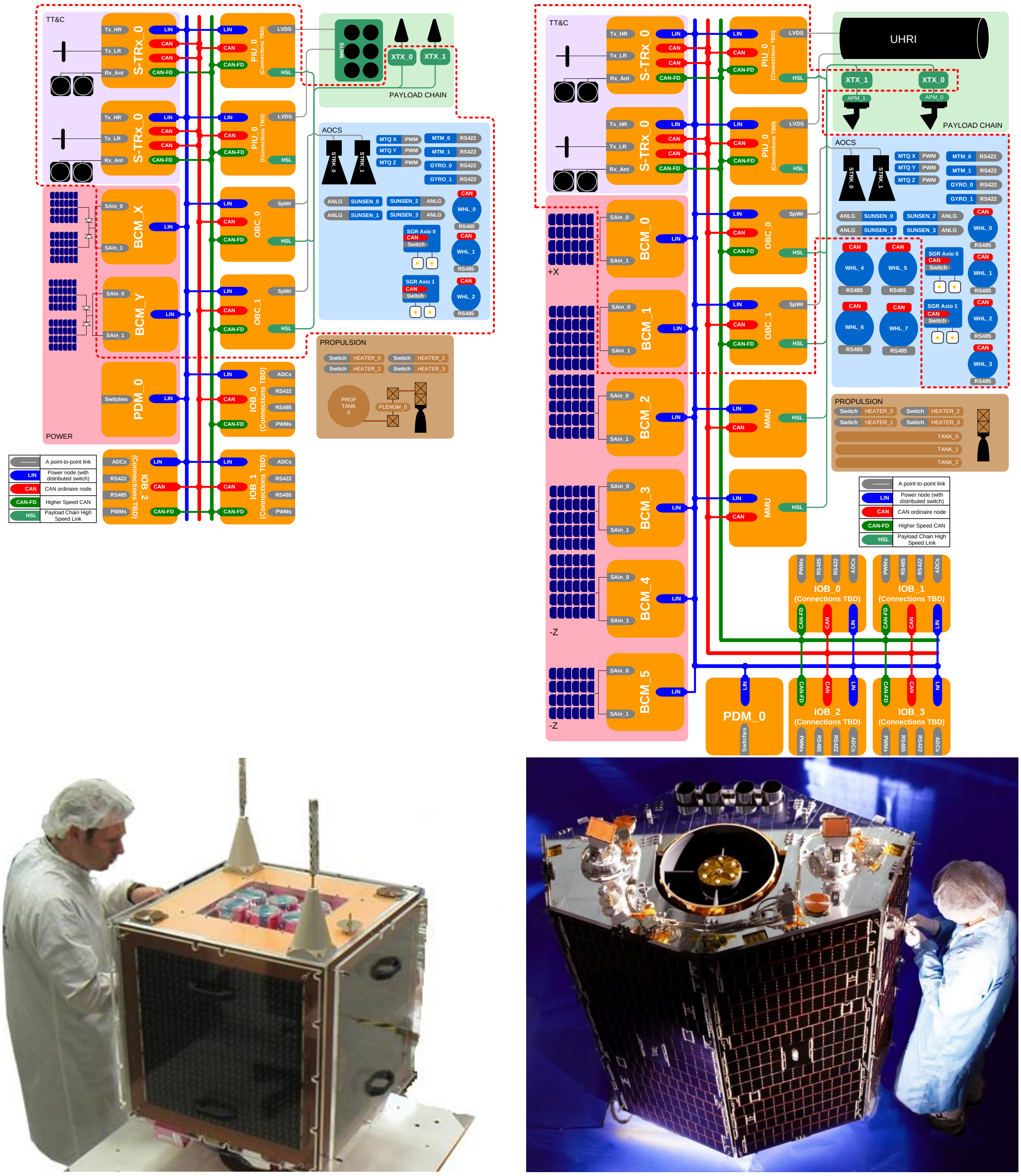

Figure 5. System Block Diagrams for Simple and More Complex X-series Spacecraft

4.1. Space Science and In-Orbit Demonstration Missions

Many requirements for this platform will come from organisations that already have a payload, want to develop their own payload, or want to pilot an idea in a cost-effective manner quickly. The low recurrent cost and high performance to mass ratio offered by the X-Series satellites make them ideal for low cost science and in orbit demonstrations missions, where an affordable and rapid solution can, for example

- Provide a platform for on orbit demonstration of new technologies, instruments, services or techniques,
- Provide risk reduction, pre-cursor or gap filler type capabilities by accommodating scientific and/or imaging payloads.

