Addressing the Debilitating Effects of Maneuvers on SSA Accuracy and Timeliness

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ABSTRACT

This paper characterizes the SSA accuracy, timeliness, and safety degradations caused by maneuvers, maneuver uncertainties, and outdated orbit determination systems' inabilities to accommodate maneuvers in both Rendezvous and Proximity Operations (RPO) and normal spacecraft operations. Maneuvers (both shared and non-cooperative/unknown) and associated maneuver uncertainties are a leading cause of degradations in safety and SSA accuracy, timeliness and often render flight safety products insufficient to meet spacecraft operator needs in today's increasingly challenging environment.

A holistic, collaborative, and technically advanced approach is needed to address these maneuver-induced SSA degradations. Practical ways to accomplish this include (1) collaborative sharing, normalization, and curation of planned maneuver and astrometric observations; (2) orbit determination algorithms suited to both planned maneuver characterization and calibration, as well as rapid non-cooperative maneuver detection and recovery; (3) incorporation of commercial SSA observational data; (4) data fusion and improved analytics; and (5) data sharing standards development and widespread adoption.

From a technical perspective, existing high Technical Readiness Level (TRL) SSA systems can help gather the necessary input data and produce and maintain actionable SSA/SDA knowledge, allowing decisionmakers to mitigate SSA degradations caused by maneuvers and get the SSA data they need to make informed space safety and sustainability decisions.

1. INTRODUCTION

Maneuvers are the lifeblood of orbit operations, constellation maintenance, orbit insertion, disposal, and achievement of mission. Just as powered and controlled flight was essential for the Wright brothers to "achieve flight", being able to maneuver in space is essential for spaceflight operations. Yet for all the good that maneuvers do to orbit operations, maneuvers are the single most important driver and weakest link to achieving SSA accuracy, timeliness, covariance realism, and safety. Long-standing orbit and conjunction assessment products provided at no cost to spacecraft operators by the US government fail to adequately address both known and non-cooperative maneuvers. Spacecraft operators have been keenly aware of these SSA capability gaps for many years, even compelling several spacecraft operators to self-form and fund the Space Data Association as a stopgap measure to address these known maneuver deficiencies.

As depicted in **Fig. 1**, relevant cases which demonstrate these SSA accuracy degradations include:

- A summary of our forensic reconstruction of the Iridium Cosmos collision which identified an increase in collision probability by an astounding 41 orders of magnitude due to the presence of a single unknown station keeping maneuver.

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- SSA for spacecraft operators who are members of the Space Data Association that regularly have degraded orbits when operator or commercial SSA data is not incorporated.
- Delays in recovering from maneuvers of up to one week as legacy SSA systems struggle to fit two-body orbits through flight segments containing maneuvers.
- Maneuvers in "unannounced" RPO-engaged spacecraft that may have errors in maneuver magnitude and/or direction, leading to unintended close approaches or collisions.

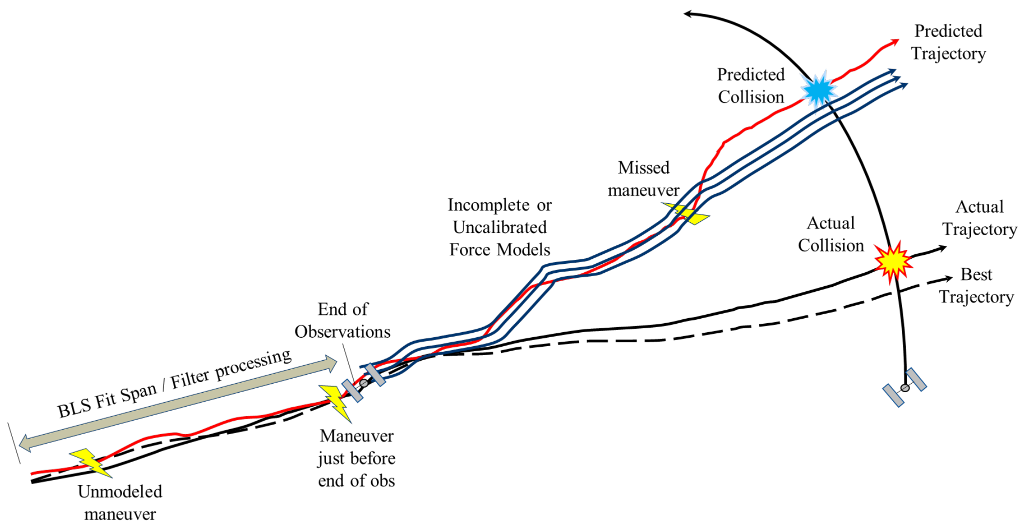

Fig. 1 - Conditions that degrade SSA. There are many conditions that can arise that prevent the accurate determination of the satellite state. Both the orbit determination and orbit prediction must be accurate. The goal is to minimize the difference of the actual and best estimated trajectories.

As shown in **Fig. 2**[1], there are many factors that in aggregate determine the accuracy of an SSA system.

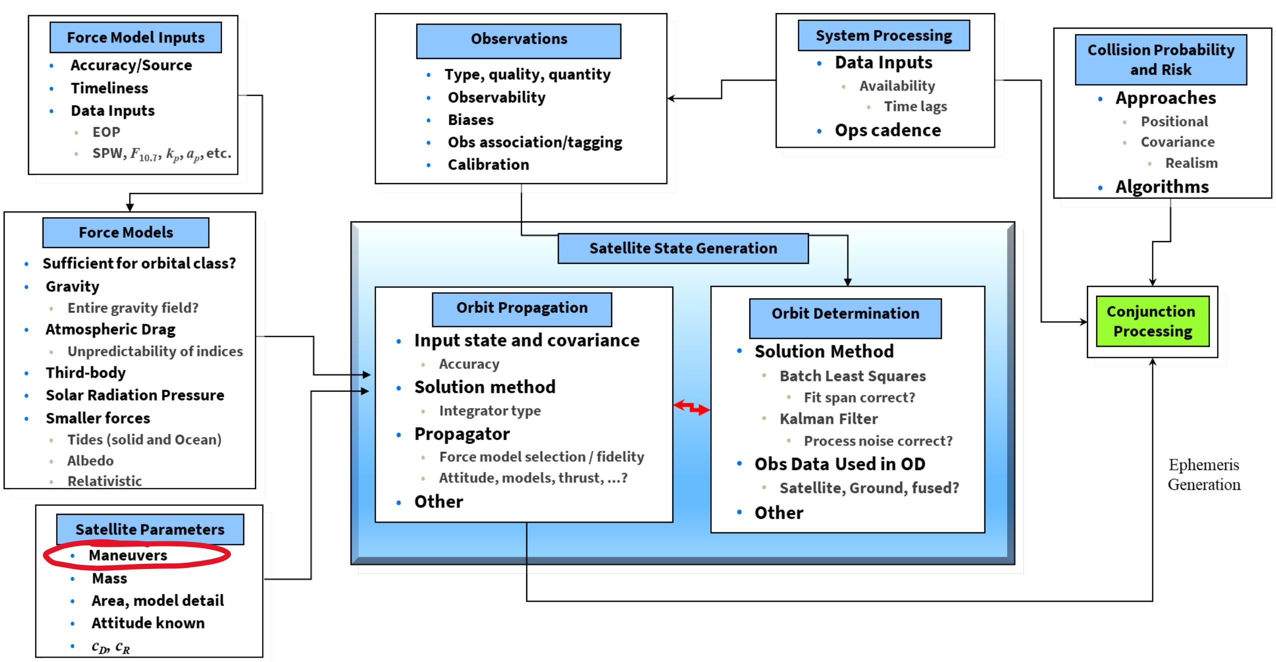

Fig. 2 - Interrelationship between factors affecting SSA and derived SSA products. There are many factors that affect the accuracy and actionability of SSA information. The satellites' orbital state generation is central to the process. Many of these factors are intertwined, making optimization of the process difficult in isolation.

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Yet maneuvers, tucked quietly into the bottom left of **Fig. 2**, are typically responsible for some of the most egregious SSA errors. The "maneuver" category encompasses much more than simply knowing that a maneuver did or will take place; one must also be able to (a) accurately calibrate the spacecraft's maneuvers, thruster performance, and pointing errors; (b) accurately model the effects of planned maneuvers; (c) fit accurate trajectories through past maneuvers; (d) accurately predict (or propagate) trajectories through future maneuvers; and (e) accurately assess and incorporate maneuver uncertainties into the downstream positional and velocity uncertainties to assess their effects on SSA information and the Space Domain Awareness (SDA) upon which it is based.

2. OUTLINE OF THE PAPER

This paper explores the various ways in which maneuvers degrade SSA and SDA accuracy, timeliness, completeness, and actionability. **These major influences are captured in the following sections of the paper** as shown in Table 1. These "major influencer" sections are followed with an examination of possible solutions to these many challenges.

Table 1 – Major SSA and SDA degradation categories mapped to sections in this paper.

Section	Maneuver-caused SSA degradation categories:
3	Unmodeled/mismodeled maneuvers
4	Orbit determination through maneuvers
5	Post-maneuver OD recovery challenges
6	Position and covariance uncertainties predicted through future maneuvers
7	Risk from unannounced spacecraft RPO and proximity stationkeeping maneuvers
8	Vulnerabilities and Space Domain Awareness degradation from adversary spacecraft maneuvers

3. UNMODELED/MISMODELED MANEUVERS

3.1 UNMODELED MANEUVERS IN THE LEAD-UP TO THE IRIDIUM/COSMOS COLLISION

The collision between the Iridium 33 spacecraft and Cosmos 2251 occurred on 10 Feb 2009 at 16:55:59.82 UTC at a relative velocity of 11.64 km/s, generating thousands of debris fragments that placed many spacecraft at risk [2, 3].

The COMSPOC Team conducted an independent analysis of this event [4] as shown in **Fig. 3** by using the SSA Software Suite (SSS) to comprehensively fuse all available data from the spacecraft operator and the SSN. Using the COMSPOC orbit refined solution and modeling two small maneuvers (consecutive 2 mm/s burns spaced half an orbital revolution apart, occurring ten hours prior to the Time of Closest Approach or TCA), COMSPOC found that the predicted miss distance reduced from 230 to 45 m and the collision probability raised from 5.e-34 to one in a thousand as compared to the government's pre-event characterization. SP predictions estimated the pre-event collision probability at 1.e-40, similar to the COMSPOC pre-maneuvers assessment and well outside the maximum probability dilution region, creating a false sense of safety.

Our findings were quite similar to those stated in Ref. [5], "*The collision between an Iridium communications satellite and another object was identified by the sensors of the Space Surveillance Network (SSN) and the Joint Space Operations Center (JSpOC) on Tuesday, 10 February* ***after*** *the collision had occurred when a support request was received from Iridium. […] During post-event analysis utilizing the observations obtained just prior to the time of closest approach (TCA) […]* ***the predicted miss distance computed was 223 m*** *and the estimated collision probability was zero. However, it was later learned that* ***the Iridium 33 satellite performed two small maneuvers several hours prior to the collision*** *as part of its planned, routine constellation maintenance. […] After the collision, the Owner/Operator (O/O) ephemeris* ***including the planned maneuver was analyzed and yielded a predicted miss distance of 60 m. […] A Pc value of 4.98e-3 was obtained*** *that more accurately reflects the threat level of the event at TCA. Again, this data was obtained after the collision.*"

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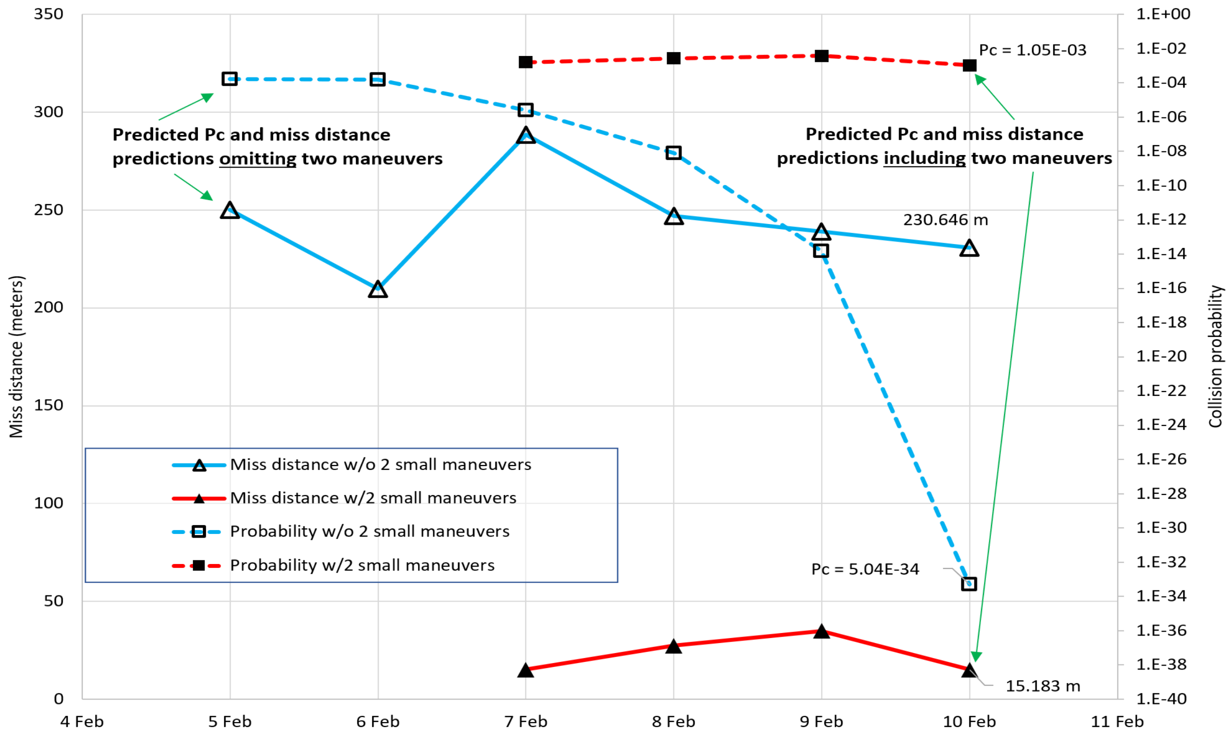

Fig. 3 - COMSPOC HiDeph reconstruction of run-up to collision between Iridium 33 and COSMOS 2251.

The figure contrasts the SSA estimates of collision probability and miss distance where the two small maneuvers were omitted (blue lines) with estimates that included the two small maneuvers Iridium did (red lines).

