

Sapphire: A Small Satellite System for the Surveillance of Space

Robert Leitch
MDA Systems Ltd.
13800 Commerce Parkway, Richmond, B.C., Canada; 604-231-2184
rleitch@mdacorporation.com

Ian Hemphill
MDA Systems Ltd.
13800 Commerce Parkway, Richmond, B.C., Canada; 604-231-2035
ich@mdacorporation.com

ABSTRACT

The tracking of man-made objects in Earth orbit is a crucial function of the Canadian Space Surveillance System (CSSS). This system will contribute information to the United States Space Surveillance Network (SSN) which maintains a global catalog of orbit elements for Resident Space Objects (RSOs). RSOs include active and inactive satellites, spent rocket bodies, and other pieces of orbital debris created by decades of human activity in space. Sapphire is a small satellite system that will form the centerpiece of the CSSS, providing an operationally flexible space-based platform for the precise tracking and identification of RSOs covering orbit altitudes in the range from 6000 km to 40000 km. The Sapphire system, including a satellite, ground segment, launch, and operations, is currently being developed by MDA for the Canadian Department of National Defence (DND), with satellite launch scheduled for 2011. This paper describes the Sapphire design. Sapphire must meet demanding performance requirements for RSO detection and pointing determination accuracy as well as system responsiveness and imaging task throughput. Sapphire will provide continuous service over a mission life of at least five years. The paper discusses the approaches used to build a robust capability into a small satellite package, including the extensive use of flight-proven heritage in the satellite subsystems. In addition, the paper discusses the role of the satellite with respect to the ground system elements and summarizes some of the major system-level tradeoffs from the design process.

SYSTEM OBJECTIVES

Overview

The DND's Sensor System Operations Centre (SSOC) will issue task lists to the Sapphire system. The purpose of these tasks is to generate up-to-date, accurate pointing vectors for Earth-orbiting objects known as Resident Space Objects (RSOs), which include active and inactive satellites as well as pieces of space debris. Sapphire will respond by commanding its space-based sensor to track and acquire images of the requested RSOs using an electro-optical telescope. The RSOs appear in these images as small points of light against a background of stars. The resulting images are downloaded from the Sapphire satellite to the ground segment for image data processing, which includes precise determination of the RSO direction in space based on identification of guide stars in each image. Tracking data products are created for the RSO tasks and transferred back to the SSOC, which is then responsible for transmission of contributing sensor data to the SSN. The Sapphire mission is depicted in Figure 1.

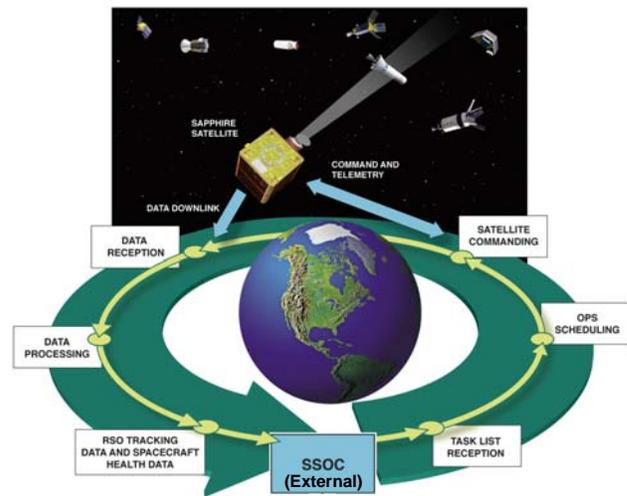


Figure 1: Sapphire Mission

Driving Requirements

Sapphire must meet a set of demanding requirements in the categories of Sensor Performance, Operations Performance, and System Robustness. The performance requirements are summarized in Table 1 and described below.

Sensor Performance is the capability of the system to detect and track RSOs using imagery acquired by the on-board electro-optical sensor. Tracking Data Accuracy refers to the absolute accuracy of the determined RSO vectors with respect to a geocentric reference frame. RSO Brightness is the range of target object brightness (as measured in visual magnitudes) for which the system is able to provide Tracking Data within the specified accuracy. These requirements drive many aspects of the system design, most significantly the design of the Payload including the optical properties of the telescope, the selection of CCD detector, and design of the detector readout chain. These requirements also drive the design of the satellite attitude control system for pointing accuracy and stability, including the selection and sizing of sensors, actuators, and control algorithms. Image data processing algorithms both on-board the satellite and within the ground segment are selected based on these requirements.

Operations Performance is the capability of the system to deliver the required data products to the customer at the specified throughput and within Data Latency constraints. Throughput refers to the number of RSOs that can be successfully observed per day with the resulting tracking data meeting all performance requirements. Data Latency is the time delay between acquisition of RSO imagery by the satellite and the transmission of the corresponding tracking data products for that RSO to the customer. The Throughput and Latency requirements drive the design of the satellite Bus subsystems related to on-board data handling and communications. Specifically, the on-board data storage memory and the RF transmission system to the ground (including downlink data rate, radiated power, coverage, and other link-related parameters) are sized to deliver this performance. The ground segment architecture, including the data reception station locations and configuration as well as the data processing and distribution network, is also driven by the mission latency and throughput needs. Data Security is an integral part of Operations Performance. Sapphire has a requirement to ensure positive control over the satellite at all times through the implementation of encryption and authentication both on the satellite and the ground.

System Robustness encompasses the specified Mission Lifetime, Reliability prediction, and operational Availability. Mission Lifetime is the total time for which the system must provide data to the customer while meeting all performance requirements. Reliability is the predicted probability of the satellite meeting or exceeding the Mission Lifetime, based on analysis of the selected design. Availability is the fraction of time the system must be fully operational and responsive to task requests over the course of the Mission Life, with constraints on the amount of contiguous time the system can remain non-operational. These requirements drive the use of redundancy within all aspects of the system, in addition to the selection of qualified subsystem designs with proven heritage. In the event of a failure, the system must be rapidly re-configurable in order to return to normal operations within the specified constraints.

