

Sapphire: Canada's Answer to Space-Based Surveillance of Orbital Objects

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Abstract

The Canadian Department of National Defence is in the process of developing the Canadian Space Surveillance System (CSSS) as the main focus of the Surveillance of Space (SofS) Project. The CSSS consists of two major elements: the Sapphire System and the Sensor System Operations Centre (SSOC). The space segment of the Sapphire System is comprised of the Sapphire Satellite - an autonomous spacecraft with an electro-optical payload which will act as a contributing sensor to the United States (US) Space Surveillance Network (SSN). It will operate in a circular, sun-synchronous orbit at an altitude of approximately 750 kilometers and image a minimum of 360 space objects daily in orbits ranging from 6,000 to 40,000 kilometers in altitude. The ground segment of the Sapphire System is composed of a Spacecraft Control Center (SCC), a Satellite Processing and Scheduling Facility (SPSF), and the Sapphire Simulator. The SPSF will be responsible for data transmission, reception, and processing while the SCC will serve to control and monitor the Sapphire Satellite. Surveillance data will be received from Sapphire through two ground stations. Following processing by the SPSF, the surveillance data will then be forwarded to the SSOC.

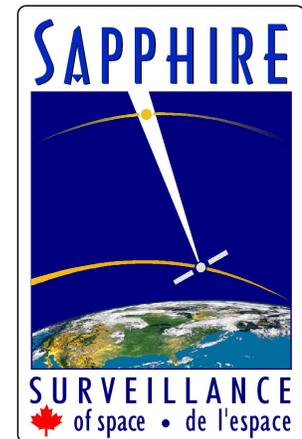


Fig. 1. Sapphire Logo

The SSOC will function as the interface between the Sapphire System and the US Joint Space Operations Center (JSpOC). The JSpOC coordinates input from various sensors around the world, all of which are a part of the SSN. The SSOC will task the Sapphire System daily and provide surveillance data to the JSpOC for correlation with data from other SSN sensors. This will include orbital parameters required to predict future positions of objects to be tracked. The SSOC receives daily tasking instructions from the JSpOC to determine which objects the Sapphire spacecraft is required to observe. The advantage of this space-based sensor over ground-based telescopes is that weather and time of day are not factors affecting observation. Thus, space-based optical surveillance does not suffer outage periods of surveillance as is the case with ground-based optical sensors. This allows a space-based sensor to obtain more data and to collect it from a more flexible vantage point.

The Sapphire launch is planned for July 2011. The Sapphire spacecraft is designed to operate for a minimum of five years. It will contribute considerably to establishing a significant space capability for Canada. This, and other current Canadian space initiatives, will have wide-ranging benefits in the area of National Defence.

Canadian Space Surveillance History

The Canadian Department of National Defence (DND) originally became involved in Space Surveillance through the Royal Canadian Air Force's research branch in 1958 when a request for contributions was received from the Harvest Moon program in which the United States Air Force (USAF) requested collaboration from amateur astronomers worldwide to provide space object data [1]. This project laid the foundation for the SSN.

As Harvest Moon evolved to the Space Track Project Office, further requests were received for observations from the Mid-Canada Line of radars. In particular, observations came from the Prince Albert research radar to assist the tracking of the MIDAS program's Discoverer firings. This level of participation increased in 1961 with the transfer of a Baker-Nunn camera from the USAF to the RCAF. It was eventually installed at RCAF Station Cold Lake, Alberta, Canada [1].

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As the number of satellites increased through the decade, an additional Baker-Nunn camera and space object identification telescope was added in St Margarets, New Brunswick on the east coast of Canada. To manage these operations and resources, the Satellite Tracking Unit was commissioned in 1975 [1].

