Combined Space-Based Observations of Geostationary Satellites

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Abstract

One of the Space Situational Awareness (SSA) science experiments of the NEOSSat mission is to learn the practicalities of combining space-based metric observations with the Sapphire system. To answer this question, an experiment was performed observing clustered Canadian geostationary satellites using both Sapphire and NEOSSat in early 2016. Space-based tracking data was collected during tracking intervals where both NEOSSat and Sapphire had visibility on the geostationary objects enabling astrometric (orbit determination) and photometric (object characterization) observations to be performed. We describe the orbit determination accuracies using live data collected from orbit for different collection cases; a) NEOSSat alone, b) Sapphire alone, and c) Combined observations from both platforms. We then discuss the practicalities of using space-based sensors to reduce risk of orbital collisions of Canadian geostationary satellites by proactively tasking space based sensors in response to conjunction data warnings in GEO.

1. Introduction

Space-based space surveillance sensors have shown significant utility in the tracking the geosynchronous space objects [1], and have found a key role in the sustainment of the deep-space space surveillance catalog [2]. These systems often employ small aperture, visible-band space telescopes designed to acquire precision angles-only astrometric (positional) measurements of Resident Space Objects (RSOs). Space-based space surveillance sensors have particular advantages in that they are not interrupted by the day/night cycle, are unaffected by clouds and other weather and that they can track geosynchronous objects at any longitude.

Canada has fielded space-based space surveillance capabilities by launching the Canadian Armed Forces' Sapphire satellite (see Figure 1 left) and the research microsatellite NEOSSat (see Figure 1 right). Sapphire is an operational space surveillance capability which is now a contributing sensor to the US Space Surveillance Network transmitting more than 3000 observations/day to the Joint Space Operations Centre. NEOSSat, with its dual mission of asteroid astronomy and Space Situational Awareness (SSA) experimentation, has produced space surveillance imagery suitable for its experimental mission despite a prolonged commissioning and on-orbit calibration period after its launch. The SSA mission of NEOSSat, known as the High Earth Orbit Space Surveillance (HEOSS) mission, initiated its experimental activities in late 2015.

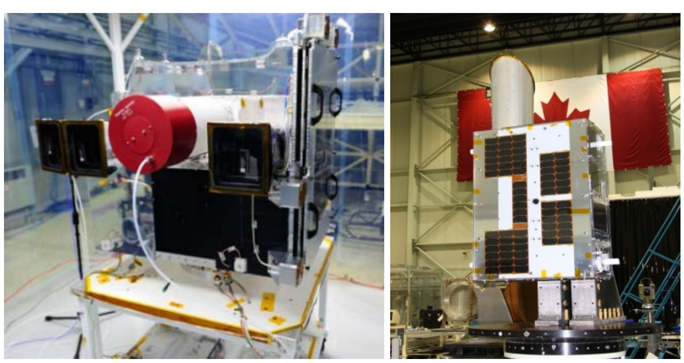

Fig.1. Left: Canadian Armed Forces' Sapphire space surveillance satellite. Right: NEOSSat microsatellite undergoing mass properties testing at the David Florida Laboratory in Ottawa, Ontario (Image credit: Canadian Department of National Defence.

One of the HEOSS experiment objectives is to perform combined space surveillance observations with Sapphire to examine the practicalities of performing such observations. Sapphire and NEOSSat were not designed to be inherently interoperable with one another; however, using Canadian Armed Forces Sapphire operator know-how, and the research flexibility of the NEOSSat microsatellite, the sensors can be used to approximate combined observation operations. In this paper we show how both NEOSSat and Sapphire were used to track geosynchronous space objects with a view toward performing coordinated orbital tracking and reducing risk of conjunctions of geosynchronous satellites. We discuss the sensors, observing geometry, and tracking data collected by both NEOSSat and Sapphire during a two-day tracking campaign in early 2016. We then examine the characteristics of each sensor's capability to perform precision orbit estimation either independently, or in a combined manner. Finally, we show how these sensors could be employed in a conjunction derisk scenario and identify the requirements and limitations for such a spaceflight-safety scenario.

2. Sensor Descriptions

NEOSSat is a microsatellite designed to perform SSA experimentation and asteroid astronomy [3]. NEOSSat is a joint project between Defence R&D Canada and the Canadian Space Agency (CSA) where the CSA performs satellite operations and DRDC performs mission scientific planning and tasking. NEOSSat's weighs 72 kg with overall dimensions of 1.4 x 0.8 x 0.4 m. The microsatellite is equipped with an attitude control system optimized for asteroid astronomy and space surveillance. NEOSSat carries a 15 cm visible-band Maksutov telescope with a beveled baffle designed to enable tracking of objects within 45 degrees of the Sun. NEOSSat is in a 785 km-altitude dawn-dusk, sun-synchronous orbit and was launched 25 February 2013.

Sapphire is the operational space surveillance capability of the Canadian Armed Forces and is a contributing sensor to the US Space Surveillance Network [4]. Sapphire is based on a Surrey SSTL-150 satellite bus with overall mass of 148 kg and is ~1 m^3 in size. The payload is a 13 cm, three-mirror, visible-band anistigmat telescope designed to track deep space objects in GEO and Highly Elliptical Orbit (HEO). Sapphire performs catalogue maintenance by responding to sensor tasking issued by the Joint Space Operations Center (JSpOC) via the Canadian Armed Forces Sensor System Operations Centre (SSOC) located at Royal Canadian Air Force Base 22-Wing North Bay, Ontario. Sapphire is owned by the Canadian Armed Forces and is operated under contract by MacDonald Detwiller and Associates (MDA) who performs scheduling, data reduction and system maintenance of Sapphire's ground and space segment.