Table 1: Sapphire Driving Requirements

| Category | Parameter | Requirement |
|------------------------|------------------------|---|
| Sensor Performance | Tracking Data Accuracy | 6 arcseconds, 1-sigma |
| | RSO Brightness Range | Visual Magnitudes 6 to 15 |
| Operations Performance | Throughput | 360 RSOs/day |
| | Data Latency | Less than 10 hours |
| | Data Security | Advanced Encryption Standard |
| System Robustness | Mission Lifetime | 5 years after commissioning |
| | Satellite Reliability | 80% |
| | Availability | 90% With outages less than 7 days long |

SYSTEM DESCRIPTION

Architecture

As shown in Figure 2, the Sapphire System includes the following elements:

- The Space Segment, composed of a satellite Bus and an electro-optical Payload operating in the visible spectral band.
- The Launch Vehicle: Sapphire will be launched as a secondary payload on the Polar Satellite Launch Vehicle (PSLV) and injected into a near circular, dawn-dusk sun synchronous orbit at a nominal altitude of 800 km.

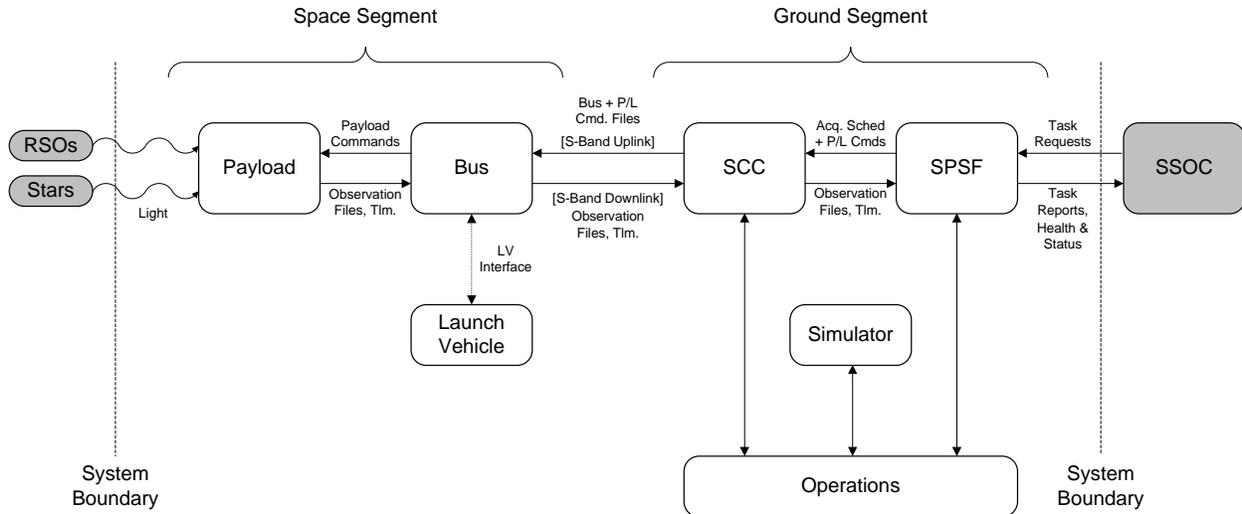


Figure 2: Sapphire System Architecture

- The Ground Segment, which includes the following components:
 - Sapphire Processing and Scheduling Facility (SPSF): located in the Sapphire Operations Facility (SOF) in Richmond, British Columbia. The SPSF provides the capabilities to accept task requests from the SSOC, schedule the RSO image acquisitions and create the associated Payload command files, receive the collected RSO imagery, and process it into RSO tracking data for delivery to the SSOC. The SPSF also provides support for system calibration, which is performed throughout the mission.
 - Satellite Control Centre (SCC): Provides all the capabilities to command the satellite and receive telemetry and image data. The SCC includes a primary S-Band antenna ground station for satellite telemetry, tracking, and command (TTC) located in Abbotsford, British Columbia. The Primary SCC control room computers reside in the SOF. Sapphire will also use a Secondary SCC service to communicate with the satellite through the Surrey Satellite Technology Limited (SSTL) ground station network in the UK.
 - Simulator: located in the SOF. Supports the development of operations procedures and training of system operators.
- Operations, including all the procedures necessary to execute the mission.

Satellite Design

The Sapphire spacecraft is a 150 kg class small satellite with two major subsystems: the Payload (sensor), and the Bus (platform). As described later in the paper, both the Payload and the Bus are based on designs with significant space flight heritage.

The Payload is responsible for collecting image data for each targeted RSO, for reducing the image data volume using a compression algorithm, and for formatting the resulting observation files and transferring them to the Bus. The Payload has two major subsystems. The Optical Imaging Subsystem (OIS) includes the off-axis Three Mirror Anastigmat telescope, its associated Charge Coupled Device (CCD) Focal Plane Assembly, and the CCD pre-amplifiers. The Data Handling and Control Subsystem (DHCS) includes the sensor readout electronics, the Payload instrument controller, and the power supply assembly for power distribution to the Payload units.

The Bus provides the structural, power, and communications interfaces to the Payload. The Bus is responsible for receiving and interpreting command files from the ground segment via an encrypted and authenticated link and controlling the satellite attitude in order to point the Payload OIS towards the target RSOs. The Bus slews the satellite between RSO targets and sets up a stable tracking trajectory for each RSO observation period. The Bus also forwards imaging command files received from the ground to the Payload. In addition to this, the Bus is responsible for receiving and storing image,