The United States' GEODSS systems were coming on line in the 1980's with advanced electro-optical cameras which essentially rendered the film-based Baker-Nunn cameras obsolete. This technology disadvantage was compounded by needed personnel cuts such that the Canadian Force's space surveillance capability was essentially decommissioned in 1992, ending Canada's 30 year contribution to the SSN. The SofS Project demonstrates the DND's commitment to reviving this capability and will reestablish a Canadian Forces (CF) contribution to the SSN with the launch of the Sapphire satellite in 2011.

Why Surveillance of Space?

Since the launch of Sputnik in 1957, thousands of objects have been accumulating in various types of orbits around the Earth. These objects include active and inactive satellites, spent rocket bodies, and a wide variety of debris of all types and sizes. The accumulation of these objects is due, in part, to factors such as poor management of the space environment, space object "breakups", and a failure to reduce the equivalent of space pollution through proper disposal and/or de-orbiting of spent space assets. The growing quantity of objects orbiting the earth now represents an ever increasing threat to the security of nations and the safety of vital (and valuable) national spacecraft in orbit. All man-made orbiting objects not only pose an impact hazard to other objects in space but may also contain hazardous materials that could pose a danger to other satellites, manned spacecraft, or the International Space Station. Thus, it is essential to know the orbital location of these objects as precisely as possible in an effort to minimize the probability of collision. This information is also important for predicting re-entry of objects in order to prevent nations from mistakenly identifying a re-entering object as a missile fired by a hostile nation – a mistake which could lead to actions yielding catastrophic results.

To aid in the task of tracking man-made Resident Space Objects (RSO), Canada has committed to the development of the CSSS. The CSSS will also serve to re-establish a partnership with the SSN by acquiring and deploying a space-based sensor which will act as a contributing sensor to the SSN. The overall SofS project objective is to gain assured access to orbital data information through this tie to the US SSN – information that is crucial to the proper monitoring and safety of vital national (primarily commercial) interests. Such data will also serve to increase the Space Situational Awareness (SSA) capabilities of the Canadian Department of National Defence (DND) who will exploit it in the furtherance of the protection of Canada and her assets.

Why Surveillance of Space *from* Space

Space-based optical sensors have considerable advantages over their ground-based brethren. Ground-based optical sensors depend upon proper lighting conditions at the sensor site in order to be able to successfully acquire tracking data – including both the time of day lighting (i.e. dusk-to-dawn shooting periods) and an appropriate phase angle (the sensor/target/sun angle). Ground-based optical sensors' effectiveness is further curtailed by atmospheric effects such as weather conditions (cloud cover and precipitation) and local light pollution. Thus, space-based sensors provide for a greater opportunity of acquiring tracking data on a wider array of targets.

Capability Deficiency

Canada requires assured access to SSA information (orbital data on satellites and space debris) in support of its defence commitments. Satellites are essential for surveillance, reconnaissance, intelligence gathering, arms control verification, geomatics, navigation, communications, meteorology, and aerospace warning. These assets are vulnerable to accidental collision with other orbiting objects and intentional attack or sabotage. The SSA data is essential for performing conjunction analysis and re-entry assessment of space objects. Both of these analysis capabilities are important for Canada, as a space-faring nation, in order to uphold its obligations under various UN conventions on outer space. Additionally, a growing number of nations have access to satellites which could be used against Canada or the CF in theatres of operation. To ensure the integrity of space-based assets, safeguard national sovereignty, and support CF operations worldwide, it is essential to be aware of foreign satellite activities.

The SSN and Canada's Contribution

The US SSN is a global network comprised of approximately 30 dedicated, contributing, and collateral radar and electro-optical sensors. These fixed, ground-based sensors were complimented until only recently by the Space Based Visible (SBV) payload of the Midcourse Space Experiment (MSX) satellite.

While the ground-based sensors are primarily in the northern hemisphere and further concentrated primarily in North America, the SBV sensor had the flexibility of essentially providing a global vantage point for tracking space objects. Following the termination of the provision of SBV data to the SSN in mid-2008, there is not currently any space-based sensor for the surveillance of space in orbit. Building upon the legacy work of the SBV, the US is presently working on the design and implementation of the Space-Based Space Surveillance (SBSS) sensors with the initial sensor presently scheduled to launch in 2009.