Both Sapphire and NEOSSat track deep-space RSOs by slewing along the direction of relative motion of the targeted RSO and exposing their CCD detectors. Sapphire and NEOSSat are sensitive to objects to magnitude 16 at geosynchronous ranges. Both systems transmit observations to their respective ground segments using S-band radio communication links where astrometric processing is performed and observations are formed.

Both NEOSSat and Sapphire follow nearly identical orbital trajectories. During the interval of 3-4 February 2016 when both sensors were performing this experiment, Sapphire was leading NEOSSat in orbit by approximately 4700 km (see Figure 2). Both NEOSSat and Sapphire generally track objects in the antisolar direction to a) benefit from favorable illumination phase angles, and b) reduce the slewing demand such that the satellites work productively on orbit which reduces the slewing intervals for the satellites. Both NEOSSat and Sapphire generally track geostationary satellites in the anti-solar direction. For the tracks acquired on the Anik F2 cluster both space-based sensors detected the target RSOs simultaneously within the field of view of their instruments (See Figure 3). This tracking approach reduces the amount of "step and stare" motions that the spacecraft need to perform to track the objects.

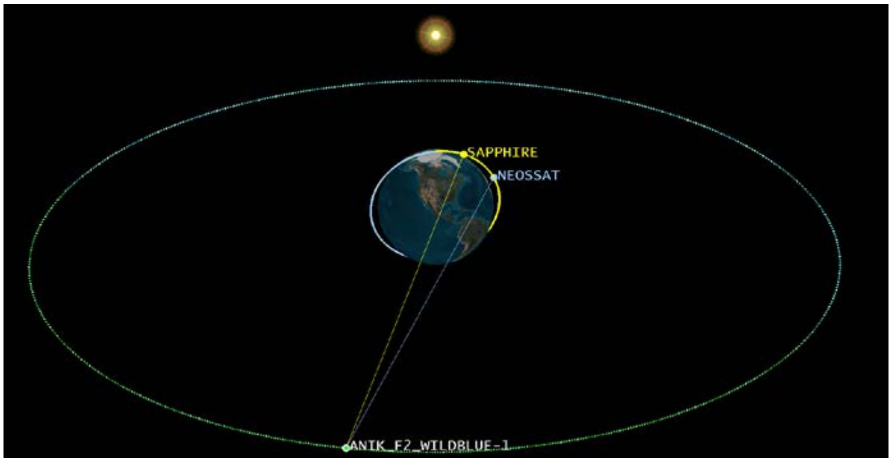

Fig.2. Observing geometry of NEOSSat and Sapphire on the Anik F2 cluster. Sapphire and NEOSSat's orbital motion is counterclockwise in this view. The angle between Sapphire, the Anik F2 cluster and NEOSSat is ~6°.

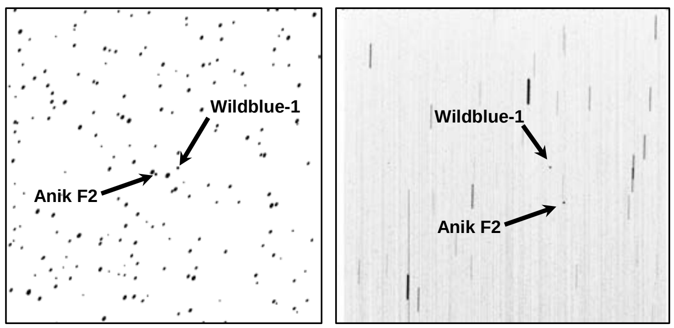

Fig.3. (*Left*): Sapphire image of the Anik F2 and Wildblue-1 geosynchronous satellites. (*Right*): NEOSSat image of the same cluster approximately 5 minutes later (From [5]).

3. SSA Data Processing

Images collected by the space-based sensors are formed by exposing their frame-transfer CCDs for approximately 4 seconds or more. This enables RSO signal to be integrated on a small patch of CCD pixels while simultaneously streaking background stars. Both point-source RSOs and streaked stars are centroided to measure observer-based J2000 right ascension and declination measurements required for astrometric tracking of the objects' orbital motion. These observations are location-stamped with the precision position of the observing platform derived from Sapphire's and NEOSSat's onboard GPS receivers. The observations are corrected for annual and orbital aberration prior to transmission to the space surveillance Network. Sapphire and NEOSSat use pixel clustering techniques to centroid both RSOs and star-streaks to form observations. Open filter photometric (magnitude) information is simultaneously formed after image processing in each respective ground system.

For this experiment, space-based observations of the Anik F2 / Wildblue-1 cluster which resides at 111.1° west longitude were collected. NEOSSat and Sapphire were configured to acquire metric observations on the cluster during the time period of 3-4 February 2016. In order to increase the imaging cadence on the NEOSSat instrument, NEOSSat collected 2x2 binned CCD imagery to increase the rate of image acquisition. This has the effect of lowering the metric accuracy of the instrument but increases the imaging cadence in an attempt to match Sapphire's imaging rate of one observation every four seconds.

Each space based sensors' orbit determination capabilities are now individually examined to learn their capabilities. Angles-only orbit data was processed using Orbit Determination Tool Kit v6.3 using an initial state formed from Anik F2's two line orbital elements obtained from ref [6].

4. Test Case A: NEOSSat measurements alone

In this case, NEOSSat angles-only measurements were used for orbit estimation. Figure 4 shows the residual ratios[1] plot of the measurements on Anik F2 after orbit estimation. The measurement uncertainty of NEOSSat is approximately 4 arcseconds which is rather coarse for deep space orbit custody. Figure 4 shows that tracks collected on Anik F2, while it was on Earth's night side, show good adherence to one another.