It is estimated that 2,600 trackable and 7,900 Lethal Non-Trackable (LNT) debris fragments were generated by this serious collision event [6]. This debris has caused[7], and continues to cause, many close approaches with operational spacecraft. Even today, Cosmos 2251 and Iridium 33 debris still account for 12% of the total the debris flux affecting spacecraft constellations in the mid-LEO altitude range [8]. By including owner/operator data (either by including these two maneuvers in SSA products directly, or by using Owner/Operator (O/O) ephemerides that incorporate maneuvers), the Iridium/Cosmos event could have easily been avoided.

Some people are fond of pointing out that the probability of collision is 1.0 if a collision actually occurred. While humorous, it's disingenuous in that this notion changes the fundamental definition of what an operationally relevant collision probability estimate represents: "The probability that an identified close approach will actually result in a collision, given the a priori positional knowledge and associated uncertainties that an SSA system has at the time that the Pc estimate was generated." Since such positional knowledge and associated uncertainties can never be perfect before the event occurs, a priori Pc estimates can never be 1.0.

Iridium's conclusion from Ref. [3] bears repeating here: "The [post-collision forensic assessment] demonstrates a collision between a maneuverable object and a non-maneuverable is preventable today. A collision between two maneuverable objects is also preventable, but as the replay demonstrates, only if the data of both parties are shared with the other."

3.2 UNMODELED/MISMODELED MANEUVER-INDUCED SSA DEGRADATIONS IDENTIFIED BY SSA ACCURACY ASSESSMENTS

One can best see the SSA degradation caused by maneuvers by performing accuracy assessments of SSA data both inclusive and exclusive of maneuvers. COMSPOC has now participated in two such comparative assessments (with

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technical performance assessments provided in Ref. [9] and [10]) of the benefits of deep collaboration and comprehensive data fusion in the Orbit Determination (OD) and prediction processes.

The latest analysis [10] was performed for the recent Department of Commerce (DOC) GEO/MEO Pilot for Space Traffic Management (STM) conducted from 5 Dec 2022 to mid-February. As shown in **Fig. 4**, ten SDA spacecraft operators collaborated with COMSPOC to generate fused orbital solutions for 100 selected Middle Earth Orbit (MEO) and Geostationary Earth Orbit (GEO) spacecraft, with over eighty five percent of those spacecraft enrolled or participating in the SDA's Space Data Center. The SDA and its spacecraft operators employed COMSPOC to receive the operator's planned maneuvers and observations in a data lake model and employ a sequential filter orbit determination to generate both smoothed (historical or reconstructed) and predictive (filter) ephemerides and covariances.

To ensure that maneuvers were rapidly detected, characterized, and calibrated so that accurate solutions can be quickly recovered, this SDA-supplied product included a non-cooperative maneuver algorithm and associated optimization. Twenty-seven of the selected one hundred spacecraft had some form of independent high-accuracy positional source such as GNSS data, laser ranging, SBAS, or IGS positional measurements or "truth ephemerides" to permit accuracy assessment against independent third-party reference ephemerides.

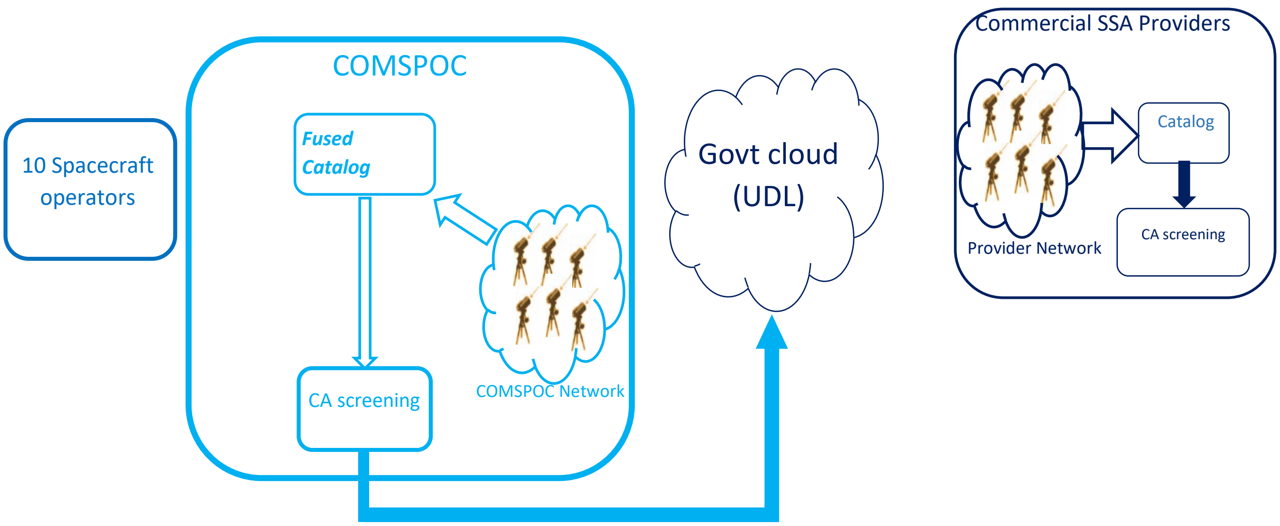

Fig. 4 - Adopted strategy for the DOC Pilot Program.

To acquaint the reader with the accuracy plot format adopted for characterizing accuracy of the MEO and GEO active spacecraft involved in the DOC Pilot Program, see **Fig. 5**. This plot format characterizes the positional error associated with a variety of SSA positional products shown in the legend at right, with TLEs (in solid black), SP ephemerides (in dash-dotted orange), operator ephemerides (in dotted purple), and fused solutions (in solid green).

We first define the axes of this accuracy plot, with the x-axis representing the date and the y-axis representing positional error in kilometers. The horizontal red line just barely visible at the bottom of the graph represents the accuracy required to use a spacecraft operator's Pc threshold [11] of one in ten thousand as a conjunction screening threshold (as derived in Ref. [9]).

The vertical blue lines depict when the spacecraft performed a maneuver, with the thickness of the maneuver bar scaled to reflect its duration. These maneuver plans were provided by the spacecraft operator Flight Dynamics Staff when available, although as can be observed later, not all maneuvers were provided.

Against this backdrop, we can see how the sequence of TLEs (depicted as thin black lines) propagates forward and the error associated with each TLE as a function of time. The orbit epoch for each TLE is represented by the up-pointing triangle at the beginning of each line. You can see that the TLE accuracy typically ranges between one and four kilometers for this spacecraft during this three-week analysis period. But you can also see that the maneuvers

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conducted by the spacecraft on 23 and 25 January introduced oscillating and secular degradations respectively in predictive accuracy in TLEs. This degradation is to be expected, as TLEs do not reflect planned maneuvers, nor can they fit through previous ones (even if known).

Next, we examine how SP ephemerides (depicted as dash-dotted orange lines) perform during this same period. You can see that while SP typically has significantly better accuracy than TLEs most of the time for this spacecraft, it sometimes exceeds the allowable error. Also notice that the same maneuvers that caused the TLE accuracy to degrade equally impacted SP accuracy - - which is to say that for unmodeled forces such as the maneuver (vertical blue line), TLE and SP accuracy are affected equally, despite the innate higher fidelity of SP perturbations theory. In fact, one interesting observation, consistent with prior operational experience, is that while SP is typically more accurate than TLE solutions in the short-term, TLE accuracy can sometimes match and even improve upon SP accuracy over propagation timespans of one to two days or more.

But this brings us to about the limit of what can be gleaned from this plot using this y-axis scale, because the area of high interest in the vicinity of or below the Pc threshold-derived accuracy constraint is simply too compressed to be visible on this linear scale.

While one could repeatedly zoom in on the y-axis to gain clarity in this accuracy depiction at higher fidelity levels, we chose instead to employ a logarithmic y-axis scale as shown in **Fig. 6**. But this switch must be accompanied by a caution: *a log scale tends to downplay large positional errors while amplifying small errors. Note that the green line spans a factor of 1,000! - - so user beware.*

Whether examining the linear or log scale accuracy plot, the impact of a maneuver is readily apparent. The two SSA systems that are typically unable to perform orbit determinations through maneuvers or do orbit predictions through maneuvers (the black TLE trend and the orange SP ephemeris of the High-Accuracy Catalog) experience substantial degradations in accuracy when maneuvers are introduced into the system. The resumption of in-family accuracy a while after the maneuver occurs (e.g., the TLE trend shortly after the 20 January maneuver) is presumably due to either (a) the time it takes to collect sufficient post-maneuver observations to fit an accurate orbit without fitting through the maneuver; or (b) generation of a TLE or SP ephemeris based upon owner/operator ephemeris or state vector data.

Note that even for this example, it is not always true that incorporation of O/O planned maneuver information yields an accurate post-maneuver ephemeris; the green and purple-dotted trend lines of the COMSPOC and O/O ephemerides also have reduced positional accuracy post-maneuver. But as can be seen, the incorporation of planned maneuver information into the COMSPOC and O/O ephemerides improves upon TLE and SP accuracies at a factor of four, with substantially reduced latency in recovery of an accurate orbit solution.

The reader is encouraged to read the complete technical accuracy assessment (Ref. [10]) to see many more instances of how maneuvers degrade orbital positional knowledge.

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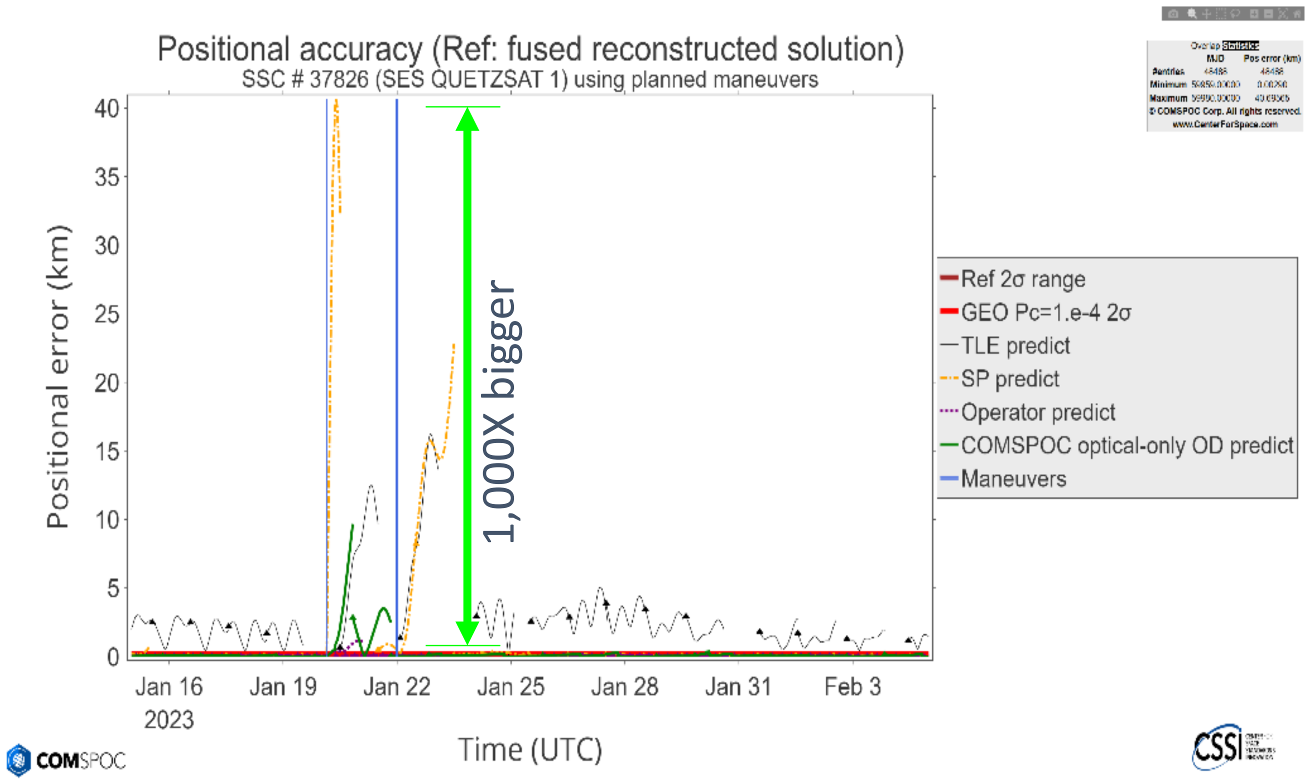

Fig. 5 - Example of STCM demonstration predict accuracy on a linear y-axis scale.

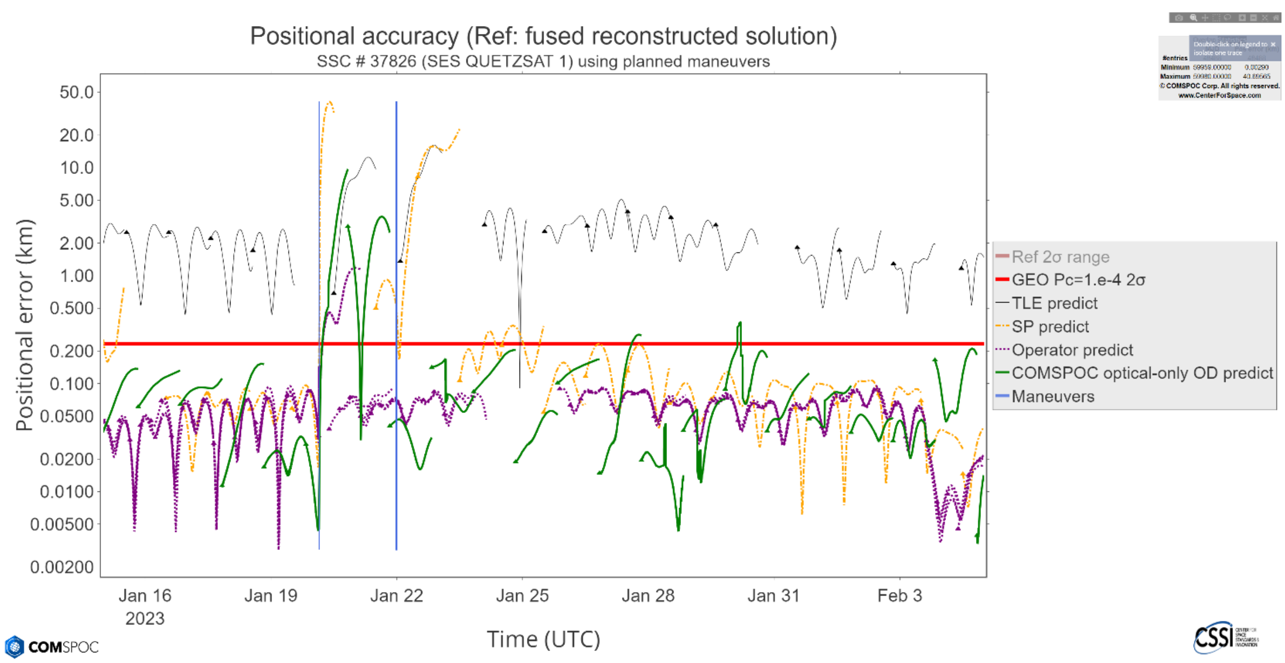

Fig. 6 - Example of STCM demonstration predict accuracy on a logarithmic y-axis scale.