Canada (specifically, the DND) has decided to pursue its own space-based contribution to the SSN in the form of the Canadian Space Surveillance System – highlighted by the Sapphire satellite (henceforth referred to as Sapphire). Sapphire will act as a contributing sensor to the SSN. As such, it will not be under US Strategic Command's (USSTRATCOM) operational control; rather, it will provide observational data to the SSN on a contributing basis.

Canadian Space Surveillance System (CSSS)

The role of the CSSS will be to secure timely access to orbital data essential to Canada's sovereignty and national security by contributing to the deep space surveillance mission of the SSN. The CSSS must be capable of providing timely, relevant, and accurate tracking data on man-made Earth-orbiting objects in deep space. The CSSS [Fig. 2] primarily consists of the Sapphire satellite, two ground stations (with the primary station located in Canada and an alternate that will be leased from the United Kingdom), a Satellite Control Centre (SCC), and a Sapphire Processing and Scheduling Facility (SPSF) in St. Hubert, Quebec.

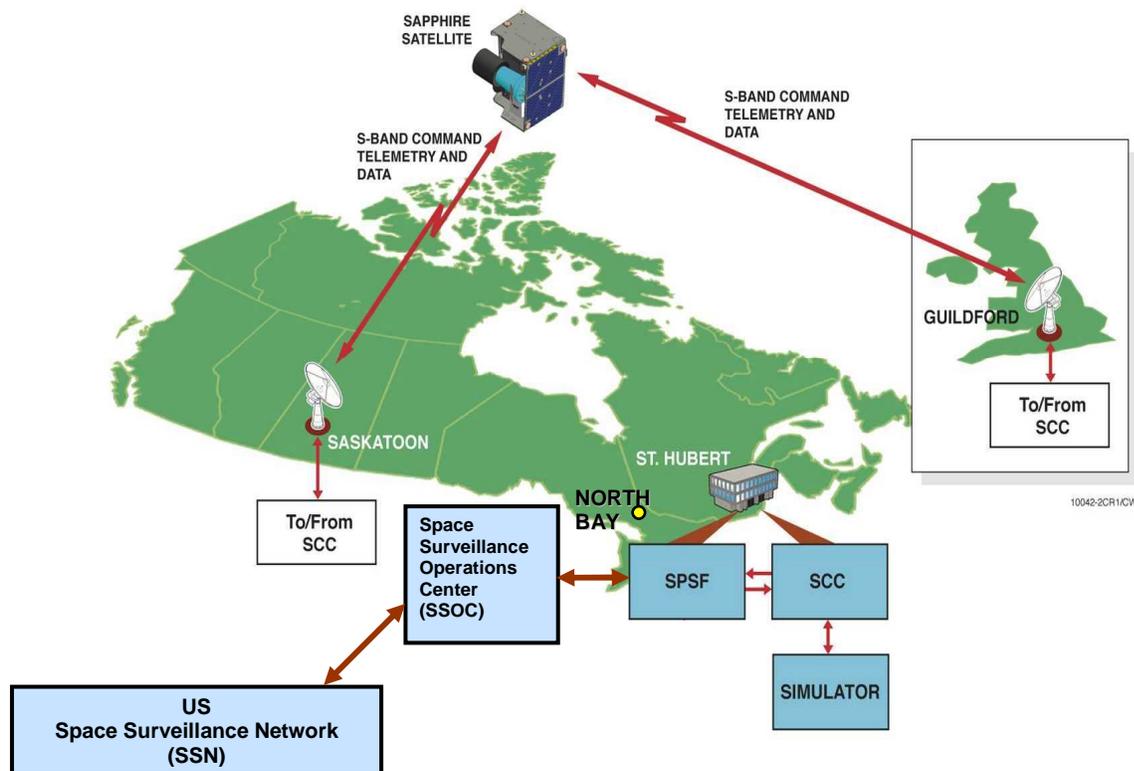


Fig. 2. Canadian Space Surveillance System (Image courtesy of MDA)

All of this will be contractor provided and operated. The link between the contractor operated Sapphire System and the US SSN will be the final, crucial part of the CSSS: the Sensor System Operations Centre (SSOC), which will be operated by Canadian Forces personnel and co-located at the Canadian Aerospace Defence Sector in North Bay, Ontario.