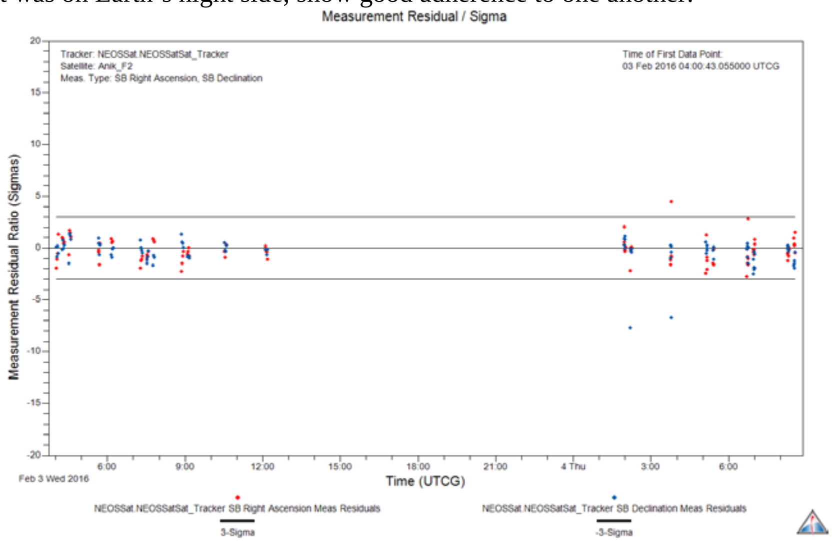

Fig.4. Test Case A NEOSSat residual ratios plot showing track of Anik F2

Figure 5 shows the 3-sigma position uncertainty of the estimated Anik F2 orbit using NEOSSat measurements only. The large upswing in the in-track position uncertainty is due to the propagation of the orbit uncertainty when no observations are available and the dip in the in-track uncertainty at 4 Feb 02:00 is due to new NEOSSat tracking data added to the filter. During intervals where observations are available, the best in-track position uncertainty tends to achieve ~5 km accuracy. In-track error growth continues as the covariance is propagated forward after 4 Feb 09:00.

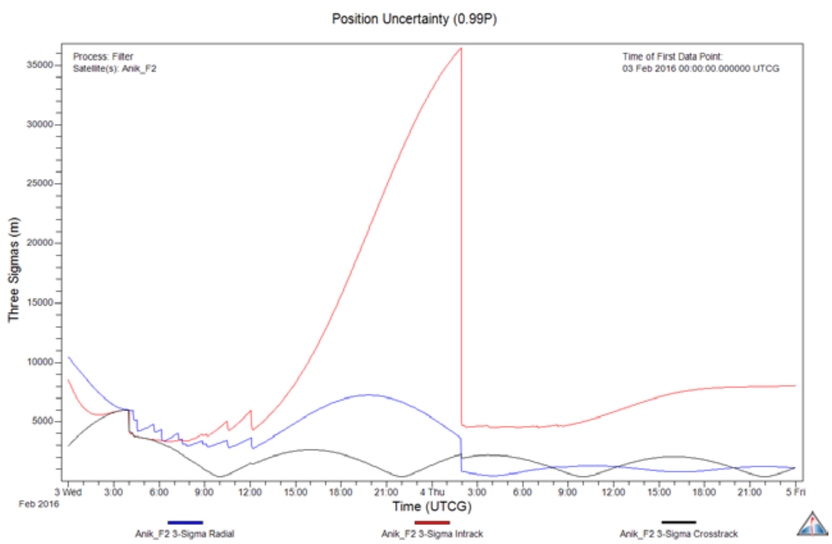

Fig.5. Test Case A: Anik F2 3-sigma position uncertainty using NEOSSat measurements

[1] Raw measurements differenced from predicted (propagated) measurements. These differences are normalized by the sensor measurement noise)

5. Test Case B: Sapphire measurements alone

In this test case Sapphire measurements were used for orbit estimation on Anik F2. Sapphire's measurement accuracy is ~4 times more precise than NEOSSat's and the relative improvement in orbit determination quality are examined in this test case. Figure 6 shows the residual ratios plot using Sapphire observations applied in the same manner as used in test case A. While the first track on 3 Feb 2016 appears to be nominally updating the filter the second track shows noticeable right ascension and declination residuals "walking-out" from the orbit during the second track. It is suspected that a maneuver has occurred during the daytime interval and was not detected using NEOSSat measurements due to NEOSSat's higher sensor measurement noise.

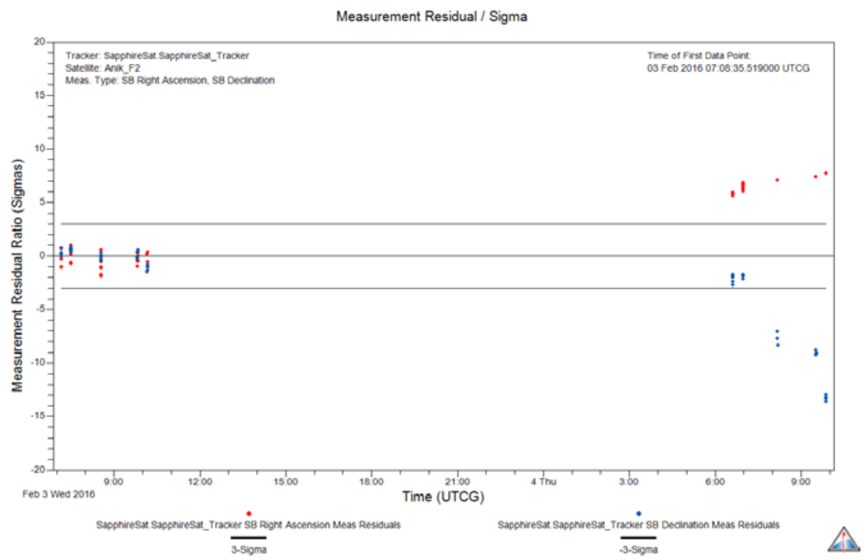

Fig.6. Test Case B: Residual ratios plot of the Sapphire measurements collected on Anik F2

Figure 7 shows the corresponding position uncertainty of Anik F2. During intervals where Sapphire measurements are available, the resulting position covariance is markedly better than test case A. The covariance however does not benefit from the additional observations during the second track on 4 Feb due to the majority of the observations being rejected by the filter. This results in the large in-track growth in figure 7.