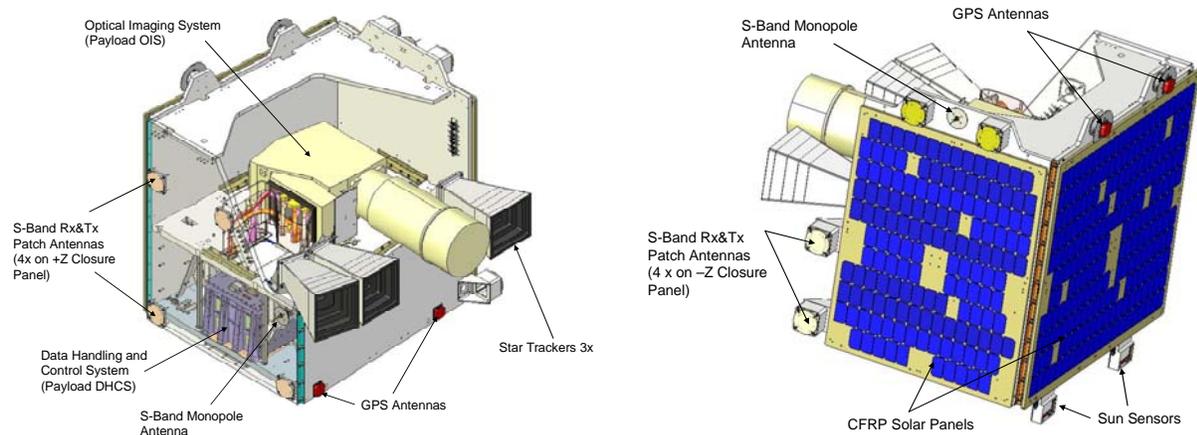


Figure 3: Satellite Configuration

ancillary and housekeeping telemetry files from the Payload until the data can be transmitted to the ground segment over an S-Band radio frequency (RF) link. The Bus is responsible for encrypting data sent to the ground segment and decrypting and authenticating uplink data received from the ground segment. The Bus communications subsystem includes fixed antennas mounted on multiple faces of the satellite in order to provide RF link coverage to the ground in nearly any satellite orientation. The space-to-ground communications link can be active while the Payload is imaging.

The satellite configuration is shown in Figure 3.

Ground Segment Design

The Sapphire mission will have a dedicated ground station for RF communications with the satellite. A 3.8-meter tracking antenna and associated S-Band RF equipment rack will be installed in Abbotsford, British Columbia. This station has a secure network link with the SOF, which will be installed in the MDA headquarters in Richmond, British Columbia. The SOF includes the SCC control room computers and operator consoles, as well as the SPSF computers. Existing SSTL TTC infrastructure in the UK will be used to provide the Secondary SCC Service. This service will include a number of ground station contacts with the Sapphire satellite every day, with a secure network link to the SOF in Richmond for command and telemetry data transfer.

All data exchanged between the SOF and the ground stations, and between the SOF and SSOC will be transmitted through an encrypted Virtual Private Network (VPN). Sapphire implements the Advanced

Encryption Standard (AES) on all ground segment links as well as the satellite uplink and downlink.

The Sapphire Simulator is a tool for training satellite operators. The satellite Bus component of the Simulator features flight-equivalent hardware in the loop, including the Bus On-board Computer running the actual flight software as well as the Solid State Data Recorder and the associated interfaces. Sensors, actuators, and dynamic behaviour are modeled in software. The Payload component is a software-based simulation that provides representative telemetry in response to commands. Built into the Simulator is its own version of the SCC control computer software, so that the Simulator is completely isolated from the operational flight SCC.

Operations

The Sapphire system has been designed for highly autonomous operations.

SCC Operations

During routine contacts with the ground station, the system automatically establishes a secure link with the satellite and uploads Bus and Payload command files. At the same time, both housekeeping telemetry and RSO observation data are automatically downloaded from the satellite. The system automatically monitors real-time Sapphire telemetry and notifies an operator by alarm if any pre-defined telemetry limits are violated. This approach is part of the heritage architecture of the SSTL Bus and SCC.

SPSF Operations

Routine Task Lists are normally received from the SSOC once per day. These can be supplemented by Interrupt Task Requests which may arrive at any time. Processing of these tasks lists to produce Sapphire imaging schedules and Payload command files is automatic, with operators having the ability to review and intervene in the process if necessary.

System Calibration

Sapphire uses a number of data correction tools to improve the quality of acquired Payload imagery. Some of these tools are applied to the imagery on-board the Payload, and some of the tools are used by the SPSF during data processing on the ground. Changes to system performance over the life of the mission will require on-orbit re-calibration of some of these tools in order to maintain Sapphire performance within specifications. The dominant cause of Sapphire performance degradation during the mission is expected to be radiation-induced damage to the CCD detectors, and in particular increases in dark current and dark current non-uniformity over the long term. Contamination is another potential source of sensor degradation over time, although this risk is mitigated by the Contamination Control Program implemented for Sapphire as described later in this paper.

Calibration imaging activities will be performed regularly. Operators will plan the calibration events and issue appropriate Calibration Task Requests to the SPSF for inclusion in the daily schedule.

SYSTEM DESIGN TRADES AND APPROACHES

Sensor Performance

Contamination Control

MDA has established an extensive Contamination Control Program for Sapphire in order to help meet or exceed Sensor Performance requirements at the end of mission life. Contamination can affect satellite performance in a number of ways. All optical surfaces are sensitive to contamination, including critical sensor components such as the telescope mirrors and baffle, star tracker optics, and the CCD detectors. Solar cell efficiency can be degraded by contamination. Contamination also affects the absorptance and emittance properties of satellite thermal control surfaces including radiator mirrors, blankets, paint, and tapes.

In general, contamination can be classified into two categories: molecular and particulate. Molecular contamination originates from out-gassing of materials used in the satellite construction. When exposed to the

vacuum environment, certain materials will release molecular species that can end up depositing on a critical surface. The result is a film of non-volatile residue (NVR) that can reduce optical throughput and degrade emittance and/or absorptance characteristics. Molecular contamination may also accumulate prior to launch as the satellite is exposed to various test facilities and environments during assembly, integration, and test. Of particular concern to telescope optics is the deposition of silicones and hydrocarbons, which are harmful to optical throughput in the visible band. The degradation effects of out-gassing on space flight optics have been well documented on the Hubble Space Telescope program ².

Particulate contamination results from the fallout of tiny airborne particles, e.g. dust, fibres, etc. Any surface exposed to air will start to accumulate particulate contamination. Space flight hardware is typically assembled and tested in clean-room environments, however even in these tightly controlled settings particles will build up with time on any exposed surface. Excessive particulate on optical surfaces will scatter light leading to loss of optical throughput and elevated stray light levels. Dust situated directly on a CCD detector will shadow pixels creating areas of reduced sensitivity and even “dead” pixels with little or no photo response. It should be noted that the launch vibration environment may dislodge particulate contamination and cause cross-contamination from one satellite surface to another. It is therefore important to control particulate contamination not only on critical optical surfaces but also other parts of the satellite.