4. ORBIT DETERMINATION THROUGH MANEUVERS

So-called “non-cooperative” (i.e., unannounced) maneuvers represent perhaps the most challenging aspect of orbit determination. Batch Least Squares (BLS) and Sequential Filter (SF) or Extended Kalman Filter (EKF) systems operate in fundamentally different ways as shown in **Fig. 7**[1]. A crucial aspect to consider is what positional accuracies can be achieved when the various OD algorithms are applied in the presence of maneuvers.

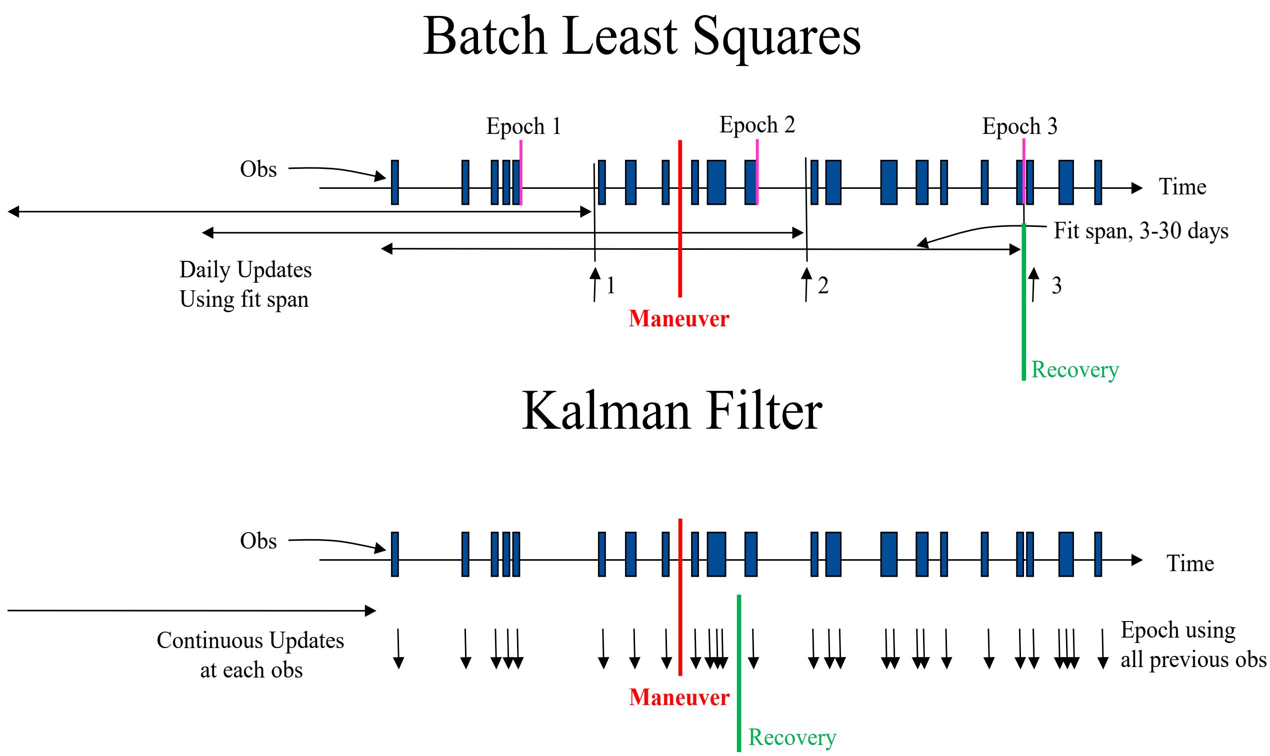

Fig. 7 - Comparison of BLS and EKF approaches in the Presence of a Maneuver. The BLS OD averages observations over a fit span, this lengthening the amount of time until full recovery can be made. The EKF, by processing each observation sequentially, reduces the time until recovery.

BLS OD systems can be especially challenged by a spacecraft that non-cooperatively performed one or more unknown maneuvers, because BLS typically tries to fit a non-maneuvering trajectory through two distinctly different orbit segments. As shown in **Fig. 8**, the resulting averaging of observations over the fit span both degrades positional accuracy, increases the positional uncertainty, and increases the time required for a full solution recovery to be made (which can often exceed the time before the next maneuver happens). In contrast, by processing each observation sequentially, the EKF approach reduces the time until recovery and avoids the accuracy degradations inherent to the BLS approach.

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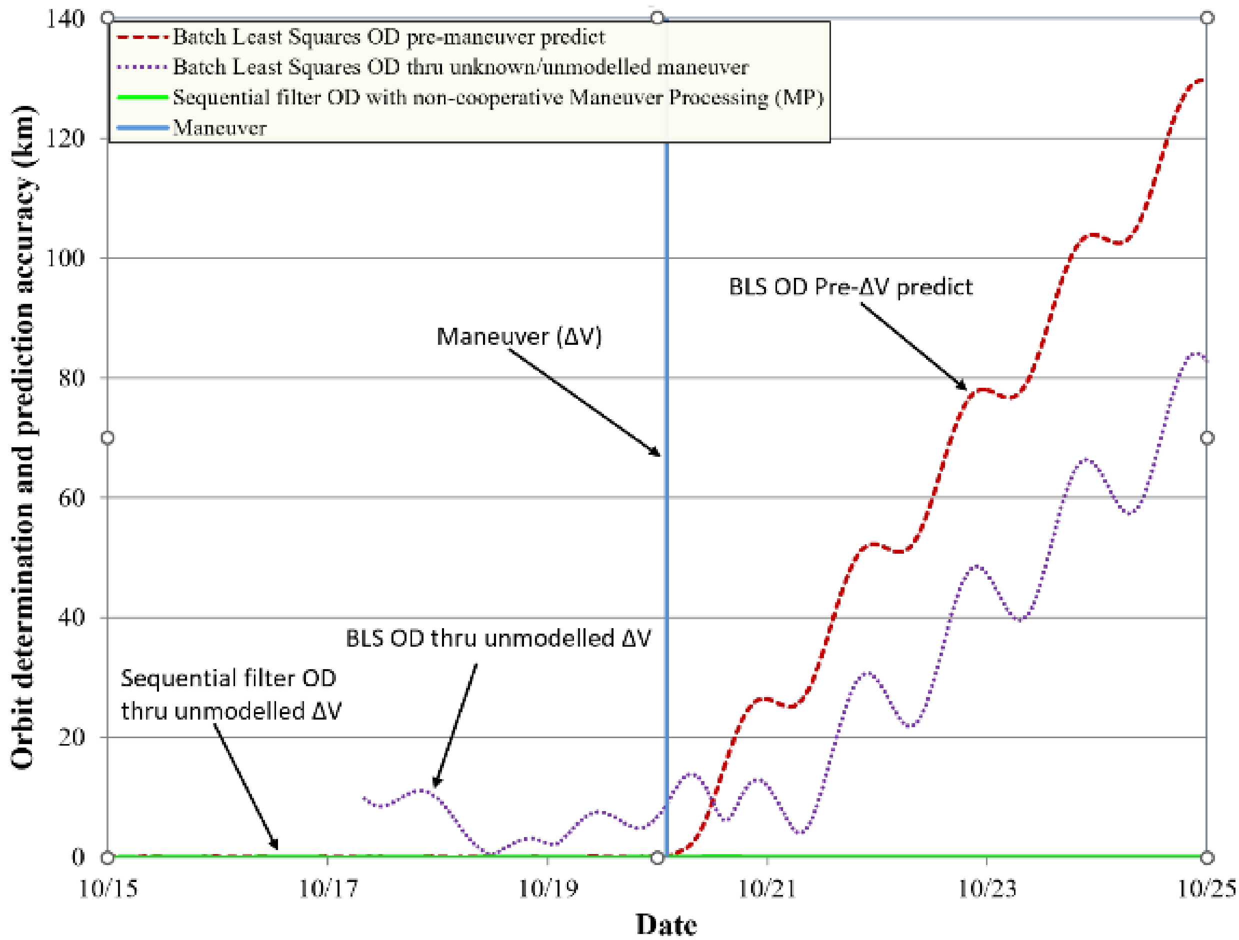

Fig. 8 - Comparison of BLS and EKF approaches in the Presence of a Maneuver. This simulation used BLS 9-day fit spans for a GEO orbit. The maneuver is processed easily with the EKF, with rapid recovery of an accurate orbital solution; the BLS errors are several orders of magnitude larger than those using an EKF. Notice as the BLS fit span begins to include the maneuver, the uncertainty rises from a minimum and continues well beyond the maneuver.

Sequential Filter (SF) or Extended Kalman Filter (EKF) OD systems typically are less challenged when processing through maneuvers, but even those must account for maneuver nuances. Even for cooperative satellite cases where the planned maneuvers are provided, orbit solutions must be carefully processed, tracked, and maintained.

Post-maneuver calibration is an important activity for accurate burn efficiency estimation, blow-down propulsion system monitoring, and mass properties knowledge, especially for GEO satellites that can maneuver quite frequently. It is not uncommon to have multiple, and perhaps even dozens, of maneuvers in a small observation span. Our experience indicates that positional differences stemming from OD processing of flight segments containing cooperatively planned and/or non-cooperatively conducted maneuvers can result in 0.5 to 10.0 km of positional difference – something that would be of great concern if a conjunction where to occur in that time frame. And even in cases where the maneuver occurs during a set of collected observations, the concern arises that a conjunction prediction initiated during the time of large trajectory variations near a maneuver would yield inaccurate positional predictions. In such a case, a non-cooperative solution would start at a higher initial uncertainty and would experience significantly higher prediction uncertainty. This effect is covered in the subsequent analysis for incorrect processing of planned maneuvers.

Maneuvers may be missed, re-planned at a different time, or the actual maneuver may differ from what a non-cooperative maneuver processing system solves for. The degree to which an orbit determination solution is degraded by the presence of such maneuvers depends in part upon the type of thruster system used in spacecraft operations (as

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seen in **Fig. 9** for electric thrust and **Fig. 10** for chemical thrust). Planned maneuvers may include a variety of errors – they may be "missed," poorly calibrated, delayed, etc.

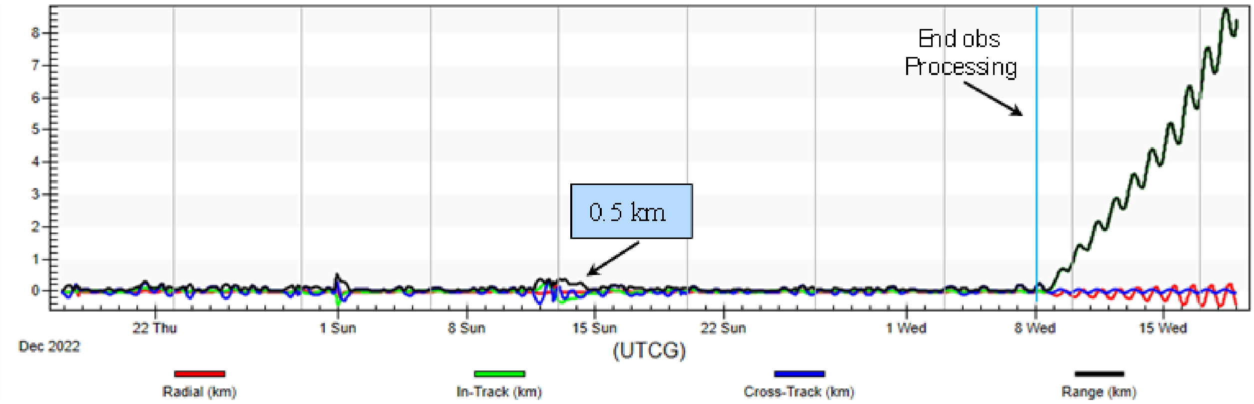

Fig. 9 - Maneuver effect during obs processing for electric thrust.

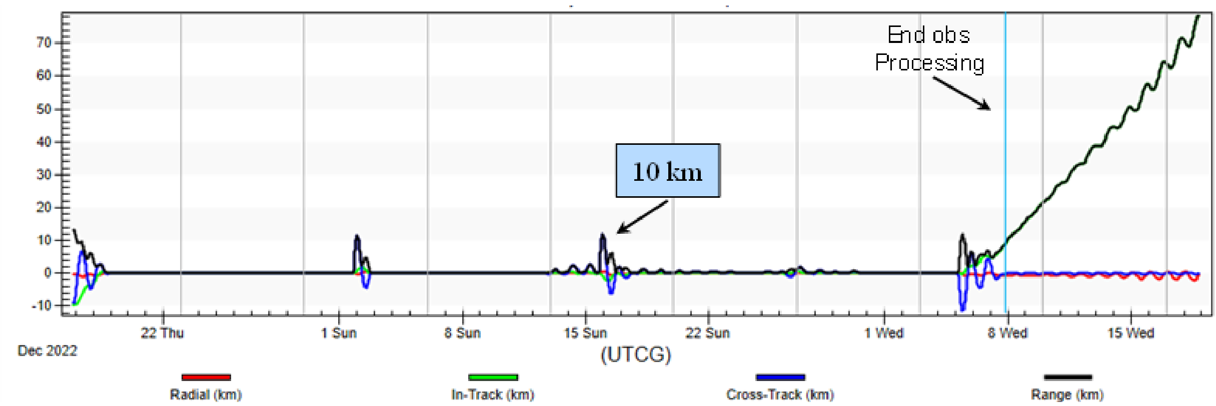

Fig. 10 - Maneuver effect during obs processing for chemical thrust.

An orbit determination sequential filter technique that has proven useful to orbit determination system operators when faced with past maneuvers is to open up the process noise of the filter. This has the effect of letting the filter "fly through" the maneuver and accept post-maneuver observations even if they deviate from the normal range. While this certainly has benefits to maintaining custody of maneuvering objects, it degrades the actionability of any collision probability estimates during that span of time because the associated positional uncertainties allowed by increasing the process noise may be off by several orders of magnitude from what a healthy solution would predict.

5. POST-MANEUVER OD RECOVERY CHALLENGES

The cadence of observations and tracking can affect a maneuver characterization, especially if the maneuver is on-going while the system processing occurs. OD processing of additional tracks taken after a maneuver has occurred (from the standard 3 as seen in the example in **Fig. 11** to 5 or more as seen in **Fig. 12**) can improve prediction uncertainty by 5 km or more in a week.

Data fusion (e.g., TDOA and/or ranging can yield an additional 5 km of accuracy over the optical only case as seen in **Fig. 13**). These effects are somewhat related to the maneuver effects described above but emphasize the benefits of processing more data past a maneuver and fusing across multiple sensor phenomenologies before doing any prediction calculations.