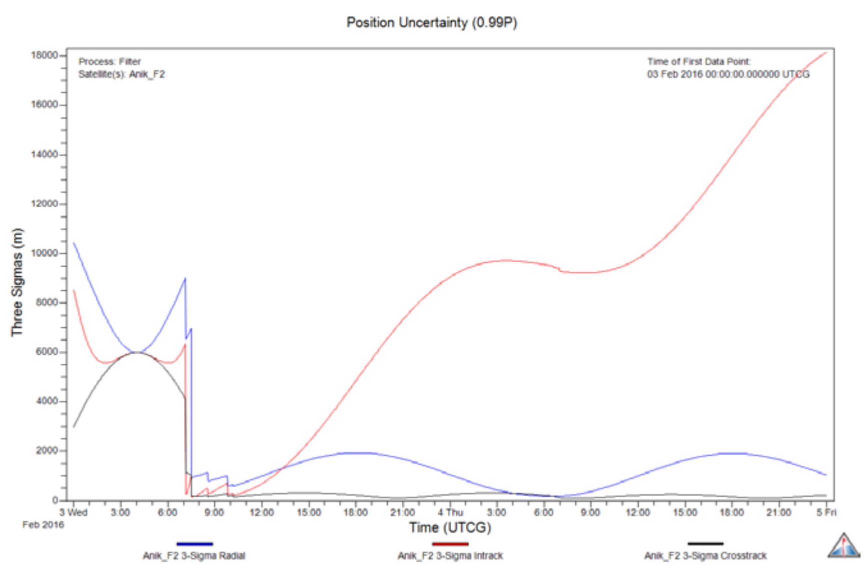

Fig.7. Test Case B: Anik F2 3-sigma Position uncertainty using Sapphire measurements

6. Test Case C: Combined measurements performance

Both Sapphire and NEOSSat observers are combined in this test case. Figure 8 shows the resulting residual ratios plot using both observers. While the first track on 3 Feb shows good agreement with one another, the second track on 4 February shows both NEOSSat and Sapphire right ascension observations rejected. This is due to the improved orbit estimate (Figure 7) where higher precision Sapphire observations shrinks the covariance causing both NEOSSat and Sapphire measurements to be rejected on the second track due to the suspected maneuver occurring during Anik F2's dayside pass. Both NEOSSat and Sapphire right ascension residuals show a positive (eastward) deviation on the second track.

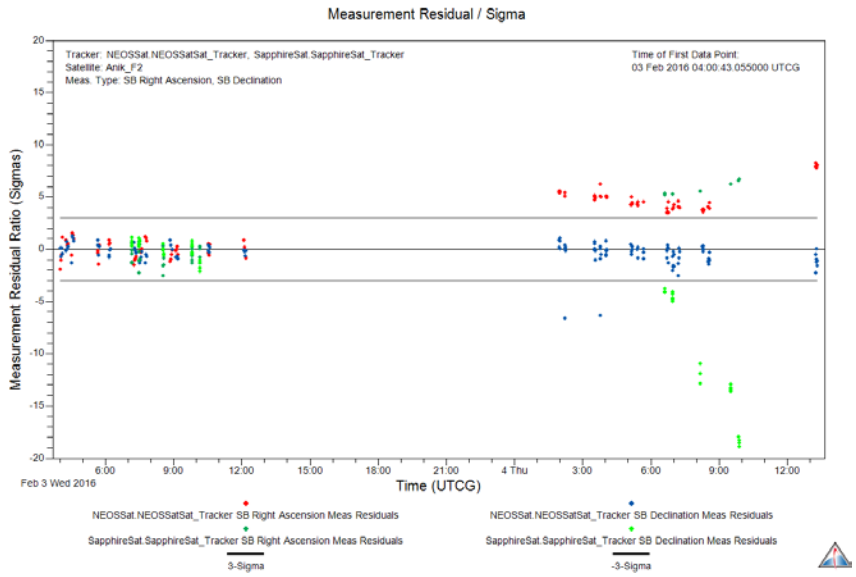

Fig 8. Test Case C, combined Sapphire and NEOSSat metric measurements

The position uncertainty shown in Figure 9 largely mimics the results of Figure 7, with exception of the NEOSSat observations updating the filter earlier in the track at 3 February 03:00.

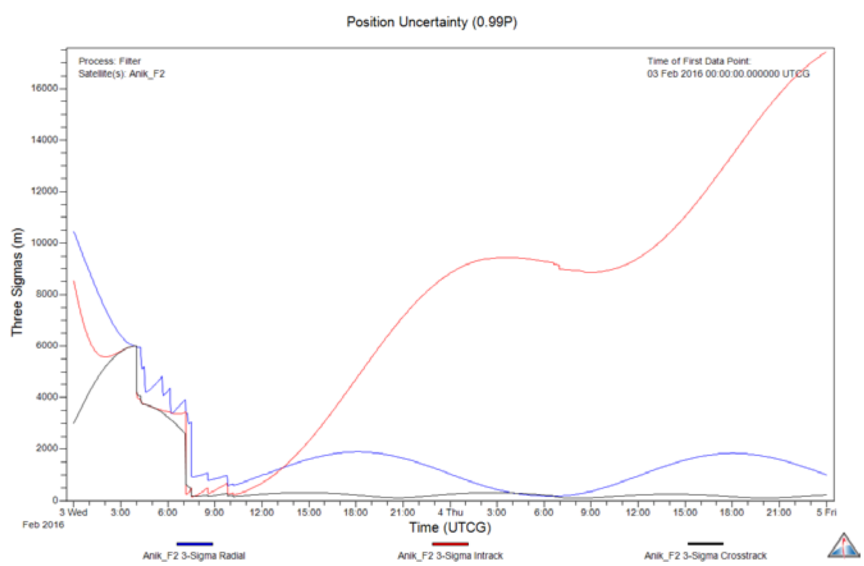

Fig.9. Test Case C: Anik F2 3-sigma Position uncertainty of Anik F2 using combined Sapphire and NEOSSat measurements