It was recognized very early in the Sapphire system development process that a contamination control program could provide significant long-term sensor performance benefits. The Sapphire sensor is an astronomical instrument that must discern very dim target objects from a noisy background. Any improvements in optical performance in terms of higher efficiency and/or reduced stray light will allow the instrument to observe and track dimmer objects. During the mission design phase, analyses were performed to model the effects of contamination on Sapphire telescope optical throughput and to establish contamination budgets for all critical surfaces on the satellite for both molecular and particulate. The resulting budgets established limits for critical surface contamination during each stage of satellite assembly, integration, and test, and through launch and on-orbit operations.

The contamination budgets were then used to derive requirements for contamination control that were levied

on the satellite subsystem suppliers. These requirements include the industry-standard guidelines for materials selection in terms of constraints on Total Mass Loss (TML) and Collected Volatile Condensable Mass (CVCM). In addition, specific cleanliness requirements were developed for the acceptance of the Payload flight hardware critical optical surfaces. These requirements include specific verification criteria for particulate and NVR contamination levels as well as the residual out-gassing rate of the telescope (OGR) as measured in vacuum by a Temperature-controlled Quartz Crystal Microbalance (TQCM). The latter requirement was necessary to limit self-contamination of the instrument over the life of the mission.

In addition to mandating the use of materials that comply with standard TML and CVCM guidelines, MDA also performed additional screening of materials for residual out-gassing rate. TML and CVCM are useful measurements of a material under specific test conditions, but these parameters do not give insight into the long-term out-gassing properties of the material. It is possible for a material to have acceptable TML and CVCM values but pose a high risk of generating molecular contamination through long-term out-gassing. To ensure that Sapphire meets end of mission performance requirements, it was necessary to analyze the impact of material residual out-gassing rates under the expected in-orbit conditions.

Even with strict materials screening processes applied to the satellite design, it is still necessary to bake out all flight hardware (and in some case ground support equipment hardware) under vacuum in order to remove potential contaminants prior to launch. For Sapphire, equipment bake-outs were performed at multiple levels of assembly. Components or sub-assemblies deemed to contain high levels of silicones or other deleterious materials were baked out separately before being integrated into units. An example from Sapphire is the set of vibration isolation dampers used in the reaction wheel assembly, constructed from a compliant rubber-like material containing high levels of silicone. These parts were baked out for over a week in a hard vacuum at over 100°C in order to drive the level of out-gassing down to an acceptable level. Payload harnesses and thermal blankets were also baked out prior to integration. The telescope housing underwent an extensive vacuum bake before integration of the flight mirrors, primarily to reduce the out-gassing rate of the black paint applied to the interior optical cavity. In general, any painted or coated surface requires an extended bake-out depending on the nature of the material applied.

Fully integrated subsystems were also baked out for Sapphire. The reason for additional bake-out at higher levels of assembly is the additional use of staking materials, conformal coatings, tapes, adhesives, and other substances applied during the satellite hardware integration process. The entire satellite Bus underwent a high temperature bake-out as part of Bus-level thermal vacuum testing. This testing was performed without the Payload units, precluding any cross-contamination from the Bus to sensitive Payload surfaces during the bake-out. The residual Bus out-gassing rate was measured using TQCMs mounted in the vacuum chamber with temperatures representative of predicted worst-case in-orbit conditions for out-gassing and molecular deposition on the optical surfaces. The measurements confirmed that the residual Bus OGR met the target rate established by the contamination control budgets. A similar vacuum bake-out and TQCM measurement will be performed on the integrated Payload.

MDA has implemented a regime of monitoring and inspection for contamination during satellite assembly, integration, and test (AIT). Satellite surfaces will be periodically measured for particulate using tape-lifts. The tapes are inspected under a microscope and the numbers of particles and their size measured to determine the particulate contamination level. A pair of Traveling Optical Witness Samples (TOWS) remains with the satellite at all times during AIT. Each TOWS contains an exposed mirror. The mirrors are periodically changed out and measured to determine the level of degradation in optical reflectance, which is used to assess the level of molecular contamination. In addition, satellite surfaces are periodically wiped using clean, polyester cloths wetted with isopropyl alcohol (IPA). These wipes, along with control samples, are then processed to determine the weight of contaminants and level of NVR on the satellite surface. These samples are also subjected to Fourier Transform Infrared Spectroscopy (FTIR) analysis to determine what molecular species were present on the surface. This type of on-going contamination monitoring is used to estimate the cleanliness of the satellite over the course of AIT, and to identify when further cleaning is necessary to remain within the established contamination budgets. Less invasive visual inspections are also used more frequently, assisted by both white and UV light sources, in order to check for signs of gross contamination on critical surfaces.

A number of approaches have been adopted for satellite-level AIT in order to reduce the level of accumulated contamination. Firstly, a clean tent will be constructed for Sapphire that provides a cleaner than class-10k environment for satellite integration and

functional testing; this clean tent resides within the larger class-100k environment of the satellite integration facility. The tent features down-flow High Efficiency Particulate Air (HEPA) filters for air exchange and walls made from ultra-low out-gassing material. Whether the satellite is inside or outside the clean tent for specific testing activities, fitted dust covers have been manufactured to protect the flight hardware from particulate fallout. These covers are made from ultra-clean, conductive material with no NVR transfer. The covers can be easily removed for access to the satellite. There are also radio frequency (RF) transparent covers that will be used for satellite-level electro-magnetic compatibility (EMC) testing. In addition, special protective measures are being taken for the telescope. The entire telescope assembly will be bagged underneath the satellite cover, and the telescope optical cavity continuous purged with clean gaseous nitrogen in order to prevent the entry of contaminated air. The telescope aperture also accommodates a removable hard cover (with purge port) for protection during ground testing.

Test chambers are inspected for cleanliness prior to entry of the flight hardware. This is especially important for thermal chambers. Chamber certification trial runs, with witness samples mounted in the chamber, are performed to ensure that the chamber will not contaminate the satellite surfaces. For vacuum chambers, the chamber background out-gassing rate (including all non-flight ground support equipment that needs to be in the chamber) is measured prior to insertion of the flight article.

