Sapphire-like Payload for Space Situational Awareness

John Hackett,
Lisa Li
COM DEV Ltd., Cambridge, Ontario, Canada
(John.Hackett@comdev.ca)

ABSTRACT

The Sapphire satellite payload has been developed by COM DEV for a Surveillance of Space mission of the Canadian Department of National Defence, which is scheduled to be launched later in 2012. This paper presents a brief overview of the payload, along with the potential for using this optical instrument as a low cost, proven Space Situational Awareness hosted payload on geostationary satellites. The Sapphire payload orbits on a dedicated satellite and hence the payload was not required to actively point. The proposed hosted payload version of Sapphire would be enhanced by incorporating a two dimensional scan capability to increase the spatial coverage. Simulations of the hosted payload version of Sapphire performance are presented, including spatial coverage, approximate sensitivity and positional accuracy for detected resident space objects. The moderate size, power and cost of the Sapphire payload make it an excellent candidate for a hosted payload space situational awareness application.

1. INTRODUCTION

The Sapphire payload is described elsewhere [1] and was developed by COM DEV on a moderate budget for MDA Systems Ltd. and the Canadian Department of National Defence and is scheduled to fly in 2012. The Sapphire payload combines the SBV heritage [2] through the telescope design/contractor, with high quantum efficiency CCDs and advanced high reliability electronics.

The Sapphire mission [3] was developed by the Canadian Department of National Defence (DND) as part of its Surveillance of Space project. MDA Systems Ltd. was the mission prime contractor, and COM DEV was the payload prime contractor. Sapphire will provide timely, accurate tracking data on Earth-orbiting resident space objects (RSOs). During operation, the agile Sapphire spacecraft is commanded to the desired orientation, and then a series of images are acquired by the Sapphire payload which is fixed relative to the spacecraft body. The images are time tagged and telemetered to the ground. Sapphire incorporates an optional onboard image correction and compression capability to minimize downlink requirements.

2. SAPPHIRE PAYLOAD

The Sapphire payload is comprised of two physically separate units that are connected by a set of harnesses, as shown in Figure 1.

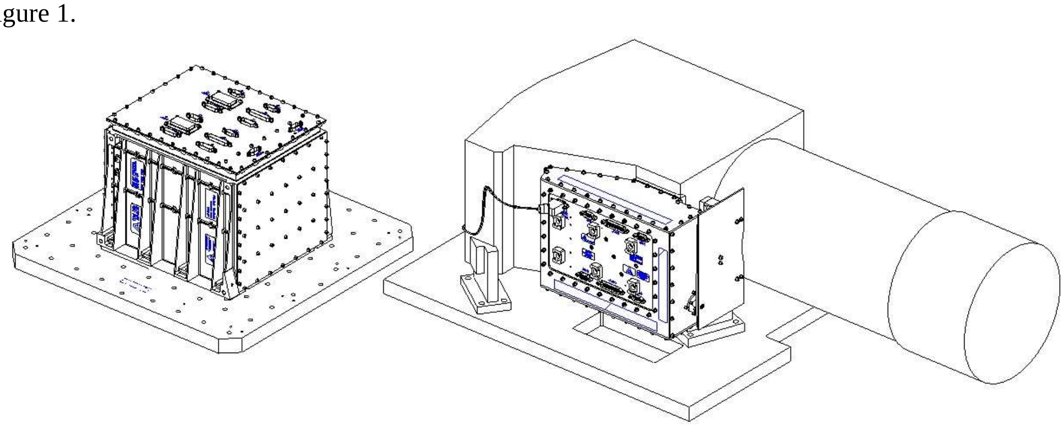

Figure 1: Sapphire Payload Comprised of Two Separate Units with Interconnecting Harnessing

To keep the electrical noise to acceptably low levels, it is necessary to include; a preamplifier in close proximity to the CCDs, and a radiative cooler to cool the CCDs.

Aside from the preamplifier, the remaining payload electronics are located remotely from the optics to minimize contamination risks and to ease the thermal design. The electronics assembly heat is conducted into the spacecraft through its mounting interface.

The payload electronics including the preamplifier and CCD are 100% redundant, and are configured as two electrically isolated systems and are normally used in cold redundant manner. It is possible to operate both the prime and redundant systems at once, and this could possibly be used to increase the spatial coverage of the system.