Sapphire System

The heart of the CSSS is the Sapphire System. This system is comprised of the Space Segment (the Sapphire Satellite) and the Ground Segment (the SPSF, SCC, a Simulator, and ground tracking stations).

As the key element of the CSSS, the Sapphire System will be able to provide continuous optical surveillance data with latency no longer than ten hours. Unconstrained by time of day limitations with respect to the “shooting period” that a ground-based optical sensor would have, the Sapphire system will be designed to provide data on a minimum of 360 tasked objects per twelve hour tasking period. The SSOC will coordinate taskings requested by the JSpOC in a cycle of tasking, scheduling, transmission (uplink), observation, data reception (downlink), and data processing [Fig. 3].

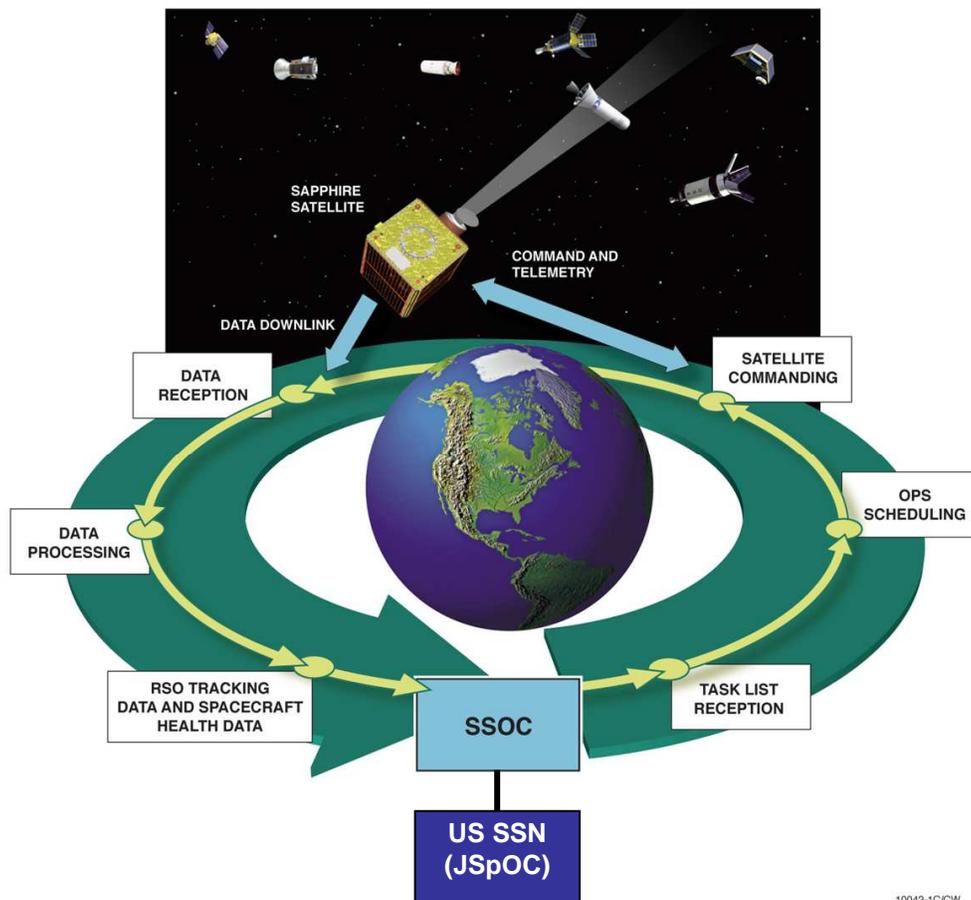


Fig. 3. Sapphire System (Image courtesy of MDA)

Sapphire Team

The primary Sapphire Team consists of experienced leaders in the Canadian Space Industry with a proven track record. The prime contractor is MacDonalD Dettwiler and Associates (MDA) of Richmond, British Columbia. MDA has sub-contracted the development of the payload to another experienced Canadian company: COM DEV of Cambridge, Ontario.