The Sapphire contamination control program is an investment over and above standard clean-room practices for space hardware. Through rigorous materials selection, monitoring, and protective measures adopted during AIT, we expect to achieve an improvement in sensor performance at end of life. Based on interim measurements of Payload and Bus cleanliness and out-gassing rate, Sapphire is on track to improve end-to-end optical throughput by between 10% and 15% (i.e. a factor of 1.10 to 1.15) relative to not having such a control program in place.

Use of RSO Track Mode

There are two basic modes of operation that a satellite can use when attempting to take pictures of an RSO. The first is to point the telescope with a fixed attitude in inertial space – this is sometimes referred to as “sidereal stare” or just Stare mode. In this mode, the background stars appear as small points of light while an RSO moving against this background produces a “streak” of light across the detector array. The second

option is to try and move the telescope along the path of the RSO during image acquisition at the predicted rate of RSO motion – this is referred to as Track mode. In this mode, the RSO ideally appears as a small point of light while the background stars streak across the detector array.

There are pros and cons to each approach. Stare mode has the potential benefit of simpler attitude control during imaging as the satellite can set up and maintain an inertially fixed attitude without having to control a rate relative to the stars. This is advantageous for systems like Sapphire that use star trackers as the primary attitude sensor. Stare mode images may also produce a smaller volume of data relative to Track mode, which improves margin on the satellite-to-ground communications link. This comes about because the background stars produce smaller pixellated spots on the detector than the star streaks produced during Track mode operations. When the images are compressed inside the Payload, the small star spots occupy less memory than would longer streaks. This benefit is offset somewhat by the fact that more stars will pass the on-board image thresholding process due to accumulated signal in the Stare mode star spots. Stare mode also has additional flexibility in being able to search an area of sky for unknown objects or RSOs with poorly known orbits. If something is there it will show up as a streak. RSO streaks can be quite obviously identified by the naked eye within the imagery, making Stare mode images more intuitive for humans to process.

Track mode has the chief advantage that it maximizes the signal-to-noise ratio (SNR) of RSO spots on the detector. Since the telescope follows the RSO during imaging, signal accumulates in a smaller area on the detector grid relative to the more thinly distributed signal in RSO streaks resulting from Stare mode. Higher SNR leads to a more accurate RSO position determination, as well as better estimate of the RSO photometric brightness. It also means that dimmer RSOs can be detected relative to Stare mode.

Given the driving requirements for Sapphire, it was decided to use Track mode as the baseline operational approach for RSO observations in order to gain as much margin as possible for end of life sensor performance. The projected data volume using Track mode imagery was analyzed and the system design, including subsystems on the satellite and the ground, was sized to cope with this volume of data. Re-pointing and setting up a stable tracking rate for the telescope is accomplished by slewing the entire satellite body. This is feasible for Sapphire due to the agile, small satellite platform with good margins on sensor

and actuator performance. In addition, this operational approach leads to a wide variety of satellite attitudes with respect to the Sun. The thermal design of the satellite is suited to this environment, and the power subsystem, in particular the solar panels and battery, has been sized appropriately (with large margins) for the intended operational scenario.

Sapphire is also capable of acquiring images using Stare mode, but this mode will not be typically used for RSO observations. Sapphire will make use of Stare mode for certain types of calibration images.

Mirror Coating Tradeoff

The Sapphire telescope optics chain includes four mirrors – three powered mirrors and one “fold flat” mirror. The mirror substrates are manufactured from solid aluminum. It was initially believed that the reflectance requirements for Sapphire could be met with an enhanced aluminum coating deposited on the aluminum substrate. The coating is designed to improve reflectance over the visible band compared to using bare polished aluminum. Aluminum mirrors with aluminum coatings have extensive spaceflight heritage and are seen as the “standard” choice for these types of optics. However, results of coating qualification tests for Sapphire revealed that the reflectance performance targets could not be met with this coating, and there was a significant reflectance deficit relative to the requirement. The project was faced with the decision of whether to accept the performance deficit of the aluminum coating, or look for a different solution to improve reflectance.

The downside of moving away from the aluminum coating, or to continue experimenting with variations on this coating, was an increase in both technical and schedule risk. The technical performance risk arises when deviating from proven flight heritage technology – will a different coating survive the Sapphire environment in space and deliver performance throughout the mission life? The schedule risk stems from possible delays in finding and qualifying a new coating that meets the Sapphire requirements.

The final solution for Sapphire was to move to a protected silver coating. This option became attractive because the telescope supplier was in the middle of qualifying the silver coating for another project. A set of qualification mirrors with aluminum substrates was coated for Sapphire and subjected to extensive environmental tests including thermal cycling, adhesion tests, and exposure to high humidity. The concern with silver coating is possible oxidation of the silver layer, or “tarnishing” of the silver over time leading to loss of reflectance. Despite the fact that the silver layer is

protected by other layers of material, any coating defects (e.g. pinholes) are targets for oxidation both on the ground through exposure to the air or in low Earth orbit through exposure to corrosive atomic oxygen. The Sapphire qualification tests showed that the coating was very robust and the technical risk was judged to be low. The upside in terms of mirror reflectance was significant – the new silver coating out-performed the aluminum coating by approximately 20% with respect to total system optical throughput (i.e. a factor of 1.20).

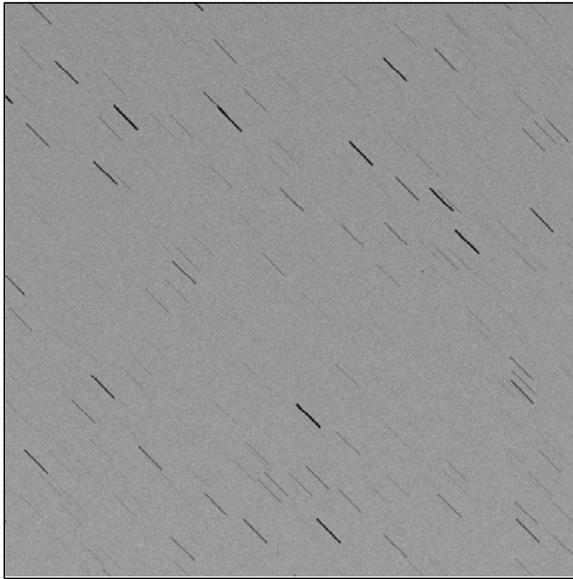
It is recognized by the project that silver coatings are more sensitive to the environment than aluminum. Therefore, a program of inspection and monitoring has been set up to check for any signs of mirror corrosion during satellite AIT. In addition, the use of continuous dry nitrogen purging in the optical cavity for contamination control will also help reduce exposure of the silver layer to the atmosphere.