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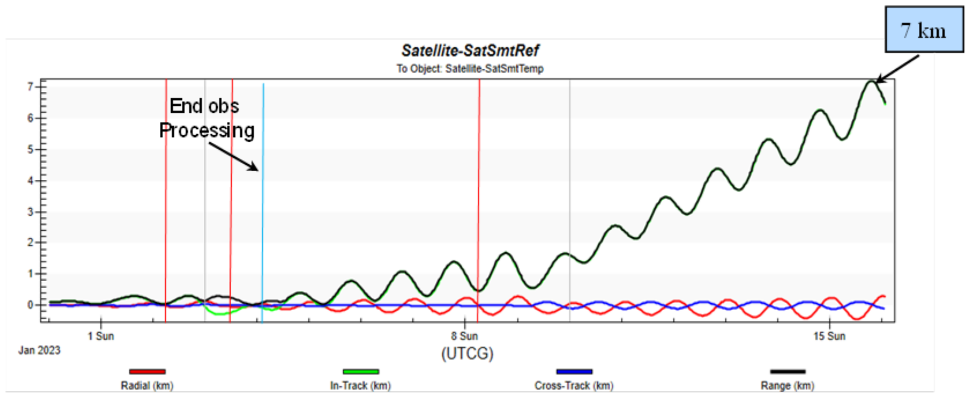

Fig. 11 - Ops Cadence Position Uncertainty (Optical Obs): Positional uncertainty where obs processing ended 5 Jan, 0154. The position uncertainty is about 7 km at the end of the interval.

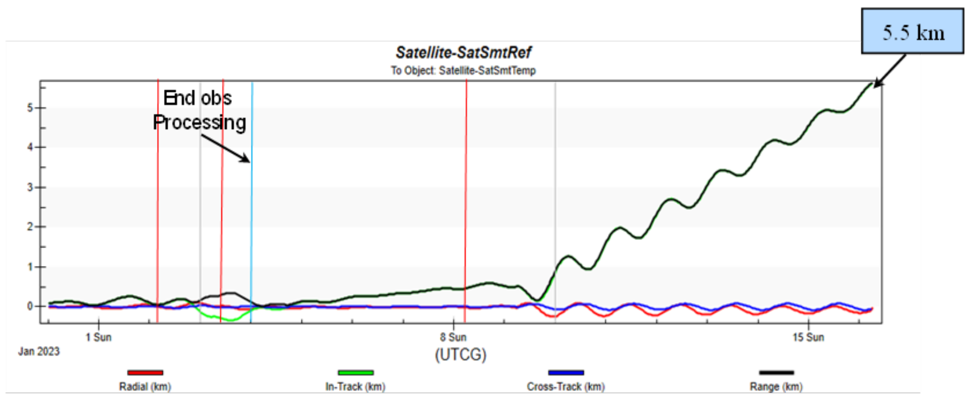

Fig. 12 - Ops Cadence Position Uncertainty (Optical Obs): Positional uncertainty where obs processing ended 5 Jan, 0636. The additional data gives about a 2 km improvement over the 10-day prediction interval from the case ending at 5 Jan, 0154.

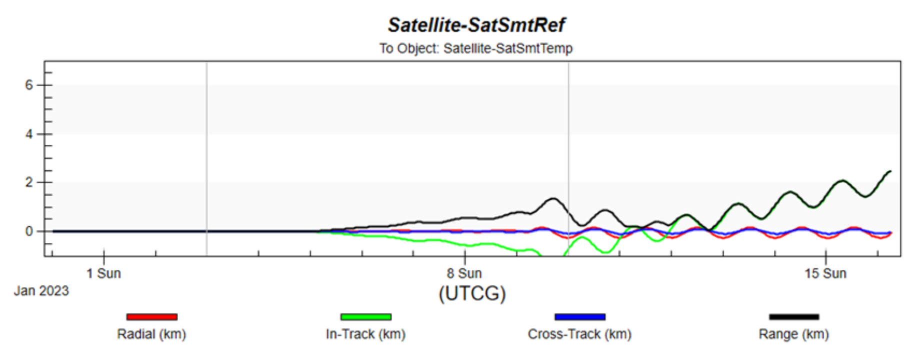

Fig. 13 - Ops Cadence Position Uncertainty Fusing ALL Obs: Positional uncertainty where obs processing of all sensor types ended 5 Jan, 0636. Data fusion gives about a 3 km improvement over the 10-day prediction interval from the optical only case ending at 5 Jan, 0636.

6. POSITION AND UNCERTAINTIES PREDICTED THROUGH FUTURE MANEUVERS

Maneuvers in the prediction period are the most important as they directly affect the downstream ephemeris (i.e., are an "extrapolation"), and since no observations are present, uncertainty tends to grow exponentially. The prediction phase is the primary concern in conjunction operations. Depending on the maneuver characteristics (In-Track, Cross-Track, station-keeping, collision avoidance, drift, etc.), the positional differences within a week can be on the order of 3-5 km, 15-25 km, or 90-100 km or more! All this depends on the number, length, size, and direction of the

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maneuvers, plus the elapsed time to the predicted maneuvers. Nevertheless, these are VERY large numbers that are critical to address with conjunction operations, planning, reporting, and use in calculations. Lack of attention here can negate the benefits of all the other maneuver accommodation strategies!

Ref. [1] examined what happens when planned maneuvers are known, unknown, missed, etc. in the prediction phase. We reproduce those analysis results here. They examine several cases as listed below. Note that they also examined the covariance to understand how it can be affected by the results.

a) Position and Covariance for a chemical thrusting satellite
b) Position and Covariance for an electric thrusting satellite
c) Position for maneuvers close and far from the end of processing
d) Another electric thrusting satellite with incorrect maneuvers and too much process noise

Fig. 14 shows the positional uncertainty arising from a generic chemical trusting satellite using optical, transponder, and TDOA observations where 1 maneuver is removed (dashed red line) a few days after the end of processing. After about 10 days, the uncertainty is about 2.5 km.

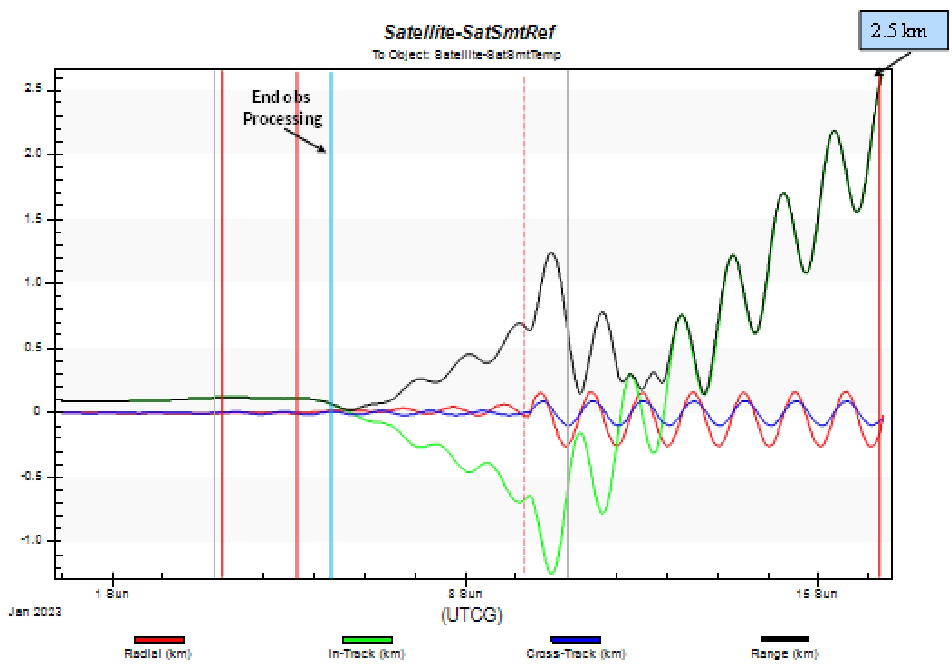

Fig. 14 - Prediction Position Uncertainty for Chemical Thrust 1 Maneuver Missing: Positional uncertainty with one maneuver missing (red dashed line). The position uncertainty is about 2.5 km at the end of the interval.

As shown in **Fig. 15**, the predicted covariance uncertainty for this case grows to 35 km! Generally, the positional errors and covariance-derived uncertainties are much closer. But maneuver-caused velocity changes are typically not considered in covariance propagation, so any additional uncertainty simply adds to the covariance, and it continues to grow unbounded, hence the large differences.

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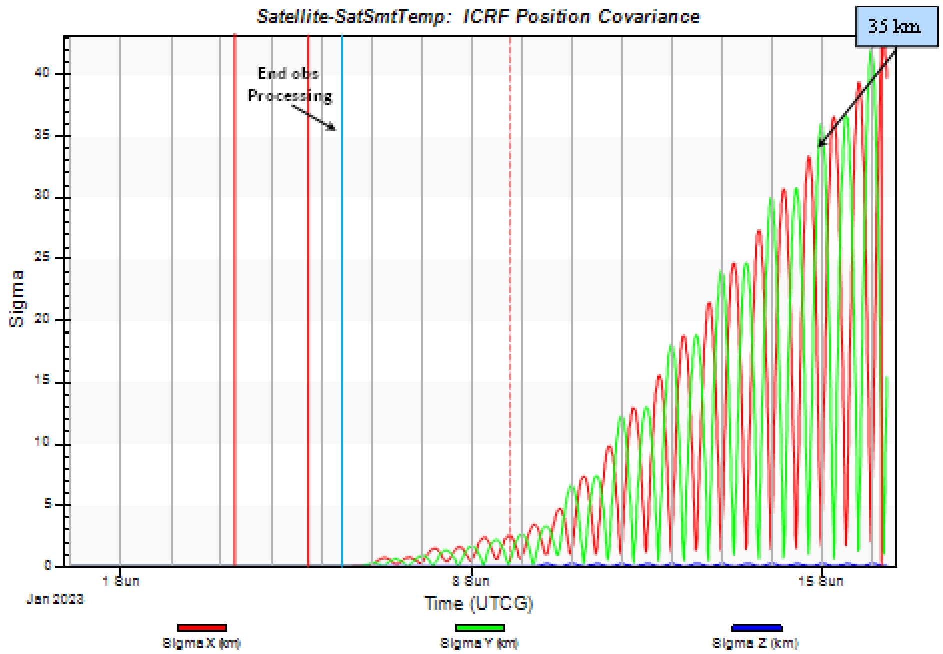

Fig. 15 - Predicted Covariance Uncertainty Chemical Thrust 1 Maneuver Missing: Covariance uncertainty with one maneuver missing (dashed red line). The covariance uncertainty is about 35 km at the end of the interval.

Examining another satellite with transponder and optical data and electric thrust (4 maneuvers per day), taking out 1 days maneuvers just after the end of observation processing, we find only a 9 km uncertainty as shown in **Fig. 16**. Notice the shape of the curve – indicating that stationkeeping is being done.

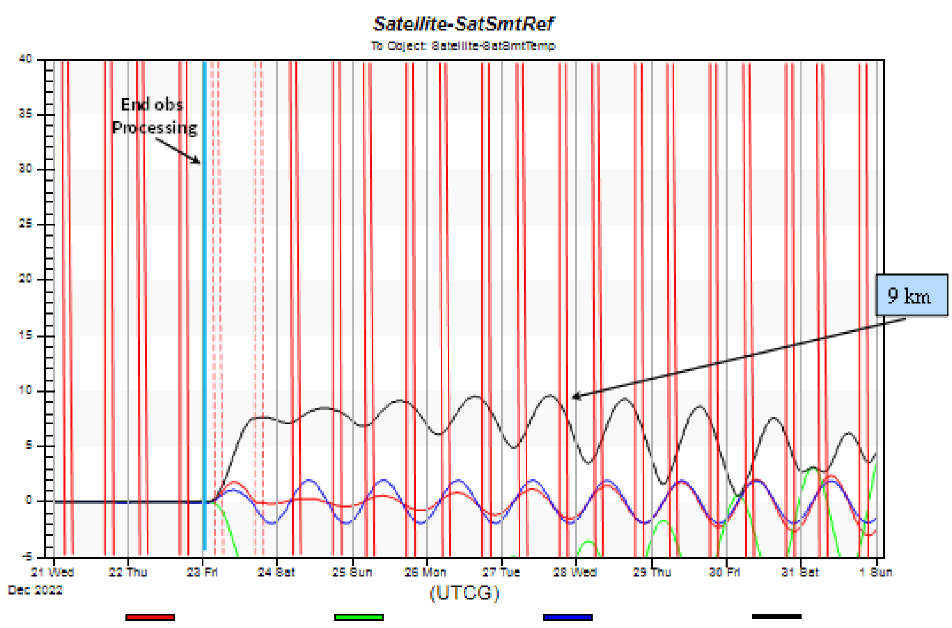

Fig. 16 - Prediction Position Uncertainty Electric Thrust 1 day of Maneuvers Missing: Positional uncertainty with one day of maneuvers missing. The position uncertainty is about 9 km at the end of the interval.

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The predicted uncertainty (**Fig. 17**) derived from the covariance again shows unbounded growth for this case and is not very consistent with the position comparison.

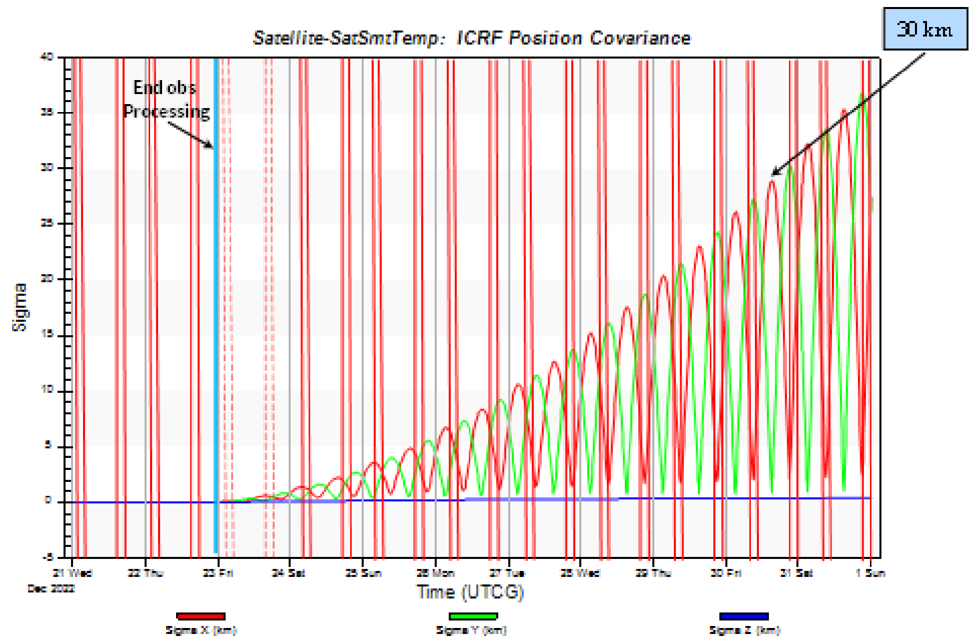

Fig. 17 - Prediction Covariance Uncertainty Electric Thrust 1 day of Maneuvers Missing: Covariance uncertainty with one day of maneuvers missing. The covariance uncertainty is about 30 km at the end of the interval – simply the result of lots of maneuver uncertainties being added to the covariance propagation over time.