Other sub-contractors and their respective areas of development include:

- Surrey Space Technologies Limited (SSTL – Surrey, England) – Spacecraft Bus, SCC, and Simulator;
- Terma Aerospace (Denmark) – SPSF
- SSG Precision Optronics (Wilmington, MA, USA) – Optical Imaging System (OIS)
- Routes Astroengineering (Kanata, Ontario) – Payload Electronics

Sapphire Project Schedule

Significant milestones have been reached within the last twelve months. With the acquisition of Canadian Treasury Board approval for the project in July, 2007, and the subsequent signing of the primary contract with McDonald Dettwiler and Associates (MDA) in October, 2007, project momentum has been increasing. The project completed the Definition Phase and is now deep into the Implementation Phase. The project recently completed a successful Preliminary Design Review with MDA, allowing progress towards the final critical design details. The Critical Design Review will be held in the spring of 2009, after which assembly, integration, and testing of the Sapphire satellite will begin at the David Florida Laboratories in Ottawa, Ontario. Launch of the Sapphire satellite is scheduled to occur no later than July 2011. Based on the latest possible launch date, the CSSS is anticipated to achieve Full Operational Capability by the end of 2011.

Significant project milestones are outlined in [Fig. 4] and include:

- Implementation Phase: began July 2007;
- Prime Contract: signed October 2007;
- Preliminary Design Review (PDR): completed June 2008;
- Critical Design Review (CDR): March 2009;
- Launch: July 2011;
- Satellite Commissioning: Launch -> Launch + ~3 months;
- Initial Operational Capability (IOC): Launch + ~3 months; and
- Full Operational Capability (FOC): IOC + ~2 months.