7. Post-Maneuver Orbit Recovery

To maintain orbit custody on Anik F2 despite the maneuver, a coarse recovery approach is to fill the dayside interval with process noise to artificially inflate the maneuvering object's covariance [7]. This permits new observations to be accepted by the filter. Figure 10 shows the dayside interval with a finite duration maneuver of $\Delta\vec{v} = 0$ but process noise uncertainty of 10 mN applied. This acceleration increases the Sapphire-refined covariance to a large enough level to accept the post-maneuver right ascension residuals during the second track.

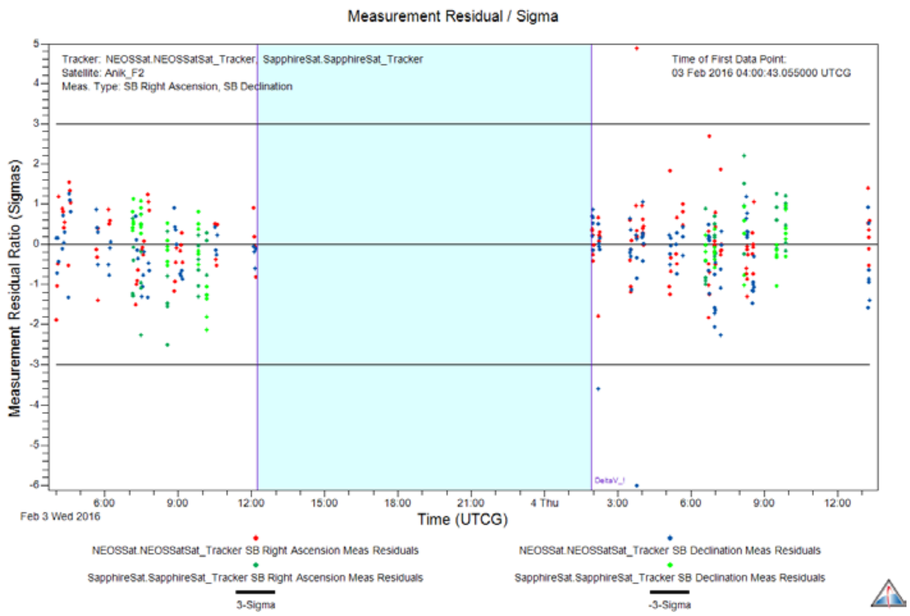

Fig.10. Residual ratios plot from combined NEOSSat and Sapphire Measurements. The blue span indicates a finite maneuver of $\Delta\vec{v} = 0$ and process noise of 10 mN. Observations are then accepted by the filter during the subsequent track.

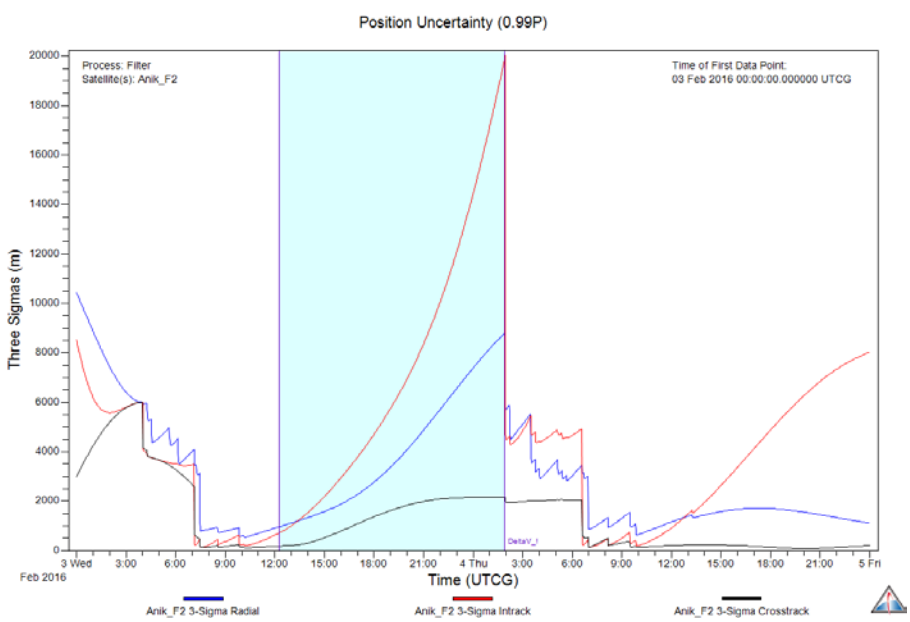

Fig.11. Maneuver orbit recovery: Anik F2 3-sigma position uncertainty using Sapphire and NEOSSat measurements

Figure 12 shows the radial, in-track and cross-track position differences between the Anik F2 operator reference ephemeris and the estimated orbit of Anik F2. It can be seen that the space-based measurements and Sapphire's measurements adhere to within 2 km during intervals where tracking data is available. The upswing in in-track position error is due to the process noise interval.