7. RISK FROM UNANNOUNCED SPACECRAFT RPO AND PROXIMITY STATIONKEEPING MANEUVERS

Uncooperative proximity satellite operations have raised the risk of collisions and have caused averse operational impacts to commercial satellite organizations. Proximity operations, among different operators, requires coordination and data exchange, to reduce the collision risk due to the maneuver uncertainty and to avoid the scenario of multiple actors simultaneously maneuvering, which would only increase the risk. For many years, satellite operators have experienced third-party operators, performing proximity operations adjacent to their satellites. To reduce the uncertainty and collision risk, these operators have reached out to the third-party operators for coordination, in the hope of establishing communications to exchange data. However, on many occasions, no response was received, and communication was not established. The commercial operators were often left to delay their own maneuvers until half an orbital revolution before the time of the close approach, hoping this would allow them to gain the latest data on potential risk inducing operations and maneuvers by the third-party operators. In some cases, costly unplanned maneuvers were performed to reduce the risk of collision.

By quantifying the risk of uncooperative proximity operations and uncoordinated maneuvers, the impact to collision risks is understood and appropriate actions can be determined in response. Such quantification can reduce the need for additional maneuvers or the cancelling of previously planned maneuvers. Currently substantial resources are being put into risk reduction, including maneuver detection and the ability to rapidly recover the post maneuvered orbit. But if the risk is evaluated to be lower than assumed, this can be significantly reduced. Conversely, if the evaluated risk is higher than what was previously expected, the benefit of cooperation in reducing these risks can be further emphasized.

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7.1 MANEUVER PATTERNS FOR UNANNOUNCED SPACECRAFT

LUCH Olymp-K, commonly known as LUCH, is a Russian signals intelligence satellite. It was launched in 2014 and has spent its entire operational life drifting around the GEO belt and parking next to commercial communication satellites of interest. **Fig. 18** shows the history of LUCH's movement around the GEO belt since it was first launched.

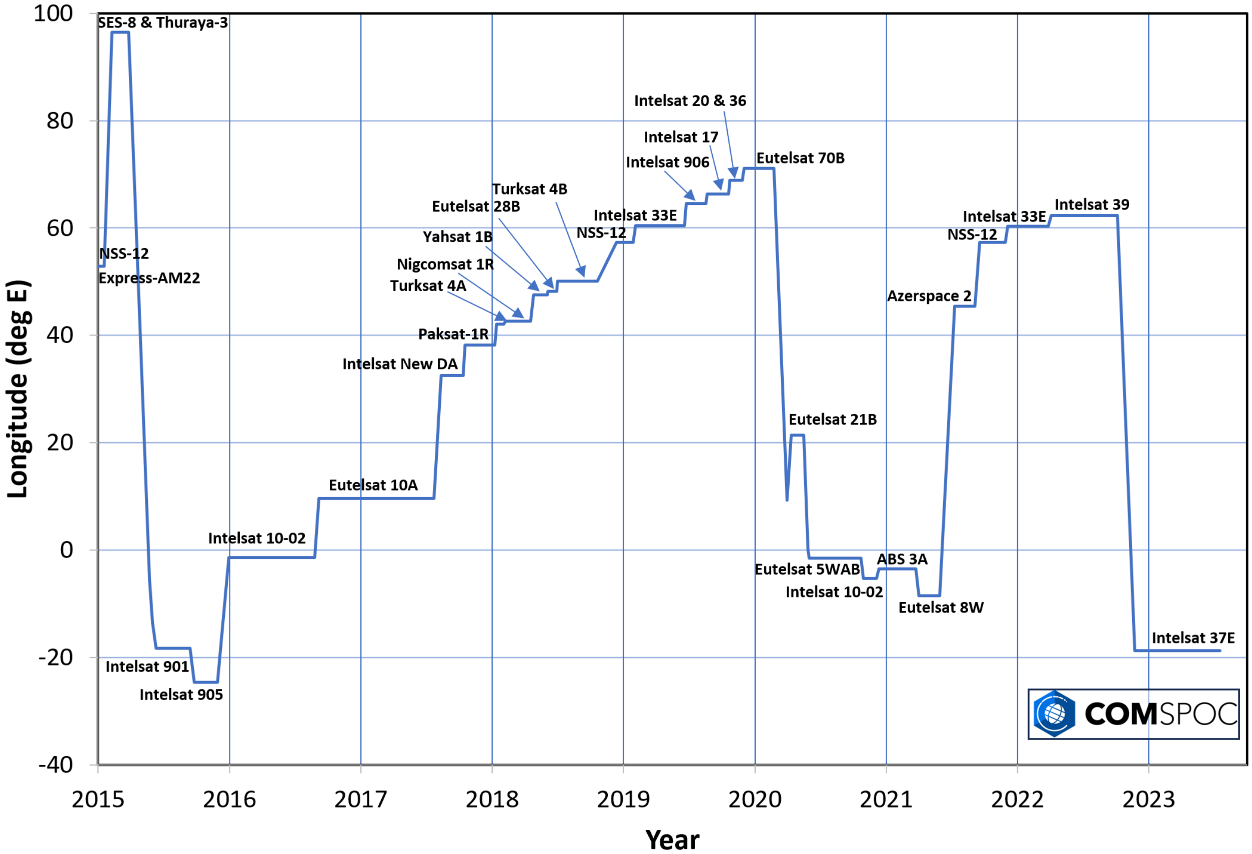

Fig. 18 - LUCH longitudinal transits of commercial communications spacecraft since 2019.

This type of behaviour is increasingly common, especially with defence-related satellites. Another example is the Chinese satellite, TJS-3 (NORAD #43874). The TJS-3 spacecraft was launched in late 2018 and has a similar mission profile to the LUCH satellite, drifting along the GEO belt and stopping for periods of time next to target satellites. This can be seen in **Fig. 19**.

Not only is this exhibited during "dwells" next to satellites, but it can also be used during "flybys" as well. In February of 2022, the Chinese SHIYAN 12-01 and SHIYAN 12-02 satellites engaged in a "cat and mouse" game with USA 270 with each satellite performing multiple maneuvers and trying to get good viewing angles for photography. **Fig. 20** shows the results of one such maneuver where SHIYAN 12-02 positioned itself with the sun to the rear and USA 270 in front in what could be an optimal viewing situation. Overall, 19 maneuvers were performed by the three satellites during a 28-day period.

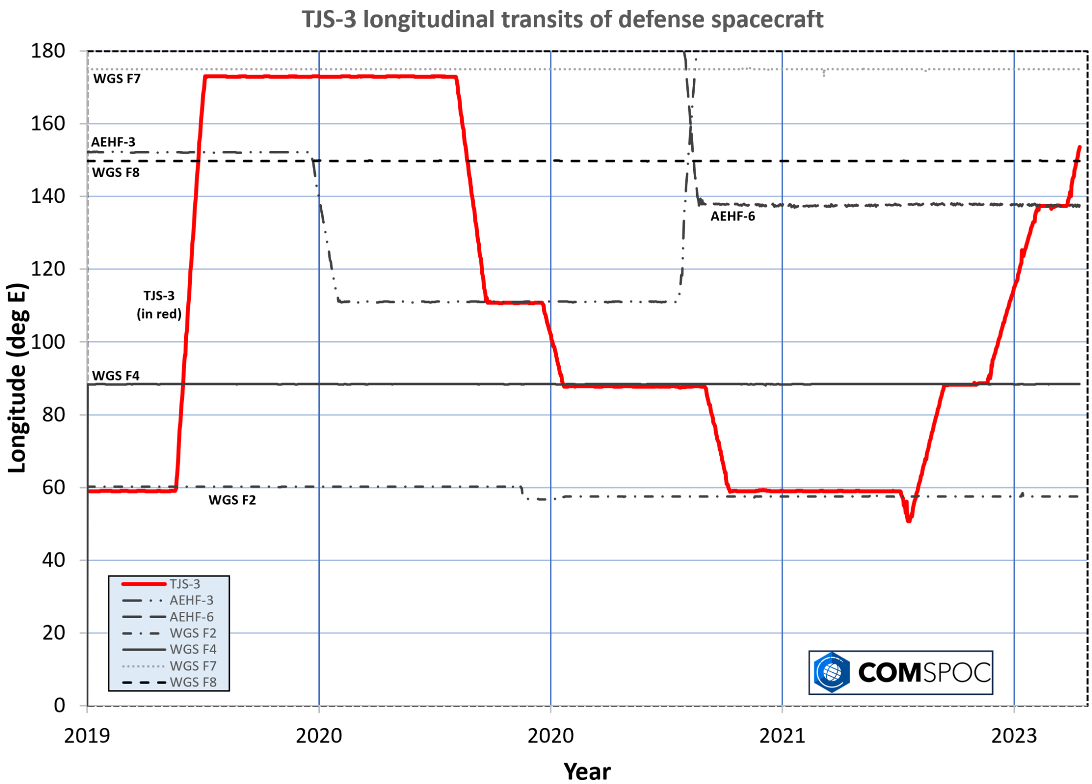

Fig. 19 - TJS-3 (red line) longitudinal transits past defense spacecraft.

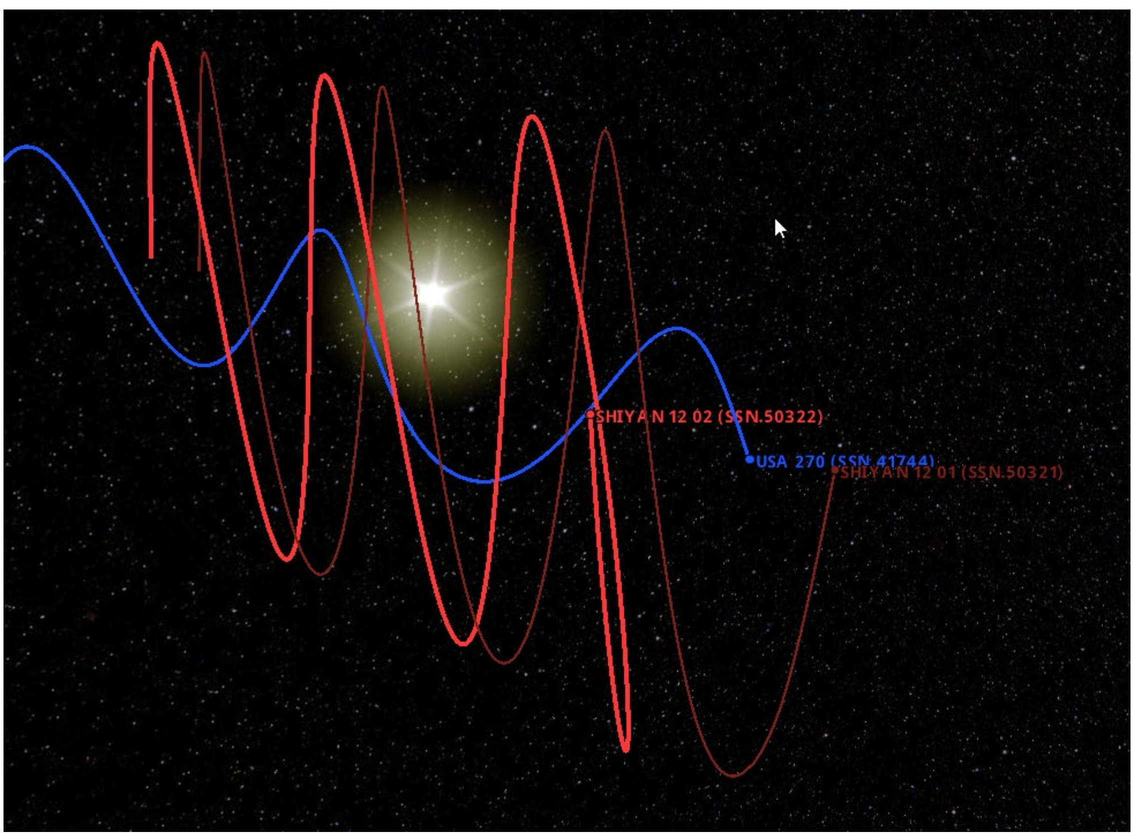

Fig. 20 - SHIYAN 12-02 imaging opportunity

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7.2 EFFECT ON SSA AND SAFETY OF MANUEVERS BY UNANNOUNCED SPACECRAFT

To effectively quantify the risk of frequent maneuvering by unreported satellites, a case study was performed on Russia's LUCH spacecraft, a satellite known for frequently relocating around the GEO belt parking, next to commercial communications spacecraft of interest. According to Joseph Chan of Intelsat, Russia has been unwilling to cooperate with commercial spacecraft operators, leaving the spacecraft operators to wonder how LUCH or other similar spacecraft know when the commercial operator is conducting a maneuver, or how the LUCH operations team accounts for errors in their planned maneuvers (in terms of both direction and magnitude).

LUCH typically performs station keeping maneuvers to maintain a relatively constant distance away from its target. It typically operates at a cadence of 2 maneuvers per day. However, even with consistent stationkeeping, it does not always maintain a safe profile with respect to its neighbours. For example, in November of 2019 LUCH came within 1.8 km of Intelsat 36 during its normal mission operations.

Maneuver risk was quantified by calculating a safety margin for how close its maneuvers come to creating a collision. To accomplish this, the magnitude of LUCH's thrust-imparted velocity change vector ($\overline{\Delta V}_{maneuver}$) can be compared to the minimum velocity change required for intercept ($\overline{\Delta V}_{intercept}$). Such comparisons give insight regarding the manoeuvre's leeway in preventing a collision should the thrusting deviate from nominal.

COMSPOC[12] maneuver process services[13] detect and characterize LUCH's movements, providing detailed maneuver information including maneuver type, direction, magnitude, burn start/stop times, and burn center time. Knowing the position vectors of both satellites at maneuver start time, a Lambert orbital transfer function[14] is used to find a family of velocity vectors that will cause LUCH to intercept the short way (less than one revolution) with minimal energy. Candidate flight-intercept times are advanced in five-minute increments for an entire day; the intercept velocity closest to LUCH's post-maneuver velocity is chosen since it represents the worst case. The magnitude of this least difference between $\overline{\Delta V}_{intercept}$ and $\overline{\Delta V}_{maneuver}$ reveals the safety margin.