Operations Performance

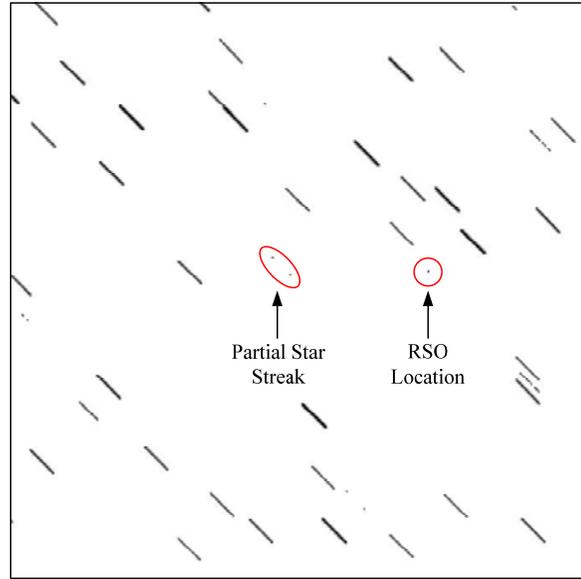
Distributed Data Processing

An important trade-off in any space system is how much data processing functionality to implement on the satellite versus the ground segment. The normal tendency is to implement complex and/or resource intensive data processing algorithms on the ground, for several reasons.

- In general, ground-based computer systems have far more available computing power in terms of processing speed and memory than space-based systems. This allows a more flexible design that is easier to develop and maintain.
- It is usually less expensive to develop, verify and maintain ground segment software than to verify and maintain the same functionality in space flight software. This fact is largely due to restrictions on flight computer resources as well as restrictions on development environments/languages, available test tools, and increased software development process overhead.



(a) Raw image including background signal, noise, and faint stars; Size \approx 2 MB



(b) Compressed image with background removed and RSO spot identified; Size \approx 40 kB

Figure 4: Simulated Sapphire Imagery

In spite of the above, adding data processing complexity to the satellite can produce significant benefits for the system. For Sapphire, a key issue became the volume of RSO imagery data produced by the Payload. The Sapphire CCD detectors have an active area of 1024 by 1024 pixels, with an average of 8 individual images acquired per RSO task. Assuming 360 RSO tasks per day and 16-bit storage per pixel, this leads to a total Payload data volume of over 6 gigabytes per day. This amount of data is a significant problem for a small satellite system, affecting the sizing of the on-board memory storage subsystems, the RF downlink subsystems, and the ground segment architecture. The heritage satellite communications subsystem can provide approximately 4 megabits/second downlink data bandwidth for Payload imagery. At this rate, it would take nearly 200 minutes of downlink time per day to get the Payload imagery to the ground. This is not feasible for Sapphire given the ground segment architecture.

Clearly some form of image data compression is required in the satellite in order to avoid redesigning the heritage communications subsystems and adding more ground reception stations to the architecture. The question becomes what form of on-board compression to use, and to what extent the satellite should be engaged in data processing prior to downlink. At the extreme end of the spectrum, one could imagine the satellite producing low-volume, finished data products

suitable for transfer to the customer. At the other end, the satellite could use a simple compression routine to package the imagery for downlink, which would then be decompressed on the ground for further processing.

Any on-board compression of Sapphire imagery must reduce the total data volume by at least a factor of six in order to fit within the Sapphire small satellite system concept. In addition, the compression process must not remove any of the valuable star or RSO signal. It became very difficult to find a simple compression algorithm that would reliably meet these derived requirements for the type of astronomical images produced by Sapphire. It was decided to implement a type of filter within the Payload to identify and isolate pixels of interest on the detector that are necessary for further processing on the ground – namely, the “spots” on the detector that correspond to bright stars and RSOs. These spots are localized areas with signal level that is significantly higher than the average “background” signal level of the image. The process of calculating the average background level of the image and then identifying spots that are statistically distinct from the noisy background is referred to as “thresholding”. Through extensive algorithm testing using simulated Sapphire images including star fields and RSOs, it was found that this thresholding method was very effective at reducing the number of pixels that needed to be transported to the ground. Flexibility was built into the operation of this function to allow tuning

of the signal threshold applied to the imagery. Within the Payload, this function was implemented in a Field Programmable Gate Array (FPGA) in order for execution performance to be compatible with the design of the Payload image acquisition timing.

A sample of simulated Sapphire imagery, showing the before and after effects of on-board compression, appears in Figure 4. The compressed image includes an example of a star streak that partially survived the thresholding process. The ground processor is able to identify partial star streaks by correlating the spot positions with expected star locations from the star catalog. In this way, partial star streaks are not confused with RSO spots.

The remainder of Sapphire data processing, including the accurate determination of the telescope attitude using guide stars in the image, is implemented in the ground segment. To perform this type of processing within the satellite would represent a large increase in complexity and computational power, likely requiring a new concept for the Sapphire Payload architecture. In the end there was no compelling reason to produce the finished data products in the satellite as the downlink data volume was manageable with the use of compression.

Automated Operations

Another classic trade-off in space system architecture is how much automation to build into mission operations. Automation has the potential to reduce the operational costs of the system by decreasing the number of full-time operators required to make the system run. There is also the potential of improving system performance through decreased latency if human processing and decision-making can be taken out of the operational timeline. However, such automation usually comes with the price of increased complexity in the ground segment software and carries higher technical and development schedule risk. In addition, it is extremely difficult to automate some aspects of satellite operations, in particular the handling unusual situations such as satellite contingencies or urgent requests for re-tasking to address a particular high-priority operational need. For example, if there are no operators watching over the satellite when an in-flight anomaly occurs, there could be a significant delay before the situation is recognized and recovery operations initiated. This could increase system outage time.