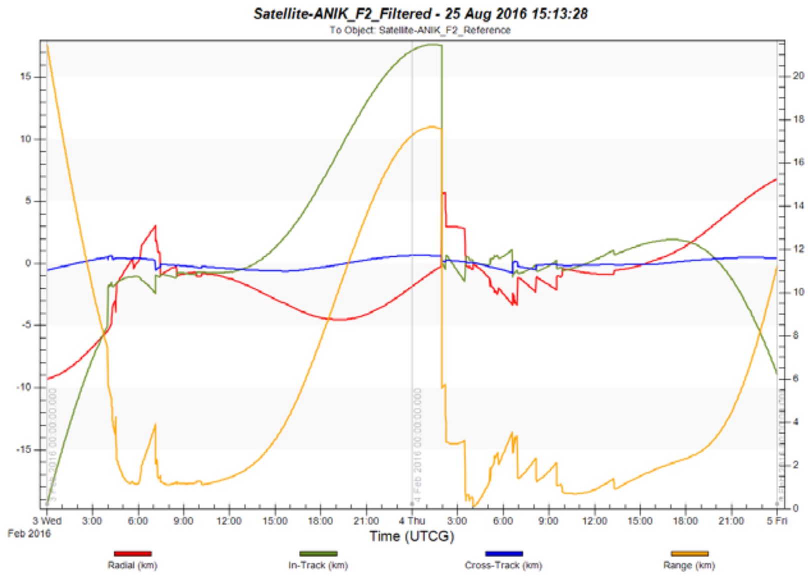

Fig.12. Radial, in-track and cross-track position differences from the combined orbit estimate from both Sapphire and NEOSSat compared to operator ephemeris.

Measurements collected on the colocated peer satellite Wildblue-1 did not exhibit residual walk-outs between tracks indicating that a maneuver did not occur during the two day tracking interval. Wildblue-1's residual ratios plot and position uncertainty are shown in Figures 13 and 14. No reference ephemeris for Wildblue-1 is available so comparison with operator-derived orbital data is not possible. As no maneuver has occurred during the two day track, the position covariance is much improved compared to the Anik F2 uncertainty shown in Figure 11 with intrack error of approximately ~1 km after several days of propagation. This indicates that the dual space based observations have done a good job estimating the radial position error of Wildblue-1.

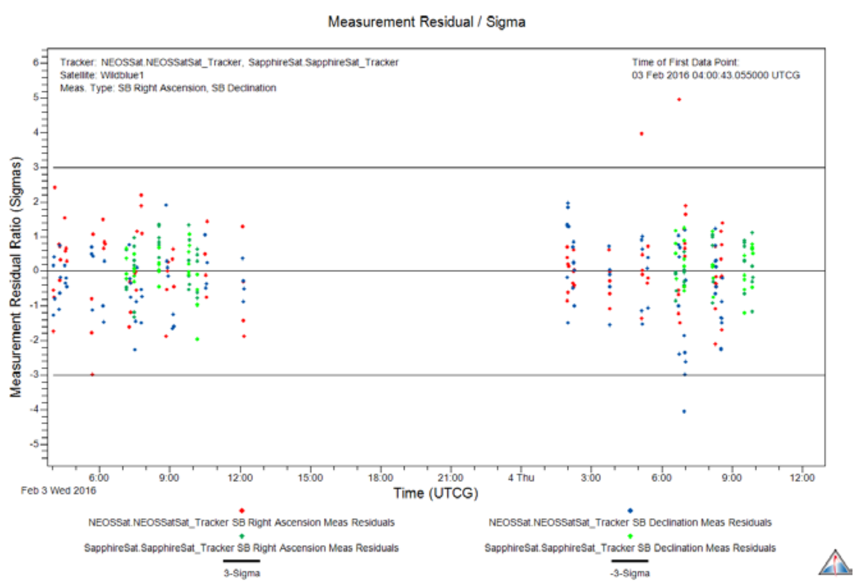

Fig.13. Wildblue-1 residual ratios plot using both Sapphire and NEOSSat measurements

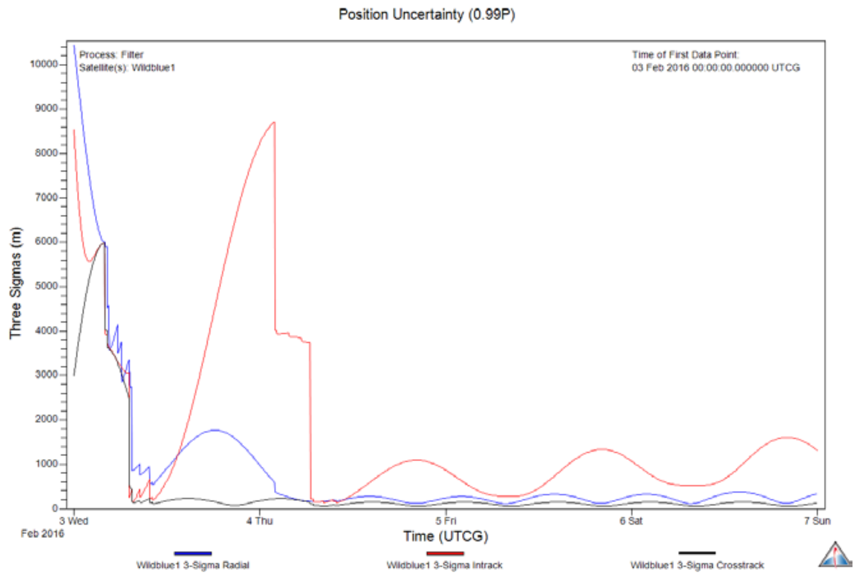

Fig.11. Wildblue-1 3-sigma position uncertainty using Sapphire and NEOSSat measurements

8. Issues for space based sensors perform Conjunction derisk observations for GEO satellites

Canada is the attributed "owner" nation of 14 active satellites in geosynchronous orbit in the space surveillance catalog. Another 9 satellites are "owned" by other nations, but flight control is performed by Canadian operators [8]. The majority of these geostationary satellites serve North American longitudes where ground based space surveillance sensors have good coverage of these satellites. The others are not visible from North America making alternative ground-based sensors, or space-based space surveillance sensors, necessary to perform orbital updates. Canada's needs for space surveillance is not limited to North American longitudes (see Figure 12).