The optical design and construction methods are based on the SBV telescope. The telescope operates in the visible and near IR portion of the spectrum and uses an all reflective three mirror anastigmatic design to minimize aberrations across the spectrum and field of view. The telescope assembly is largely thermally isolated from the spacecraft, and its temperatures are controlled through radiation balance.

The Sapphire payload mass is 28.5 kg, and is comprised of 18.8 kg for the telescope, 8.1 kg for the electronics and 1.6 kg for the harnessing. The average power consumption is 14 W, with periodic increases to 20W to support internal modes of operation. The image output data rate from the payload is 10Mbps.

3. HOSTED PAYLOAD

With the recent launch of the CHIRP hosted payload on a commercial geostationary satellite, it is likely that other controlled cost hosted payload missions may be considered. The moderate size, power and cost of the Sapphire payload make it an excellent candidate for a hosted payload space situational awareness application. The significant optical performance and high reliability of the payload are suitable for RSO monitoring from either a low earth orbit (LEO) or geostationary orbit (GEO).

To increase coverage, a two axis gimbal mirror with baffle could be added to a Sapphire-like payload to enhance its performance as a hosted payload on a GEO or other platform. If emphasis is placed on covering the region near the GEO belt, the resulting scan angle requirements are approximately +/- 90 degrees and +/- 5 degrees for azimuth and elevation respectively. LEO hosted applications will require larger elevation ranges and will likely have more operational constraints to avoid stray light sources.

There are a number of such optical scanning mechanisms developed for space applications that can be considered. It is expected that a small development activity would be required to customize the mechanism for a specific hosted payload application.

4. COVERAGE FROM GEO

The coverage of the GEO-belt region has been modeled for a Sapphire-like payload hosted on a geostationary spacecraft. The modeling was performed using Satellite Tool Kit (STK) software v.9.2.3 from AGI. Animations of the coverage were created using scan patterns that are examples only, as each customer may have their own operational preferences. The scan patterns avoid looking towards the sun and avoid looking within a small angle of the Earth. For a single payload the coverage of the GEO belt is very good, however there are two small sectors that are not visible; on the opposite side of Earth and very nearby the host spacecraft. A summary of the scanned coverage is illustrated in Figure 2 for a single Sapphire-like hosted payload.

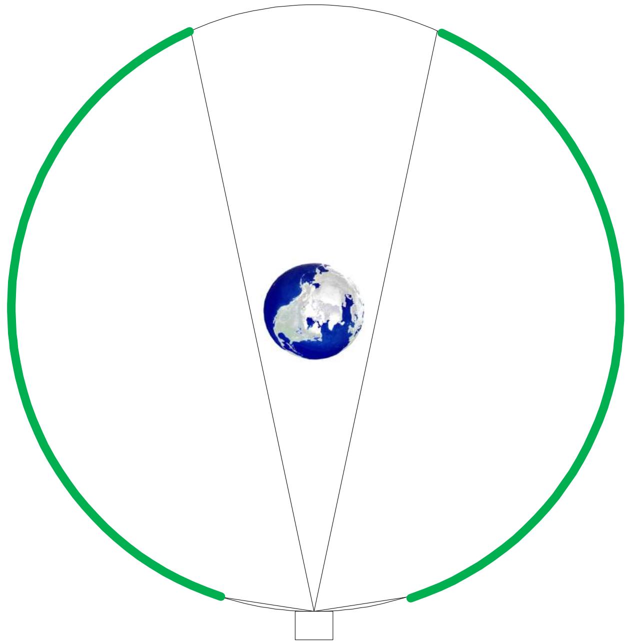

Figure 2: Coverage of GEO-belt Region for a Single Sapphire-like Hosted Payload

The addition of a second Sapphire-like hosted payload somewhere between 30 and 150 degrees away would yield 100% coverage of the GEO belt and provide faster average revisit times. Figure 3 shows a comparison of systems that contain a single hosted payload (left) and dual hosted payloads (right). The elevation (i.e. height of the GEO belt) coverage is shown in the figure as a single swath that would be stitched together with a series of smaller images.