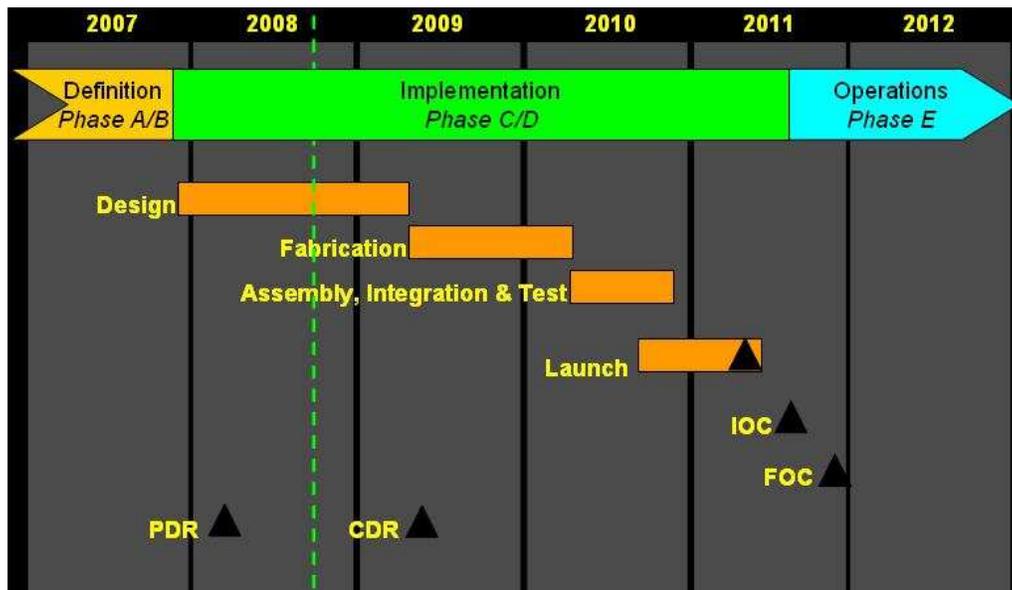


Fig. 4. Surveillance of Space Project Schedule

Sapphire Mission

The number of man-made objects in Earth orbit has been growing steadily over the last 50 years. These objects consist of active and inactive satellites, spent rocket bodies, and debris produced either during the launch and insertion phases of a satellite or during satellite breakups or collisions (either intentional or unintentional).

Significant in-orbit events, such as the intentional destruction of the Fengyun 1-C satellite by China in January 2007, have also contributed to large “spikes” in the number of catalogued objects being tracked by the SSN. This particular event has led to approximately 2600 objects being added to the SSN Satellite Catalogue; however, predictions from NASA’s Orbital Debris program suggest that the true number of debris pieces greater than 1 cm in size from this event may approach 150,000 pieces or more [2].

Sapphire’s mission will be to provide tracking data in the form of angles-only (right ascension and declination) observations on tasked objects. Due to constraints imposed by the optical sensor system, Sapphire will be limited to acquiring tracking data on objects ranging from 6000 km to 40000 km in altitude – a range essentially considered to be “deep space” with respect to the surveillance of man-made space objects.

Sapphire’s ability to conduct 24/7 tracking operations will prove to be an excellent niche sensor for tracking deep-space objects. The increase in coverage Sapphire will add to the SSN will ensure that deep space objects can be tracked during periods where ground-based optical sensors are not able to operate. This will be especially useful in maintaining tracking on maneuvering deep-space satellites (particularly high interest objects).

Sensor System Operations Centre (SSOC)

The CSSS requires 24/7 manning of the SSOC. The SSOC will consist of standard desktop computers and associated peripheral equipment. The SSOC will be the CF link between the contractor operated Sapphire system (satellite, ground stations, and control centre) and the JSpOC, where the Sapphire data will primarily be sent. The SSOC will be located within the Canadian NORAD Air Defence Sector operations room in North Bay, Ontario. The main mission of the SSOC will be to receive surveillance of space observation requests from the JSpOC in order to generate a task list for the Sapphire system. After observational tasks are complete, the SSOC receives data back from the Sapphire system and forwards it to the JSpOC to be integrated into the Space Surveillance Network’s space object catalog.

Sapphire Satellite

Sapphire [Fig. 5] will be a Canadian Forces space-based space surveillance sensor, forming one part of the Canadian Space Surveillance System. It will be a unique small satellite (approximately 150 kg) using a small Three Mirror Anastigmat (TMA) telescope similar in design to the Space Based Visible sensor on the US MSX satellite. The optical sensor will have a 1.4 deg field of view to observe man-made objects in deep space (6,000 – 40,000 km altitude). The satellite will be in a sun-synchronous, dawn-dusk orbit. In other words, the satellite will maintain a relatively constant aspect with respect to the sun, with its ground path on Earth always being close day/night terminator. The satellite’s telescope will point away from the sun so it can observe objects with an aspect that provides the maximum amount of reflected sunlight (best possible phase angle).

Optical Payload

The Sapphire Payload will maximize design heritage from the optical payload of the MSX’s SBV [3]. The optical imaging system of Sapphire will consist of a 15 cm telescope with an effective field of view of 1.4°. The required pointing accuracy of the OIS is required to be better than six arc seconds; however, the desired pointing accuracy is significantly better than this – on the order of two arc seconds. Allowing for inaccuracies in the predicted position

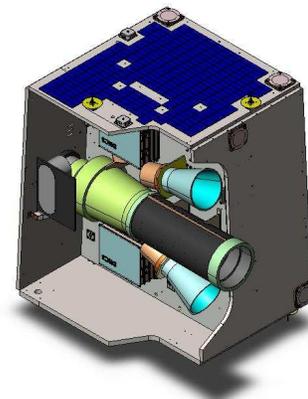


Fig. 5. Sapphire Satellite
(Image courtesy of MDA)

of the target object, system requirements were written to ensure the accommodation of predicted target position errors of up to 25 arc minutes. The imaging system will also include a baffle to minimize stray light and an aperture cover to protect the sensitive optics during transport and integration.