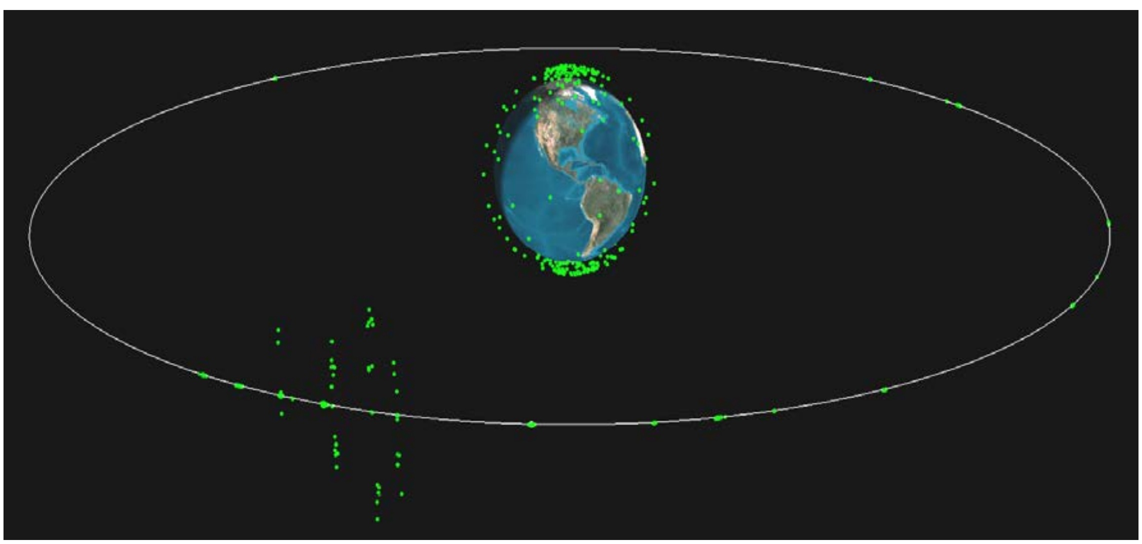

Fig.12. Close approach locations of all Canadian conjunction warnings at TCA between 2010-2013 for Low Earth Orbit (LEO) and Geosynchronous (GEO) satellites. Canadian LEO conjunctions tend to cluster around Earth's poles where sun-synchronous orbits' great circles intersect. Geostationary satellite conjunctions tend to occur in Earth-fixed locations on the equator. Inclined Canadian GEO satellite create vertical structures. Some Canadian controlled satellites, such as APSTAR-5 (top left of Figure 12 in GEO orbit) are not visible to space surveillance sensors in North America (from [8]) however space surveillance coverage is required.

Canada regularly receives Conjunction Data Messages (CDMs) [9] for active geostationary satellites (the primary satellite in the CDM message) warning of close approaches of secondary objects at a rate of approximately ~1 warning per day. The warning times between date of CDM generation and Time of Closest Approach between the objects (TCA) is approximately 5 days [8]. With warning times of this timescale, avoidance manuevers can be planned to coincide with station keeping operations to reduce excess propellant consumption.

Telesat Canada classifies close approaches on their geostationary satellite fleet into four main types [10] (see Table 1). The majority of geostationary satellite conjunction warnings issued to Canada tend to be warnings for 1) co-located Canadian geostationary satellites and 2) drifting objects performing simple/slow flybys [8]. Co-located satellite conjunction warnings tend to be regarded as lower priority as the spacecraft operator often performs eccentricity and inclination control on both primary and secondary satellites in the co-located pair to ensure passive safety in their relative orbits. Drifting objects (Slow flyby) tend to be recurring events as several Canadian geostationary satellites operate near the geostationary potential well at 105° West. Satellite operators effectively colocate with the secondary object in order to reduce collision risk between the objects [10] until the object drifts out of the station keeping box.

Table 1: Characteristic Geostationary Flyby Types

Flyby Type	Description	Secondary Object Examples
Simple Flyby	Secondary drifts through box at high relative velocity	Telstar 401 / SL-12
Slow Flyby	Secondary takes several days to traverse a geostationary station keeping box	Solidaridad 12
Elliptical Orbit Objects	Geosynchronous transfer orbit Secondary (flybys with high relative velocities	Geosynchronous Transfer Orbit rocket bodies
Highly Inclined	GEO secondary objects with high inclinations >> 1 deg which cross several station keeping boxes	Solar Dynamics Observatory

For a space-based sensor to perform conjunction derisk observations[2], the sensor operators need to consider the following timeline complications for responsiveness from the space-based sensor:

- Tasking a space-based sensor generally requires a minimum of ~24 hours due to limited pass opportunities from the Sapphire / NEOSSat ground segments. Return observations are generally guaranteed within the subsequent 24 hours after acquisition.
- The primary and secondary geostationary objects may not have favorable phase angle geometry for up to 20 hours. Space-based sensors tend to view within the anti-solar direction with a field of regard of ~60° angular diameter. This limits the fraction of the geosynchronous belt available for viewing.
- An active Canadian primary satellite is likely to perform continuous thrusting to maintain station-keeping. As shown in the previous sections, post-maneuver estimation using space-based sensors can require up to 2 post-maneuver tracks (nominally acquired over 2 days) to estimate the new post-maneuver orbit.