The available payload volume is a 530x430x400mm contiguous volume, with access to 5 sides of the cuboid shaped spacecraft. The 30kg bus can accommodate 45kg of payload, and provide 35W of Orbit Average power and 85W peak power in a standard spacecraft configuration.

The spacecraft structure can be modified as demanded for different missions, and in its simplest form a payload is carried on top of the core avionics providing an instrument field of view over more than an entire hemisphere. Designs for three reference missions using the X-50 platform have been developed. The X-50 Earthmapper and TrueColour+ variant are described in more detail (Bradford 2013) and (Cawthorne 2014).

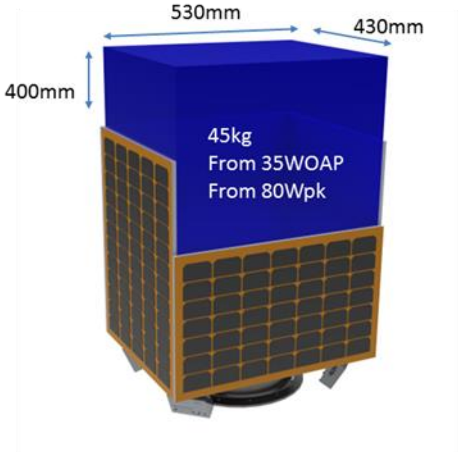

Figure 6 Typical Payload Allocation for Minimal Configuration Spacecraft

Figure 7 below shows an example of the imagery that the SSTL-X50 Earthmapper, Truecolour+ and Precision variants will provide.

5.1. SSTL-X50 "EarthMapper"

The SSTL-X50 "EarthMapper" mission is a global imaging system delivering coverage of the Earth's land area in 5 days. Flown as a constellation of 5 spacecraft the entire global landmass can be imaged every day. The mission payload is a 22 m Ground Sample Distance (GSD), 12 bit digitisation, multispectral imager with Landsat 7 equivalent spectral bands in Red, Green and Near-Infrared supplying high quality commercial imagery with a signal to noise ratio greater than 100:1.

A 600 km ultra-wide swath results in large areas of the Earth landmass being imaged frequently. The EarthMapper imager has been successfully demonstrated in orbit on the Deimos-1 mission (launched 2009), UK-DMC2 mission (launched 2009) and NigeriaSat-X mission (launched 2011).

The EarthMapper satellite continuously images the sunlit landmass and is particularly suited to applications requiring a high temporal revisit rate and wide area coverage such as mapping and cartography; commercial agricultural monitoring; disaster management; flood and water quality monitoring.

20m, 600km swath, NIR, R, G, all land mass daily Courtesy DMCii	5m, 390km swath SWIR, NIR, R, G, B Courtesy RapidEye	0.7m, R, G, B, 17km swath 1m HD Video

Figure 7. Example Imagery from the SST-X50 Earthmapper, Truecolour+ and Precision Spacecraft

5.2. SSTL-X50 "TrueColour+"

Within the X50 class of missions, the SSTL-X50 TrueColour+ mission is a unique Earth observation mission aimed at dramatically improving the performance of the previous DMC satellites. The new instrument will continue to deliver the traditional green, red and near-infrared bands with the trademark DMC wide swath, but will add to these blue and SWIR bands. In addition the resolution is improved to cater for the ever increasing demand for image detail.

The SSTL-X50 TrueColour+ mission delivers multispectral image data in Short Wave Infrared at 19 m GSD, and Red, Green, Blue, Near-Infrared at 5 m GSD. All bands have a wide swath of 390 km, are digitised to 12 bit with a signal to noise ratio greater than 100:1. The system has the capability to deliver approximately 4 million km2 multi-spectral imagery per day.

This combination of large area coverage, multi-spectral bands, medium resolution and wide swath, all packaged in a low cost and compact 50 kg class satellite, offers raw data that can be processed into a wide range of value added products. Examples include high accuracy land cover classification; urban and rural mapping; scientific and commercial agronomy; vegetation health and yield management for commercial or national users; water quality and geological mapping.