In **Fig. 21**, the LUCH maneuver magnitudes are depicted in blue, and the additional velocities needed for collision are depicted in orange. The greater the blue relative to the orange, the less the safety margin. This depiction illustrates relative magnitude and does not quantify the angular difference that might exist between $\overline{\Delta V}_{intercept}$ and $\overline{\Delta V}_{maneuver}$.

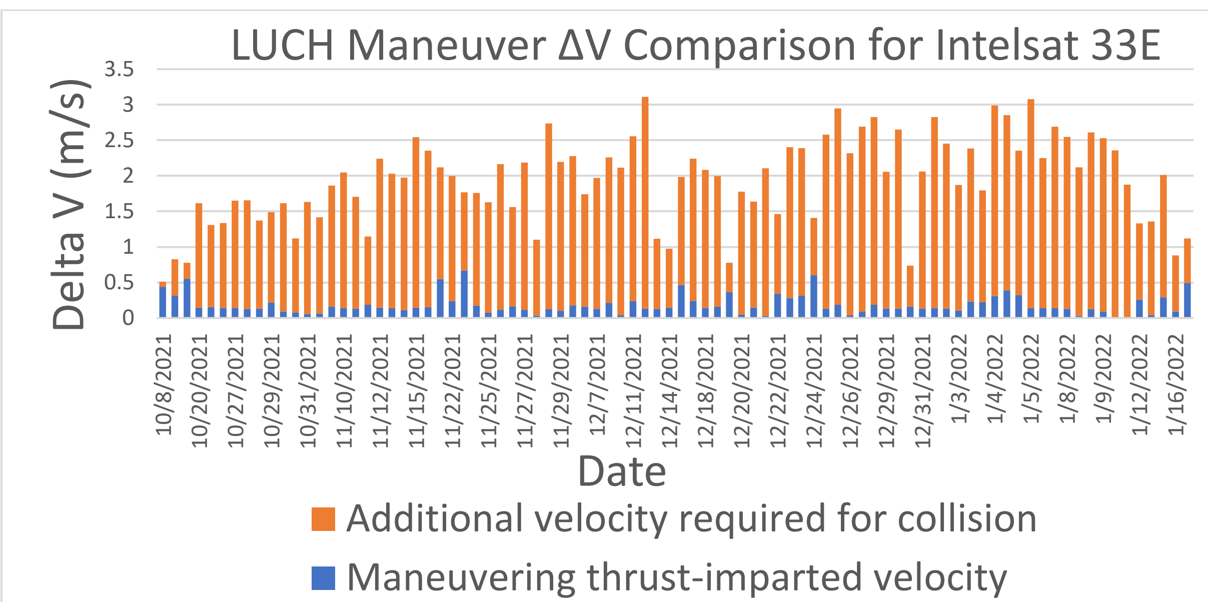

Fig. 21 – Comparison of the difference between the magnitude of (a) Luch's as-conducted imparted velocity vector; and (b) the worst-case Intelsat 33E intercept/collision-inducing Luch maneuver.

While most of the maneuvers LUCH performs tend to be small, it can perform maneuvers with a relatively high velocity change. Despite this fact and the risk of a misfire, LUCH continuously and actively maneuvers even during periods where such a maneuver could be considered large enough to cause a collision. Furthermore, it should be noted that while many significant maneuvers were detected in the analysis period, smaller maneuvers may have also occurred.

Beyond the risk of a misfire while maneuvering causing a collision, some maneuvers performed have simply too small a margin of error, as was found in data for October 2021 at the lefthand side of **Fig. 21**. On 8 October 2021, a maneuver with a magnitude of 0.441 meters per second was calculated to have occurred, with an additional safety margin of only 0.071 meters per second. At only 16.1% of the actual maneuver magnitude, this leaves little margin for error and could be considered an inherently risky maneuver. This is only further exacerbated by the repeated maneuvers of similar scale that followed shortly after, combined with the risk of Intelsat maneuvering, and introducing further positional uncertainty. Furthermore, the high frequency of maneuvers makes orbital determination more difficult and less accurate, increasing the position uncertainty and diminishing the confidence and safety of Intelsat's own operations.

Table 2 Intelsat alert data from for March 2016 close approaches with Luch.

Alert ID	SSCID	Primary Satellite	Secondary Satellite	TCA	Action Thresholds
3146549	1002	INTELSAT 1002	LUCH (OLYMP)	3/2/16 7:27	No
3146550	1002	INTELSAT 1002	LUCH (OLYMP)	3/3/16 7:44	Yes
3155271	1002	INTELSAT 1002	LUCH (OLYMP)	3/4/16 7:23	Yes
3155272	1002	INTELSAT 1002	LUCH (OLYMP)	3/5/16 7:29	No
3155273	1002	INTELSAT 1002	LUCH (OLYMP)	3/6/16 7:35	No
3155274	1002	INTELSAT 1002	LUCH (OLYMP)	3/7/16 7:44	No
3166089	1002	INTELSAT 1002	LUCH (OLYMP)	3/8/16 7:55	No
3328278	1002	INTELSAT 1002	LUCH (OLYMP)	3/14/16 7:04	No
3328279	1002	INTELSAT 1002	LUCH (OLYMP)	3/15/16 7:36	No
3328280	1002	INTELSAT 1002	LUCH (OLYMP)	3/15/16 20:19	No
3328281	1002	INTELSAT 1002	LUCH (OLYMP)	3/16/16 8:46	No
3328282	1002	INTELSAT 1002	LUCH (OLYMP)	3/16/16 19:01	No
3328283	1002	INTELSAT 1002	LUCH (OLYMP)	3/17/16 18:20	No
3345856	1002	INTELSAT 1002	LUCH (OLYMP)	3/18/16 5:49	No
3345857	1002	INTELSAT 1002	LUCH (OLYMP)	3/19/16 5:51	Yes
3345858	1002	INTELSAT 1002	LUCH (OLYMP)	3/20/16 6:06	Yes
3315415	1002	INTELSAT 1002	LUCH (OLYMP)	3/21/16 6:52	Yes
3315415	1002	INTELSAT 1002	LUCH (OLYMP)	3/21/16 6:52	No
3402287	1002	INTELSAT 1002	LUCH (OLYMP)	3/21/16 23:38	Yes
3315416	1002	INTELSAT 1002	LUCH (OLYMP)	3/22/16 6:52	Yes
3315416	1002	INTELSAT 1002	LUCH (OLYMP)	3/22/16 6:52	No
3432526	1002	INTELSAT 1002	LUCH (OLYMP)	3/22/16 20:24	Yes
3315417	1002	INTELSAT 1002	LUCH (OLYMP)	3/23/16 6:51	No
3315417	1002	INTELSAT 1002	LUCH (OLYMP)	3/23/16 6:51	No
3432527	1002	INTELSAT 1002	LUCH (OLYMP)	3/23/16 10:08	No
3432528	1002	INTELSAT 1002	LUCH (OLYMP)	3/23/16 17:58	No
3432529	1002	INTELSAT 1002	LUCH (OLYMP)	3/24/16 15:37	No
3453543	1002	INTELSAT 1002	LUCH (OLYMP)	3/26/16 2:40	Yes

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Table 2 displays alert data from Intelsat, with action threshold indicating whether LUCH's proximity required preventative action by Intelsat for safety of flight. In just a single month, dangerous operations by LUCH forced Intelsat to take preventive action to maintain flight safety 9 times. Cooperative satellite flight planning, open communications, and better operations management should be encouraged to prevent risks, damage, and high costs in space flight.

8. VULNERABILITIES AND SPACE DOMAIN AWARENESS DEGRADATION FROM ADVERSARY SPACECRAFT MANEUVERS

A mature Space Domain Awareness (SDA) system must maintain full awareness of when adversarial spacecraft operate or maneuver in a manner that poses a risk to important assets. Among the various ways of disabling or destroying spacecraft, one of the common ones is that of either (a) kinetic collision, (b) proximity-based explosion, or (c) rendezvous maneuvers leading to prevention of mission.

The "opportunity window" for employing such interceptors is time-dependent and varies as a function of target as shown in **Fig. 22**. Given sufficient inputs on the interceptor's capabilities, launch site(s), likely targets, and timing, one can see that it would be extremely valuable to be able to know what assets might be vulnerable at what times and locations.

From either one-on-one, one-on-many, or many-on-many combinations of chaser/target pairings, one can see that the risk could be evaluated using a threat assessment metric as shown in **Fig. 23**.

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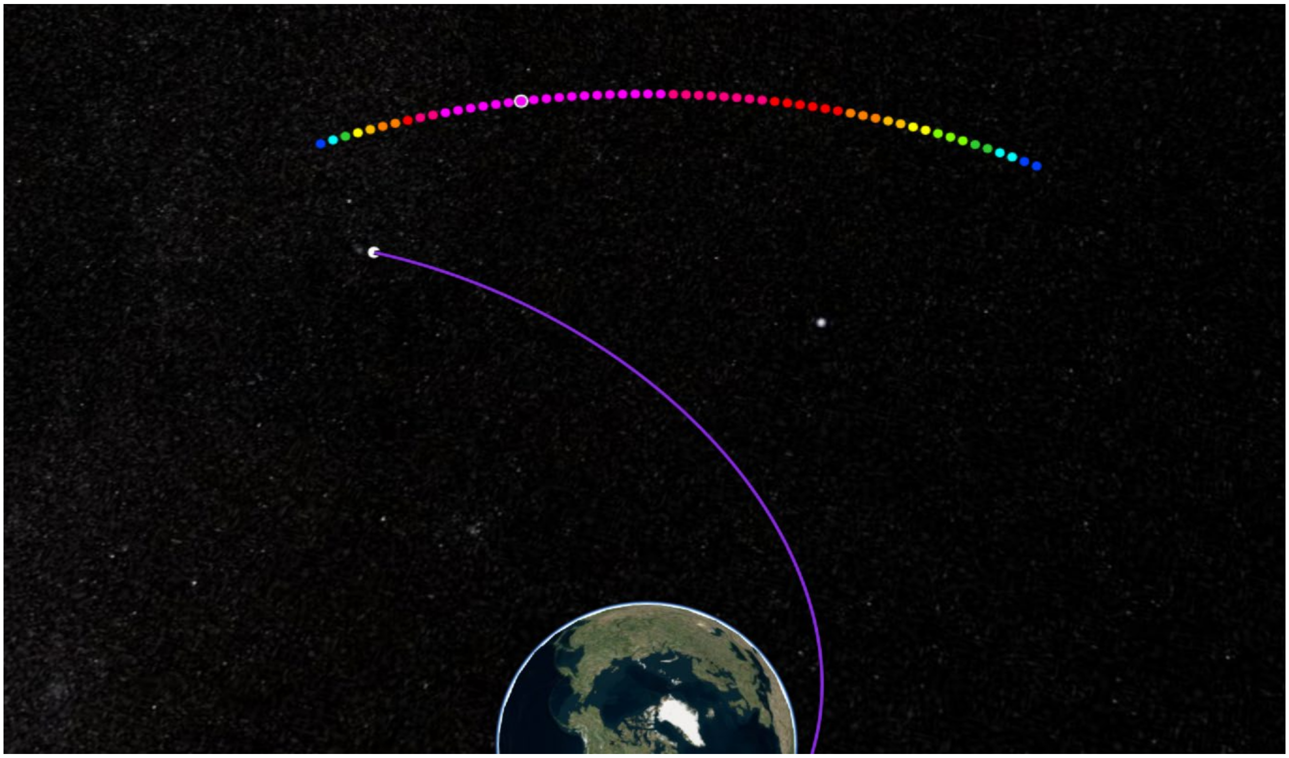

Fig. 22 - Kinetic interceptor target vulnerabilities in GEO, color-coded by overall vulnerability.

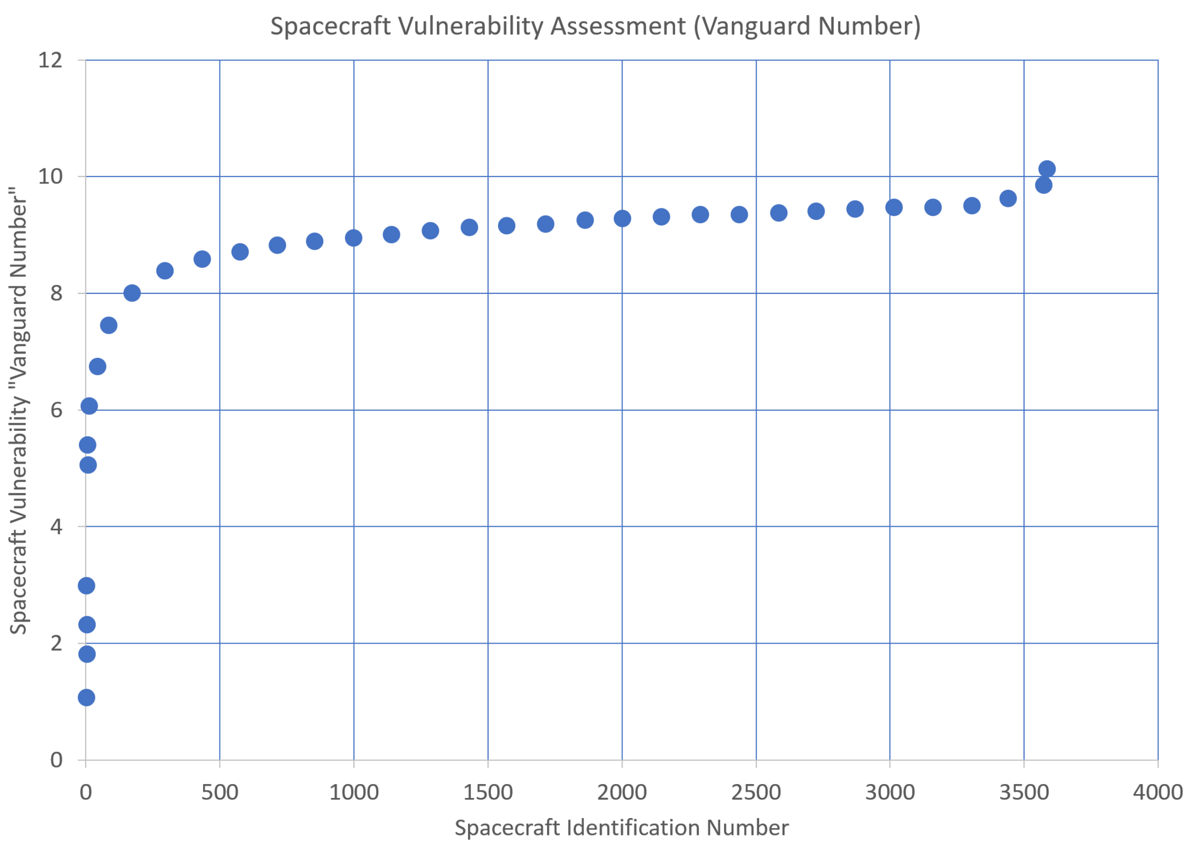

Fig. 23 – Threat vulnerability assessment metric for all chaser/target pairings of interest.