Tracking Methods

There are two different methods that may be used for tracking space objects. The method chosen will be determined by the automated Sapphire scheduler to provide the best results. The first tracking method is referred to as Sidereal Stare Mode (SSM), in which the sensor moves to compensate for the rotation of the Earth; thus, stars will appear as point sources and satellites will generally appear as streaks. SSM ensures satellites will appear as distinct streaks against a background of point-like stellar objects.

The second tracking method employed by Sapphire is referred to as Track Rate Mode (TRM), in which the sensor tracks the area in space where the object of interest is expected to be; thus, the stars will appear as streaks while the object of interest appears as a point source. For dim or flashing near-geosynchronous objects, TRM allows the object's irradiance to accumulate on the fewest pixels, thereby providing a higher signal-to-noise ratio and improving the probability of detection.

Orbit & Operational View

The ideal orbit for a space-based space surveillance sensor such as Sapphire is a sun-synchronous orbit at an altitude of approximately 750 km, and a Local Time of Ascending Node of 06:00.

Because the Sapphire sensor's position is fixed on the satellite (i.e. telescope pointing depends entirely on the spacecraft attitude), this orbit allows for relatively constant anti-sun viewing with minimal attitude changes [Fig. 6], and provides the greatest sun aspect angle to maximize the amount of reflected light from the satellite. Another important benefit of this orbit is the ability to keep one side of the satellite facing the sun to maximize power generation with minimal solar panels.

It is envisioned that the majority of Sapphire's viewing targets will be satellites in GEO. Therefore this orbit, combined with the use of Track Rate Mode will provide ideal conditions for imaging satellites as dim as visual magnitude 15.

Conclusion

The SofS project is on track to provide the Canadian Department of National Defence with a new capability to improve space situational awareness with its own surveillance of space system: the Canadian Space Surveillance System (CSSS). The SofS project is now in the detailed design phase and anticipates reaching full operational capability by the end of 2011. This capability will revive a key NORAD commitment almost 20 years after the decommissioning of Canada's last Baker Nunn space object identification camera, and the end of Canada's capability to perform space surveillance in 1992. This new space-based capability comes at a time when space assets have been becoming increasingly more critical to successful military operations. The ability to know what space objects are overhead, and when, can have an important impact on the outcome of vital missions.

References

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2. NASA, *Fengyun 1-C: One Year Later*, Orbital Debris Quarterly News, Vol. 12, 2008

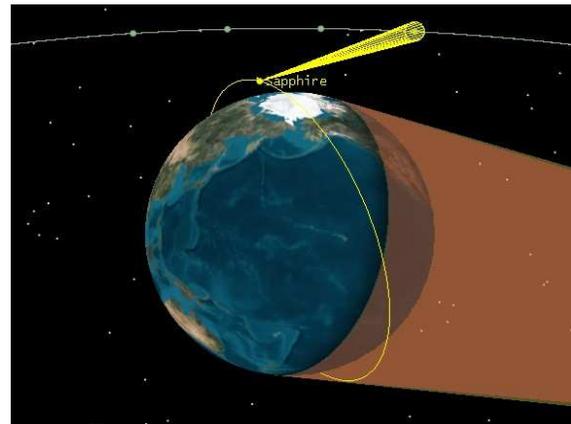


Fig. 6. Sapphire Orbit
(Image Courtesy of DRDC, Canada)

3. Harrison, D.C. and Chow, J.C., *The Space-Based Visible Sensor*, Johns Hopkins APL Technical Digest, Vol. 17, 1996.