Figure 13 shows the approximate timeline of conjunction derisk observations overlaid with sensor tasking acquisition and download times for a space-based sensor.

[2] Conjunction derisk is the active tracking of both the primary and secondary objects in a Conjunction Data Message prior to TCA. The intent is to increase the information of their orbits to learn if the risk of collision merits a collision avoidance maneuver.

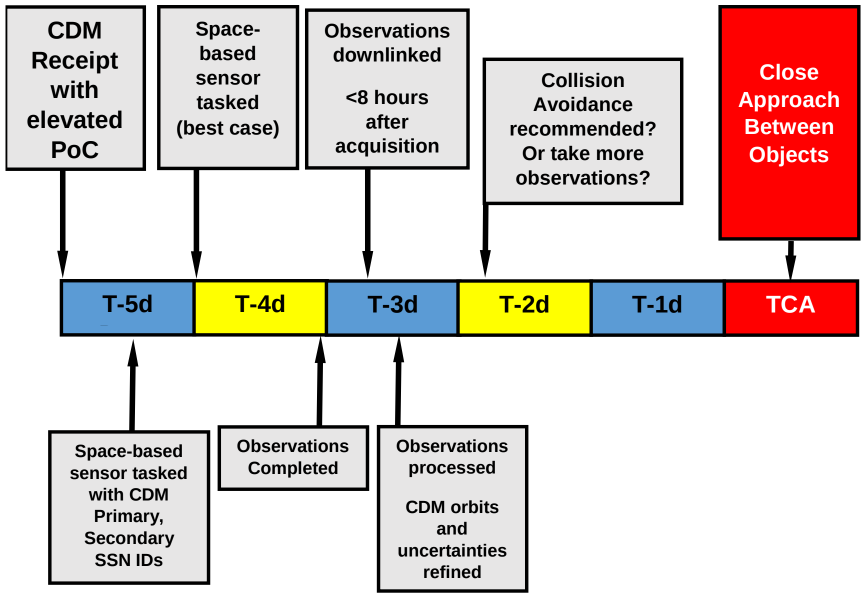

Fig.13. Timeline for conjunction derisk observations using space-based sensors

Figure 13 shows that the sensor tasking cycle, availability of ground-station passes, and the possibility that the primary and secondary GEO objects may not have favorable anti-solar viewing geometry for up to ~20 hours after tasking, limits responsiveness for space-based space surveillance sensors to perform conjunction derisk observations. By the time that the orbiting space surveillance sensor has downlinked its observations the primary could have performed another station keeping maneuver corrupting the measurement truth. In NEOSSat's case, tasking requires 2 days lead time and a subsequent day to downlink imagery due to fewer ground station accesses available to this space segment. If NEOSSat alone were updating the orbit track, it could leave only one day to perform collision maneuver assessment prior to TCA leaving little margin for analysis and assessment.

It is recommended to engage the GEO satellite operator such that their ephemerides are used to predictively mitigate the effect of planned maneuvers on the collision assessment and focus the space-based sensors on tracking the secondary (inactive) object. The inactive object is likely to only be influenced by natural orbital perturbations making the space-based observations more applicable for its orbit estimate for longer periods of time. Operator ephemerides, coupled with updated trajectories on the secondary object, will help refine the orbital estimate prior to TCA. Future upgrade possibilities could include the use of Northern Canadian ground stations to achieve regular (<1.7 hour) accesses to Sapphire or NEOSSat reducing the time to task and downlink imagery from the space segments.

The NEOSSat satellite collected observations using a binned mode of operation of its CCD in the dual tracking experiment. This was performed to increase the rate of observation acquisition on Anik F2 but resulted lower astrometric accuracy (~4 arcseconds) causing lower accuracy position uncertainties seen in Figure 5 (~5 km in-track error). Higher precision is available from the sensor and observations with accuracies of ~1 arcsecond would improve coordinated observations between Sapphire and NEOSSat. As it currently stands, the higher measurement noise of NEOSSat could not detect small maneuvers performed by Anik F2 whereas Sapphire did sense its in-track displacement making their coordinated operations awkward in the face of maneuvers.

One of NEOSSat's system benefits is that it can track areas of the sky that Sapphire tends to not normally track within. Sapphire primarily tracks in the anti-solar direction to the high tasking load that it services on a given day, NEOSSat could track a broader region of the sky with phase angles up to 140 degrees. This can extend tracking to the dayside regions to further increase orbit custody on larger, brighter, geosynchronous space objects.

9. Conclusions

Dual observers performing space surveillance measurements on geosynchronous objects can maintain orbit custody on geosynchronous space objects. The availability of the sensors, which is unaffected by weather, permits routine daily tracking of space objects enabling regular orbit updates. Space-based space surveillance instruments are usually tasked to track objects on Earth's night side where phase angle geometry brightens the targeted space objects and lowers the slew demands on space surveillance sensors. After two tracks, in-track orbit uncertainties can be as low as 0.5 km for Sapphire and 5 km for NEOSSat. The anti-solar viewing geometry tends to reduce space-based space surveillance sensors' ability to detect maneuvers as orbit recovery can take up to two days.

While combining NEOSSat and Sapphire data in a fused scenario offered lessons in sensor coordination, the larger sensor noise of NEOSSat was less effective at estimating orbital tracks of Anik F2. One advantage of the NEOSSat sensor is its ability to track in regions of space that are not limited to the anti-solar direction. This offers a wider tracking arc of target orbital motion. This will be explored in the future as a means to increase orbit custody by performing high phase-angle observations of space objects and help to learn new ways to employ space telescopes to help ensure safety of flight in space.

10. Acknowledgements

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