The level of operations automation for Sapphire is largely driven by the selection of the heritage satellite Bus and Satellite Control Centre technology from SSTL. These heritage subsystems were already designed for streamlined operations with a minimalist

approach to operator intervention. Operators are notified by the system via email if there is an out-of-limits condition or if automated processing fails at any stage. Otherwise, the system is able to function without requiring manual input from the operators. This concept was extended for Sapphire to the new SPSF component of the ground segment. The scheduling and data processing functions of the SPSF run autonomously. The scheduler in particular even responds automatically to “interrupt” task requests from the SSOC and is able to re-plan operations to accommodate the re-tasking; this includes the generation of new upload products for Payload commanding. The interfaces between the SSOC and the SPSF, and between the SPSF and the SCC, operate automatically using a “drop box” protocol. A subsystem waits for an input file to arrive in its in-box. When the file arrives, the subsystem detects presence of the file and begins automated processing. When processing is complete the subsystem places its output products into the in-box of the next subsystem in the chain. The role of the human operator in this process is to monitor the system and respond to anomalous conditions, as opposed to being directly involved in the processing flow.

The staffing concept for Sapphire during the routine phase of the mission is to have operators at the Sapphire Operations Facility (SOF) during normal business hours, and to have operators on call to support alert messages from the automated system outside of these hours. The primary function of the operator is health monitoring, trouble-shooting, and maintenance of the relevant systems.

Sapphire is able to streamline operations by selecting heritage systems including built-in automation, and extending these concepts to the newly developed parts of the ground segment.

Operations Facility Location

The Sapphire Operations Facility (SOF) consists of the SCC control room computers as well as the SPSF, in addition to all of the interface equipment necessary to implement the Sapphire network architecture. The SOF supports the external interface to the SSOC, as well as Sapphire-internal interfaces to the primary SCC ground station in Abbotsford and the Secondary SCC service in Guildford, UK. From the SOF, Sapphire operators will run the mission. Different options were explored for the location of the SOF, including co-locating within an existing satellite operations facility versus establishing a new facility. Given the relatively small size of the Sapphire mission, the most cost effective approach was to leverage off the infrastructure of an existing building

with secure access, office space, power, network connections, and maintenance support.

The final decision was to house the SOF within the MDA Richmond facility. The SOF is therefore co-located in the same building as the mission prime engineering team that oversaw development of the system and performed system-level assembly, integration, and test. This arrangement has a number of advantages for Sapphire operations. The biggest of these is direct access to system engineering expertise in the event of anomalies with the satellite or the ground segment. By streamlining communications between the mission operators and the system engineering support team, system outage times can be reduced. As well, proximity to the development team means that operators have more resources available for on-going training and response to routine questions regarding the use and function of the system. The tight coupling between the operations team and the system engineering team afforded by co-location will help ensure that there is a continuous monitoring of system performance as the mission progresses. This relationship will also make it easier to implement and test any desired system enhancements that are identified over the course of routine operations. In addition, the Sapphire operations team will be able to draw from the pool of system engineers at MDA Richmond for the staffing of operator roles.

It is anticipated that the decision to locate the SOF within the MDA facility will ultimately lead to reduced operations costs and shorter system outages.

System Robustness

Use of Designs with Space Flight Heritage

Satellite Bus

The Sapphire satellite Bus is based on the SSTL-150 platform, designed and built by Surrey Satellite Technology Limited in Guildford, UK. The primary structure, avionics, and power system are largely re-used from the design of the RapidEye satellite. RapidEye is a low Earth orbit constellation of five satellites used for optical remote sensing. MDA was the prime contractor for this mission, with SSTL subcontracted to provide the satellite Buses and perform satellite-level integration. The constellation was launched on August 29, 2008, and began full commercial operations in February 2009. Approaching two years of in-orbit experience, this constellation provides space flight heritage for the Sapphire Bus design. Some RapidEye elements that have been changed for Sapphire include: the star trackers, the battery, and the solar panel technology. All of these

new items have flight heritage on other missions. Sapphire will be launched on a Polar Satellite Launch Vehicle, and the mechanical environment of the launch has changed relative to the RapidEye program which used a different rocket. The Sapphire version of the SSTL-150 Bus has been fully qualified to withstand this new environment.

Payload Telescope

The optical portion of the Sapphire telescope was designed and built by L-3 Communications SSG-Tinsley, in Wilmington, Massachusetts, USA. The Sapphire telescope is based on the design of the Space-Based Visible (SBV) telescope that flew on the Midcourse Space Experiment (MSX) satellite. MSX was launched in 1996 into an 898 km altitude sun-synchronous orbit, with SBV one of several payloads on-board. The mission of SBV is very similar to Sapphire – SBV was the first demonstration of “surveillance of space” from a space-based platform². SBV has been a Contributing Sensor to the US Space Surveillance Network since 1997. Sapphire and SBV share the same basic telescope architecture and properties:

- Three-mirror Anastigmat (TMA) off-axis imaging optical design
- All aluminum housing and mirror substrates
- Similar aperture size
- Excellent stray-light rejection.

This telescope design has a proven track record of imaging and detecting RSOs from space. In addition, MDA has flight experience with this class of telescope as the RapidEye payload features an all-aluminum TMA. This architecture is considered to be a low-risk, well-suited technology for the Sapphire application.

Payload Focal Plane Assembly

The Sapphire Focal Plane Assembly (FPA) was designed and built by e2v Technologies in the UK. The FPA consists of two CCD detectors (the Sapphire prime and redundant units) mounted onto an invar adaptor plate with flex harness connections for interfacing to the Optical Imaging Subsystem pre-amp assembly. This same package previously flew on a mission called Microvariability and Oscillations of STars (MOST). MOST is a Canadian micro-satellite launched in 2003 with a primary mission of asteroseismology, involving long-term observations of stars³. The MOST sensor has been very successful and continues to produce scientific data from a roughly 825 km polar orbit. The e2v detector model used is the CCD47-20bi (back

illuminated, Advanced Inverted Mode Operation), which has extensive flight heritage in addition to MOST as a sensor for star tracker applications and other space payloads. The FPA is another example of proven, reliable, fit-for-purpose technology built into the Sapphire satellite design.