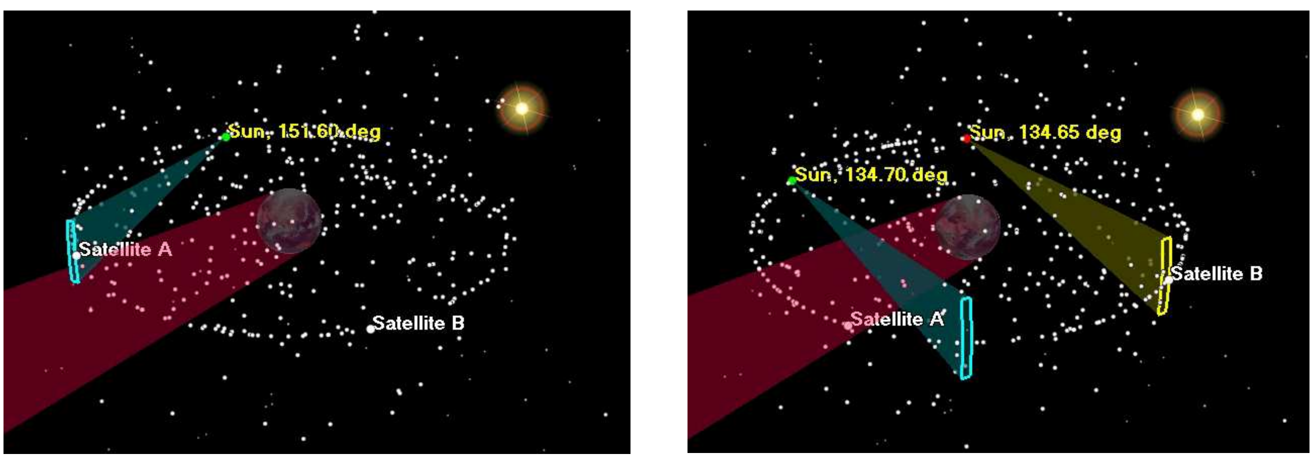

Figure 3: Comparison of Single and Dual Sapphire-like Hosted Payload Systems

Note that satellite B is not visible to the single hosted payload system at any time, since it is in geosynchronous orbit. A second hosted payload (red dot) is shown at approximately 40 degrees from the first hosted payload. With two Sapphire-like hosted payloads, 100% of the GEO-belt region can be covered. For a single hosted payload, about 80% of the GEO-belt region can be covered. The scan time depends on various parameter settings, but for a full raster pattern with long integration times it takes approximately 2 hours to cover the available portion of the GEO-belt (80%). For a system with two hosted payloads the time required to scan 100% of the GEO-belt region depends on their relative locations, but it could be accomplished within less than 2 hours.

5. PERFORMANCE

The two most important performance criteria are RSO sensitivity (or faint limit), and RSO positional error.

The sensitivity limit of the system can be calculated for a given signal to noise ratio requirement, which in itself must be carefully defined since the point source could be aligned to the CCD pixel grid in many ways. However the signal to noise ratio metric is really an intermediate requirement, and in fact the customer is likely more concerned about the positional accuracy achieved by centroiding a spot in the image from a point source.

Table 1 shows the approximate single pixel SNR, including the scan mirror effects, for 4 second and 10 second integration times for various faint magnitudes, assuming geostationary velocities. Table 1 also shows the sensitivity performance in terms of RMS positional error versus object brightness, which were obtained by performing a Monte Carlo style simulation of the centroiding process using standard centroid algorithms.

Table 1: Approximate SNR and RSO Positional Error versus RSO Brightness

	4 second integration		10 second integration	
RSO Brightness [AVM]	Centroid Error per Axis [pixels]	1 Pixel SNR	Centroid Error per Axis [pixels]	1 Pixel SNR
18	0.41	1.1	0.39	2.2
17	0.38	2.7	0.32	5
16	0.30	6.3	0.22	11.6
15	0.20	13.2	0.12	23.2
14	0.10	25.1	0.046	42.2
13	0.041	43.9	0.021	71.4
12	0.020	72.7	0.010	116.6
11	0.010	117.5	0.004	187.0
10	0.004	187.6	0.002	297.9

The Monte Carlo style simulations were run using the following methodology;

- A portion of the area detector (CCD in this case) was modeled using 0.1 CCD pixels as the element size, for example a 10 x 10 CCD pixel area was modeled with 100 x 100 elements.
- A Gaussian energy distribution spot model was used for this analysis, although actual test data has been used separately and shows reasonably good correlation with the Gaussian model.
- The location of the spot centre can be defined in units of 0.1 pixels relative to the pixel physical boundary, this allows pixel phasing effects to be modeled.
- The energy distribution is then “binned” into CCD pixels, and a standard signal and noise calculation is made per pixel.
- Then a sample image is generated on a CCD pixel basis using the pixel signal and pixel RMS noise as the mean and standard deviation for that statistical estimate of that pixel value, following a Normal noise distribution.
- Then the centroid of the spot for the sample image is calculated and stored.
- The steps in last two bullets are repeated many times, and the resulting centroid locations are analyzed to determine the average pixel position and the RMS variation of the centroid location in pixels.