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9. SOLUTIONS

Spacecraft operators conduct launch, early orbit, stationkeeping, collision avoidance, and disposal maneuvers for a variety of disparate reasons. Stationkeeping strategies are not all the same. Early orbit checkout, phasing, and constellation insertion strategies differ. And as shown in Ref. [15], the triggers and even post-maneuver risk reduction targets for collision avoidance maneuvers are not harmonized across orbit regimes or even within an orbit regime. These differences cause an overall unpredictability in when and to what degree spacecraft operators or spacecraft onboard processors will decide to maneuver.

This inherent uncertainty in when maneuvers will occur can be addressed either:

a) **Reactively**, in which case one would want an ultra-responsive "Ferrari" approach that can rapidly adapt to unknown (or "non-cooperative") maneuvers by algorithmically detecting, characterizing, solving for, and refining them; or
b) **Proactively**, by comprehensive crowdsourcing and sharing of maneuver-relevant data and observations.

9.1 REACTIVE APPROACHES TO ADDRESS MANEUVER-INDUCED SSA DEGRADATION

The non-cooperative accommodation of maneuvers by commercial SSA systems such as COMSPOC is key to minimizing reaction time and not only maintaining track custody but also solution accuracy. Key elements of this include using a sequential filter that doesn't try to fit one or more maneuvering flight segment(s) with essentially maneuver-free orbits (as most Batch Least Squares OD methods are forced to do). But even with a filter, it's also critical that the filter itself incorporate the ability, in observation space, to detect and solve for the maneuver(s) that might have happened, and then further refine the estimated maneuvers as more observations come in as discussed in Ref. [12]. This leads to substantially reduced latency in maintaining a good positional knowledge post-maneuver, as was shown in the DOC GEO/MEO Pilot technical performance assessment [9, 10].

Fig. 24 shows the reaction time to a series of maneuvers (blue-shaded vertical boxes) for an active GEO spacecraft, comparing the reaction time of the BLS OD method that cannot model maneuvers with a sequential filter that can. In this plot, a 2+ day latency in recovery of the orbit is observed; we have often seen cases (including in the DOC GEO/MEO Pilot) where this recovery time can be as much as 5 days.

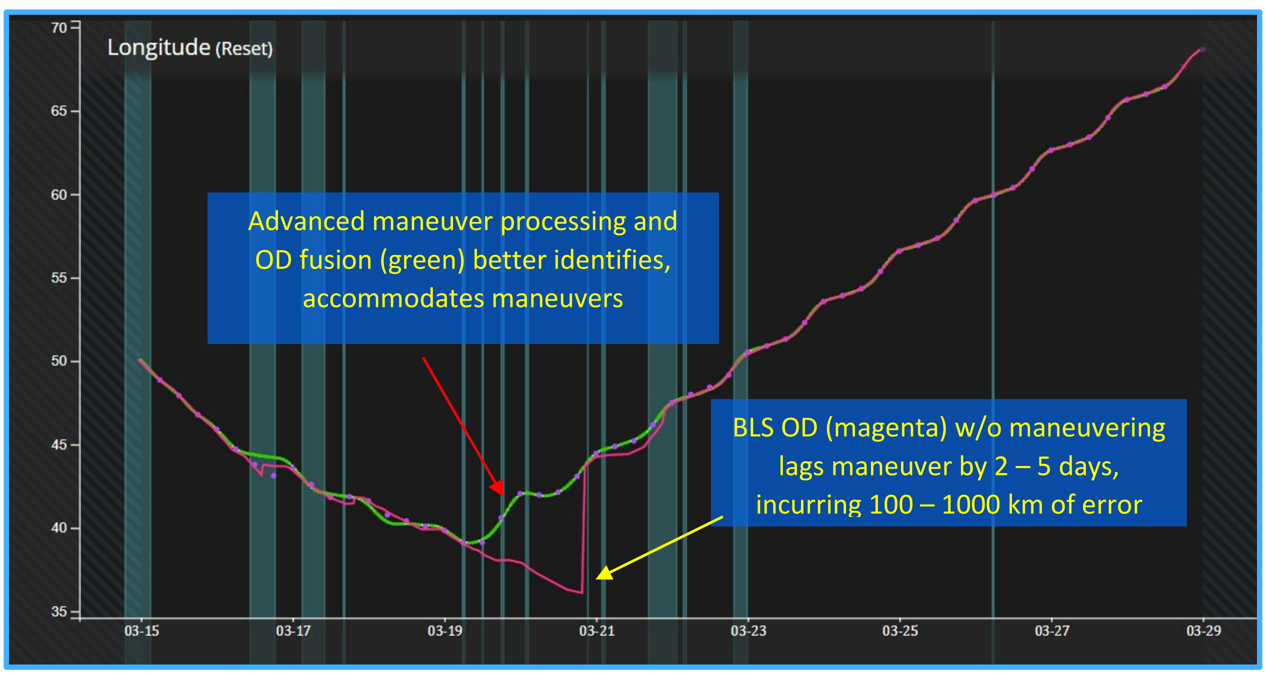

Fig. 24 - Comparison of post-maneuver reaction time between BLS OD without noncooperative maneuver processing and SF/EKF OD with noncooperative maneuver processing.

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9.2 PROACTIVE APPROACHES TO ADDRESS MANEUVER-INDUCED SSA DEGRADATION VIA DEEP COLLABORATION

As discussed in Section 3.2, SSA accuracy can be maintained by incorporating spacecraft operator planned maneuver data and observations using a comprehensive data fusion engine. By aggregating the accuracy trends for all active spacecraft involved in the DOC GEO/MEO Pilot across a statistically significant number of individual spacecraft, conclusions can be reached regarding the relevance, utility, and error profiles of the SSA products being used for these spacecraft. The one hundred spacecraft shown in **Fig. 25** yielded a plethora of data sets to be statistically analyzed over a three-week data collection period. Data fusion and track processing achieved for these 100 space objects is shown in **Fig. 26**, with each of the "Box" symbols located in the "Processed Tracks" column indicate that spacecraft owner/operator (O/O) tracking observations are being ingested by the SSA Suite and data fusion is accomplished in the Orbit Determination (OD) process. For each of the 100 spacecraft in the figure, one of the symbols typically denotes the operator's raw observations being ingested, with black symbols denoting GNSS operator data. Inclusion of COMSPOC optical data is represented by the grey symbols. As noted in the header of the figure, the absence of a symbol in the "Upcoming Maneuvers" box does not necessarily indicate that we aren't incorporating maneuvers into the solution, but rather that during the time in question, it can also indicate that the operator did not plan or conduct any maneuvers.

Generating meaningful accuracy statistics from all this accuracy data was accomplished via accumulating the error distribution as shown in **Fig. 27** for each SSA provider as a function of time. From such distributions, a percentiles-of-accuracy graph can be generated as shown in **Fig. 28** and **Fig. 29** (linear and logarithmic accuracy scales for GEO) and **Fig. 30** and **Fig. 31** (linear and logarithmic accuracy scales for MEO).

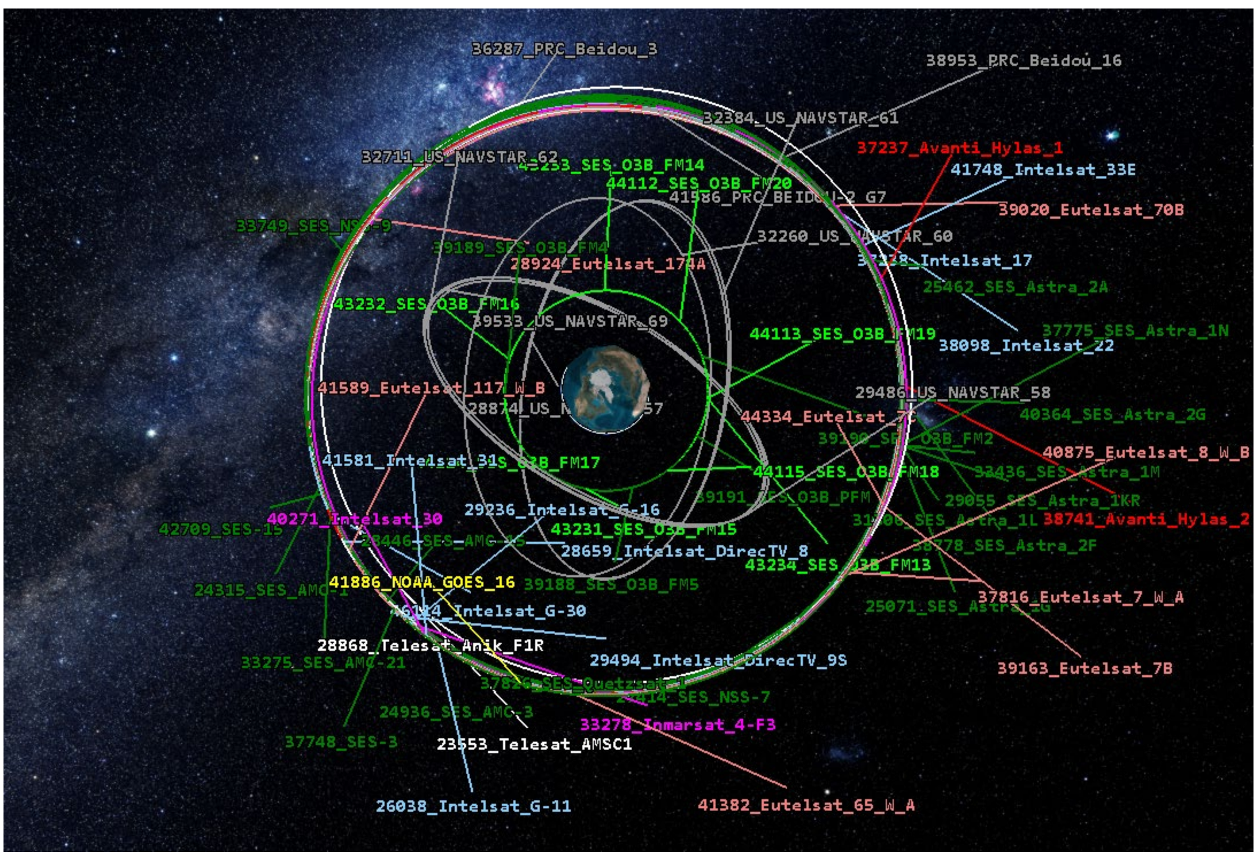

Fig. 25 - Depiction of 18 MEO and 82 GEO active spacecraft included in the DOC Pilot Program.

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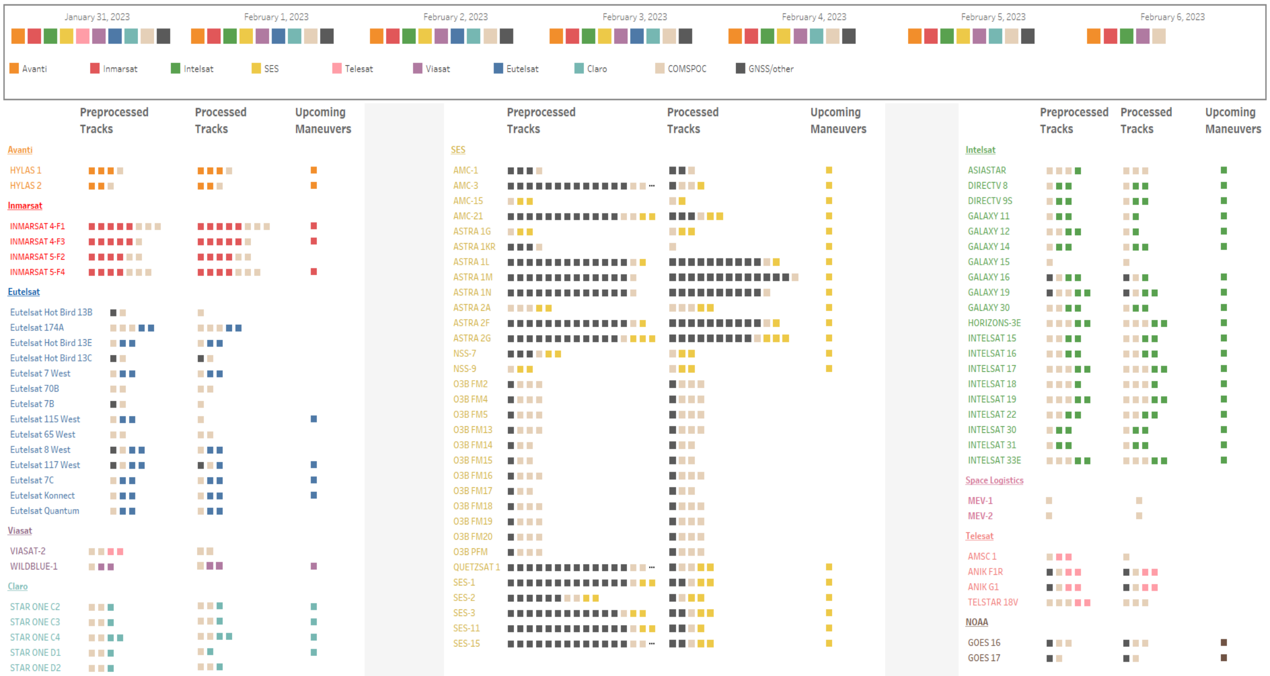

Fig. 26 - Satellite-specific data fusion achievements in the DOC Pilot Program.