5.3. SSTL-X50 "Precision"

The SSTL-X50-Precision imaging spacecraft will weigh around 80kg-160kg depending on specifications of design lifetime and data capacity. This spacecraft mission achieves sub-metric imaging capability by careful selection of sensor technology and designing for a relatively low orbit altitude, whilst maintaining usability for commercial users. The spacecraft is designed for a sun-synchronous reference orbit of 500km, with a 10:30 nodal time. It is targeted at use in a constellation to provide high temporal resolution, at the cost of a typical single high resolution satellite.

The optical instrument utilises commercial off the shelf (COTS) detectors and electronics components in order to minimise costs and development time-scales; SSTL has an established and tested method for selecting COTS parts – including detectors – which minimises and manages risks. This approach has been tested on both commercial and ESA projects. A single telescope incorporates both push-broom and high frame-rate sensors, providing 1m GSD video over a 2.5 x 2 km area, and 0.7m GSD imagery over a 17km swath.

Figure 8. SSTL Prototype SSTL-X50 precision, Launched July 2015

The imagery sensor uses a pushbroom array and supports 4 channels in the NIR, Red, Green and Blue bands, which can be combined on the ground to provide pan imagery. The bands are selected to be the same as the SSTL DMC satellites and the LandSat series of satellites. A major advantage of using a staggered array is the significant reduction of artifacts in the sampled image, aiding sharpening in post processing.

The video sensor uses CMOS sensor technology, and provides up to 30 frames per second capability. In practice much lower frame rates are sufficient for the majority of applications. Nevertheless significant data volumes can be generated in a short period of time, and the spacecraft can be equipped with up to 1Tbyte of solid state storage, and with 80-500Mbps downlink capability. For video, standard H264 compression can be applied on-board. For imagery, on-board compression is implemented in ratios of up to 1:2.5 lossless, or greater ratio when some loss is accepted. Quantisation of pixels is 12 bits, and imagery quality is designed with SNR >100 in all bands.

In order to achieve a reasonable revisit-time on its own, or in constellation, the spacecraft is agile with a Field Of Regard (FOR) of ±40 degrees. This corresponds to an 860km FOR on the ground. A single SSTL-X50 Precision can

Figure 9. Example SSTL-X50 Precision Still Images (simulated 70cm)

image any point on the Earth's surface (land mass or water) an average of once every 2.5 days. If a constellation of 5 Precision spacecraft were to be employed in a single orbital plane this revisit time would increase to be daily, with around two opportunities per image target per day at mid and higher latitudes.
Employing a 500Mbps X-band downlink to a ground station (located at a suitable location such that its view is not obscured, e.g. by terrain), will allow for up to 640 image squares per day (with an image dimension of 17×17 km) when using a lossless compression factor of 2, and up to 960 image squares per day when using a lossy compression factor of 3. This equates to between 185,000 km2 and 280,000 km2 per day. These throughputs are based on 10 bit image data.

A lower cost variant of this spacecraft delivers approximately 300,000 km2 coverage per day of 3 m GSD panchromatic and 6 m GSD multispectral Red, Green and Blue imagery, with 24 km swath width. Data is digitised to 12 bits with a signal to noise ratio greater than 100:1. The imager can also be operated in a single image or video mode depending on the end user application. The attitude control system enables a ± 20 degree across track roll capability that offers a 400 km wide field of regard; this wide field of regard makes possible frequent access opportunities to any location on Earth. The payload is developed from the high resolution imager operating successfully on the Beijing-1 mission (launched 2005).

6. SUMMARY

This paper has described the next generation of SSTL small satellite platforms, the X-Series. This series of platforms builds on 30 years of small satellite engineering experience at SSTL, whilst also incorporating many up to date technologies, protocols and production processes. The platforms utilise automated manufacture and test techniques, which have been qualified specifically for use in space.
The main innovation in the X50 series spacecraft is to implement an automated production and test process for spacecraft production. Although such techniques are widely used in other industries, SSTL has need to spent extensive effort in qualifying and developing processes which support the particular needs and requirements in the production of electronic assemblies for space.

SSTL has developed several reference missions to utilise the resulting low cost and rapid delivery platforms, and the SSTL Precision spacecraft design has been described in more detail. This spacecraft design is ideally suited to a constellation of satellites that would supply an owner, or group of owners, with an affordable high resolution, high revisit system at the overall cost of a single, larger high resolution satellite. End user applications of this system include rapid high-quality land cover assessment and mapping, global high-resolution situational awareness; commercial quality data suitable for online mapping and geographic information system (GIS) services; disaster management.

7. REFERENCES

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