The relationship between signal to noise ratio and the RMS centroiding error is well behaved, as shown in Figure 4.

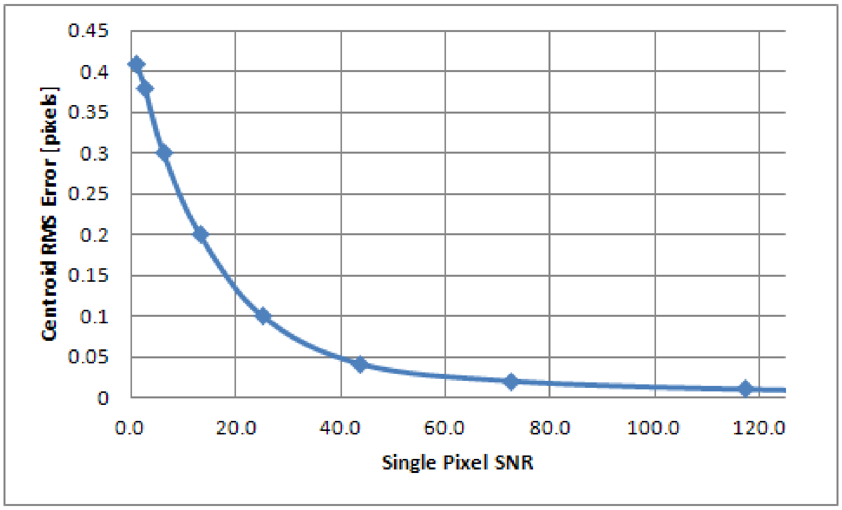

Figure 4: Centroiding Error versus Single Pixel SNR for 4 Second Integration Time

During operational planning the nominal scan rate can be slowed to allow for longer integration times to detect extremely faint objects. Since the objects of interest are likely to be moving at similar speeds to the host spacecraft, long integration times can be used without smearing the signal over many pixels.

The geocentric location error budget is derived for each mission but includes the angular uncertainty of the object in the image with respect to reference stars within the same image, the time uncertainty of the observation (and hence the host satellite spatial uncertainty due to time uncertainty), and the spatial uncertainty of the host satellite (assuming perfect time knowledge). The latter two elements are influenced by the details of the host spacecraft.

6. SUMMARY

The Sapphire payload can be readily modified to include a two-axis scan function, and is then very well suited for a variety of hosted payload space situational awareness missions. Approximate coverage and performance estimates for a GEO based hosted payload are presented to allow potential users to assess the suitability of this payload for their applications. The moderate size, power and cost of the Sapphire payload make it an excellent candidate for a hosted payload space situational awareness application.

7. ACKNOWLEDGEMENTS

The authors wish to thank and acknowledge; the Department of National Defence (DND) and MDA Systems Ltd for selecting COM DEV to provide the Sapphire payload, and L-3 Communications Integrated Optical Systems – SSG and e2v technologies for their contributions to the Sapphire payload. The authors are grateful to AGI for its assistance in modeling the Sapphire payload in a geostationary orbit.

8. REFERENCES

[1] Hackett, J., Brisby, R., Smith, K., "Overview of the Sapphire payload for space surveillance", SPIE Vol. 8385 Surveillance Technologies (2012).

[2] Wang, D., Gardiner, L., Wong, W., Hadfield, P., "Space based visible all reflective straylight telescope", SPIE Vol. 1479 Surveillance Technologies (1991), pp. 57-70.

[3] Maskell, P. and Oram, L., "Sapphire: Canada's Answer to Space-Based Surveillance of Orbital Objects", Advanced Maui Optical and Space Surveillance Technologies Conference, September 2008, SSA & SSA Architecture.