Image Data Processing Algorithms

Terma in Copenhagen, Denmark, was selected to design and build the Sapphire Processing and Scheduling Facility (SPSF). This computer system contains the algorithms for processing the downloaded Sapphire imagery, establishing the precise attitude of stars and RSOs in the images, and creating RSO tracking data products. Terma has extensive experience in this type of image processing application as they also design and manufacture space flight star trackers. By leveraging off their domain expertise and access to heritage models and algorithms, Terma is able to produce a compact, robust data processor for Sapphire.

Use of Redundancy

The Sapphire system design includes substantial redundancy. The Payload electronics includes two complete strings of equipment in cold redundancy. Each independent string includes a CCD detector, calibration lamp, pre-amp electronics, readout electronics, instrument controller, and power supply electronics. If one of the equipment chains was to fail, the cold redundant chain would be powered up and the satellite restored to full function. The only element of the Payload that does not have redundancy is the structural aspects of the telescope itself, including the telescope housing, mirrors, and radiator. These structural elements have been qualified to survive the Sapphire mechanical and thermal environments and are extremely high reliability assemblies.

Similarly, the heritage satellite Bus features a robust design with redundancy as summarized in Table 2. The only Bus subsystem that does not have redundancy is the structure. However, the structure has successfully passed proto-flight qualification for the Sapphire mechanical and thermal environments and is a very high reliability item.

There are no deployable items on the satellite other than the separation system, and no propulsion subsystem. This significantly reduces the complexity of the satellite design, making it easier to meet the reliability requirement.

The ground segment architecture also includes redundancy in order to reduce the duration of system outages in response to equipment failures. At an

architectural level, the system uses two separate ground station antenna facilities during routine operations: the Primary SCC ground station in Abbotsford, and the Secondary SCC service from SSTL in the UK. If an outage occurs at one of these facilities, then satellite operations can continue using only a single antenna until the system has recovered. Outages in the Primary SCC ground station are mitigated by having equipment spares for critical items. For example, the antenna motor drive assembly is fully spared as this is a long lead item and also a mechanism subject to wear.

Redundancy is also built into the Sapphire Operations Facility (SOF) computer systems, including the Primary SCC control room computers and the SPSF. If an SCC workstation experiences a failure, the remaining SCC workstations can be rapidly re-configured to restore function while the computer hardware is replaced. As well, spare units are kept for items such as the network routers that provide secure communications with the remote Sapphire sites and the SSOC external interface.

Sapphire is a small satellite system that has been designed with redundancy in both the space and ground segments in order to meet demanding requirements for mission robustness.

Table 2: Bus Redundancy Summary

| Bus Unit | Redundancy | Hot/Cold |
|----------------------------------|------------|----------|
| Solar Panel Sections | 4 out of 5 | Hot |
| Battery Strings (parallel) | 2 out of 3 | Hot |
| Power Conditioning Modules | 1 out of 2 | Hot |
| Power Distribution Modules | 1 out of 2 | Hot |
| Solid State Data Recorders | 1 out of 2 | Cold |
| On-Board Computers | 1 out of 2 | Cold |
| Data Handling Communications Bus | 1 out of 2 | Hot |
| GPS Receivers and Antennas | 1 out of 2 | Cold |
| Reaction Wheels | 3 out of 4 | Hot |
| Magnetometers | 1 out of 2 | Hot |
| Magnetorquers (each of 3 axis) | 1 out of 2 | Hot |
| Sun Sensors | 1 out of 2 | Hot |
| Star Trackers | 1 out of 3 | Cold |
| Star Tracker Data Processors | 1 out of 2 | Cold |
| Star Tracker Interface Modules | 1 out of 2 | Cold |
| S-Band High Rate Transmitters | 1 out of 2 | Cold |
| S-Band Receivers | 1 out of 2 | Hot |

CONCLUSION

Sapphire is a small satellite mission with demanding requirements for Sensor Performance, Operations Performance, and System Robustness. In arriving at a system design to meet these requirements, a number of important trade-offs were performed. To help improve Sensor Performance at the end of mission life, the decision was made to implement a comprehensive Contamination Control Program. In addition, an RSO tracking mode was selected for routine observations in order to increase the RSO spot signal to noise ratio. The final choice of telescope mirror finish was a qualified protected silver coating to enhance end-to-end optical throughput. Several trade-off decisions were also made to help meet the mission Operations Performance objectives, including the implementation of a sophisticated on-board compression scheme to significantly decrease the volume of Payload imagery data. Automation has been built into the design of the ground segment in order to reduce operator workload and improve system latency in terms of both planning and end product delivery time. The operations facility has been located in the same building as the mission prime system engineering team in order to facilitate operator training and provide faster recovery from unexpected system outages. Finally, the mission System Robustness requirements for Sapphire have been addressed by selecting satellite and ground segment designs with proven heritage, and by incorporating redundancy to improve overall reliability.

Acknowledgements

The authors wish to acknowledge the contributions of the DND customer to the Sapphire program, and all the insight and experience they have shared in the field of space surveillance. We would also like to thank the MDA Sapphire project team for their contributions to the development of this system.

References

1. Maag, C., Millard, J., and M. Anderson, "An In-Depth Assessment of Internal Contamination in the Wide Field/Planetary Camera", *Journal of the IES*, May-June 1990, pages 29-35.
2. Stokes, G.H., von Braun, C., Sridharan, R., Harrison, D., and J. Sharma, "The Space-Based Visible Program", *Lincoln Laboratory Journal*, Volume 11, Number 2, 1998, pages 205-238.
3. Walker, G., Matthews, J., Kuschnig, R., Johnson, R., Rucinski, S., Pazder, J., Burley, G., Walker, A., Skaret, K., Zee, R., Grocott, S., Carroll, K., Sinclair, P., Sturgeon, D., and J. Harron, "The MOST Asteroseismology Mission: Ultraprecise Photometry from Space", *Publications of the Astronomical Society of the Pacific*, Vol. 115, September 2003, pages 1023-1035.