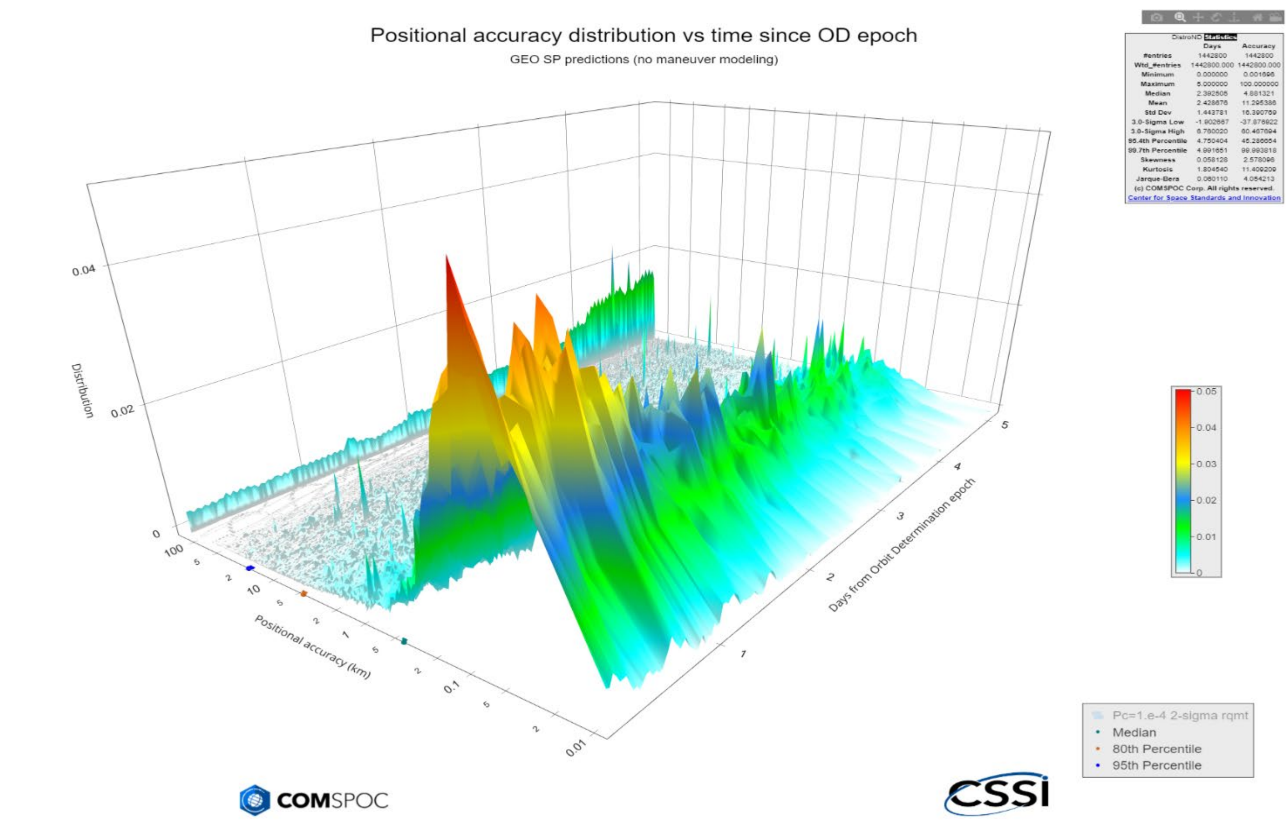

Fig. 27 - SP accuracy distribution for GEO spacecraft, 15 Jan to 4 Feb 2023 (linear accuracy scale).

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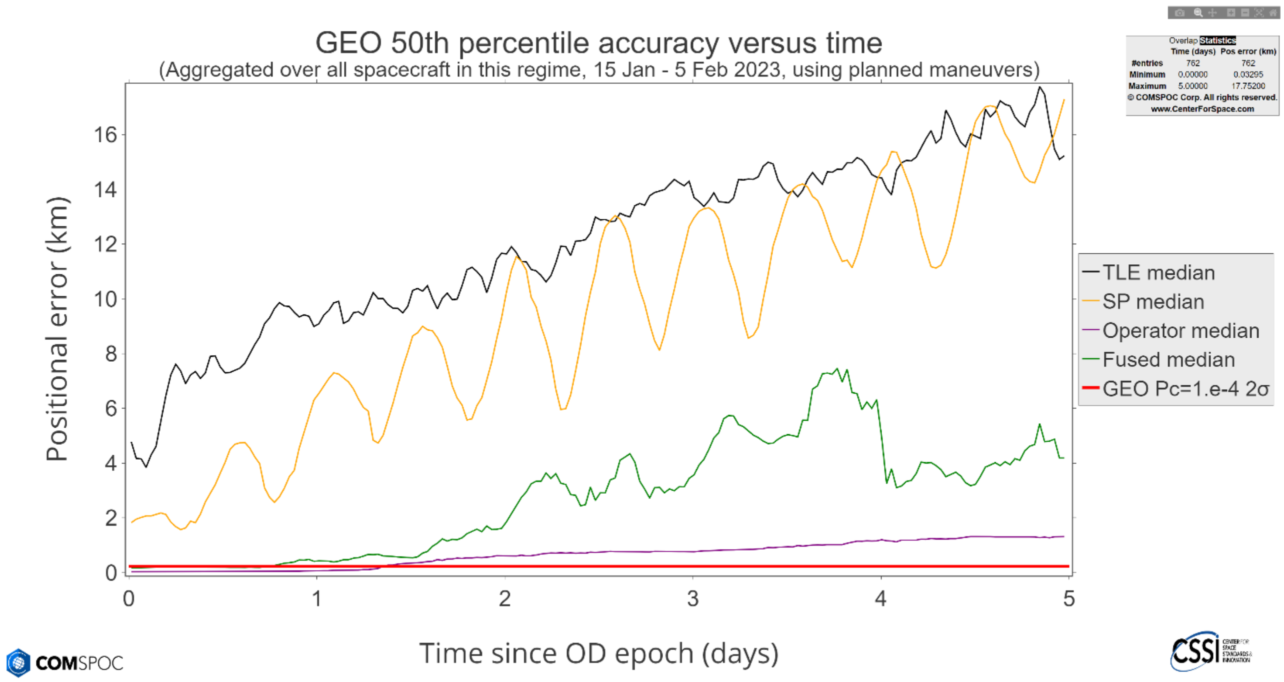

Fig. 28 - Typical accuracy of a variety of SSA products aggregated across six GEO independent 3rd party reference spacecraft (linear accuracy scale).

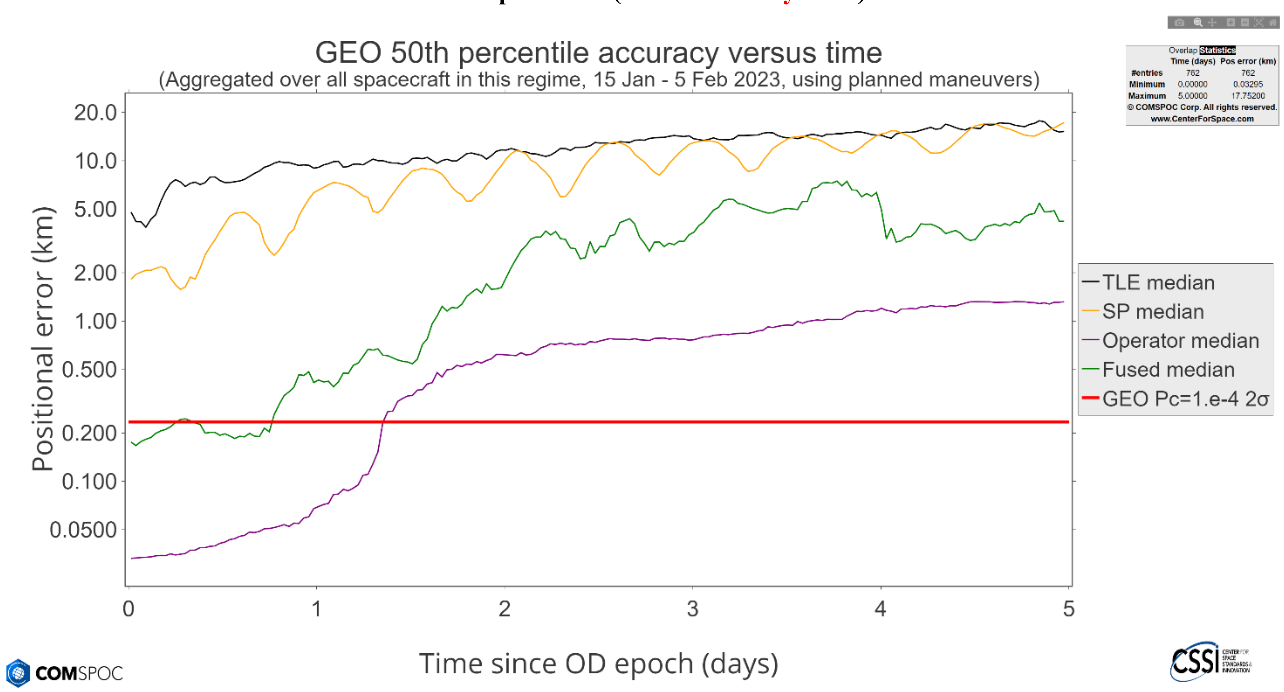

Fig. 29 - Typical accuracy of a variety of SSA products aggregated across six GEO independent 3rd party reference spacecraft (logarithmic accuracy scale).

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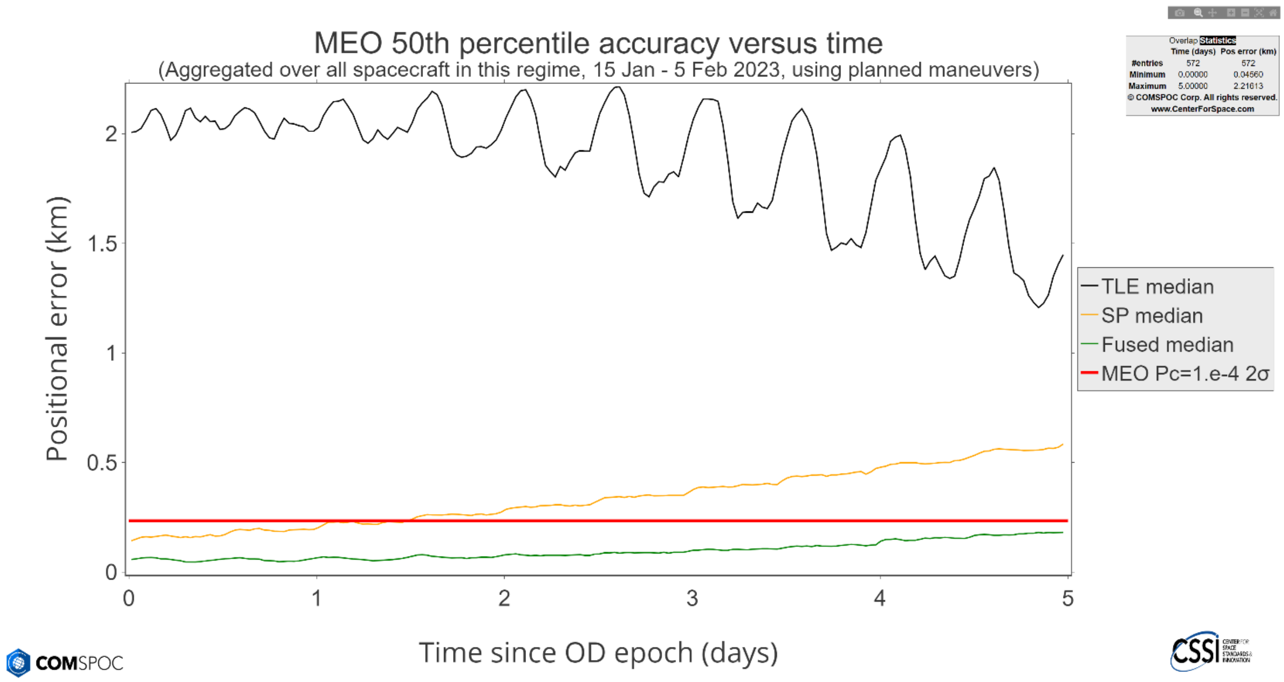

Fig. 30 - Typical accuracy of a variety of SSA products aggregated across six MEO independent 3rd party reference spacecraft (linear accuracy scale).

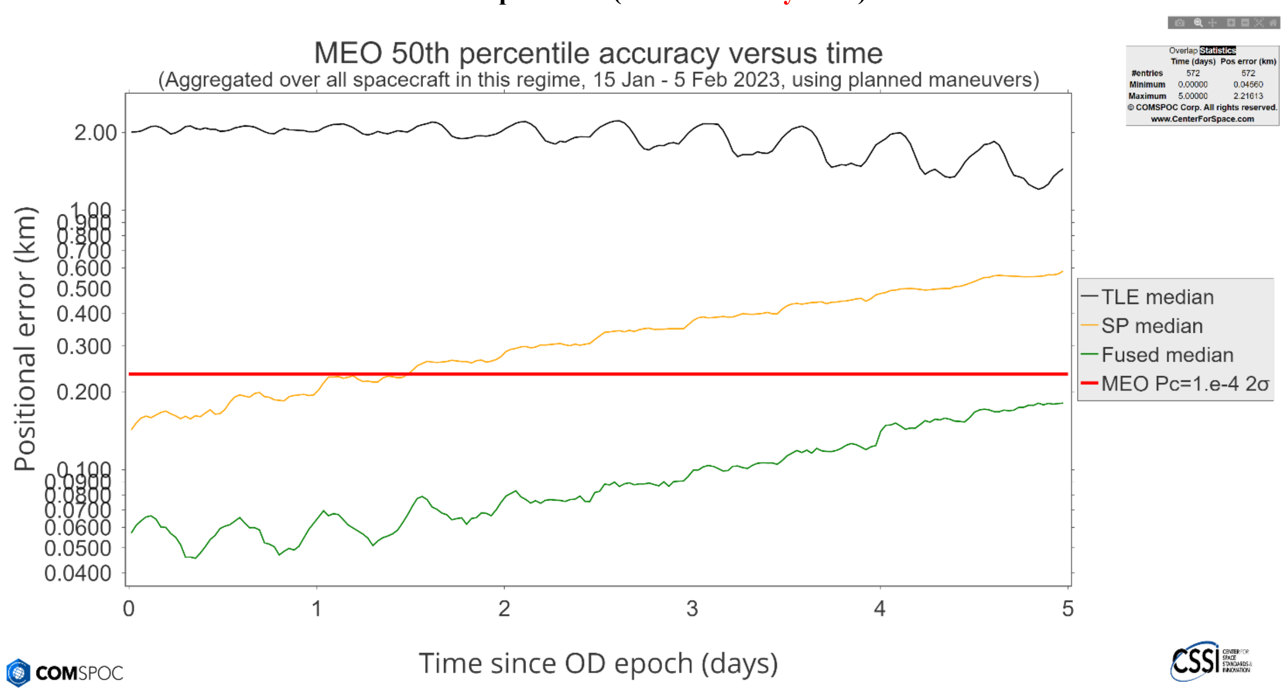

Fig. 31 - Typical accuracy of a variety of SSA products aggregated across six MEO independent 3rd party reference spacecraft (logarithmic accuracy scale).

Spacecraft that frequently maneuver pose even more challenges to SSA systems. It can even be difficult to fit a smoothed (post-facto) ephemeris in such cases. Consider **Fig. 32** and **Fig. 33**, which clearly separate the performance of BLS OD systems without maneuver modeling capabilities from SF/EKF systems that do model maneuvers.

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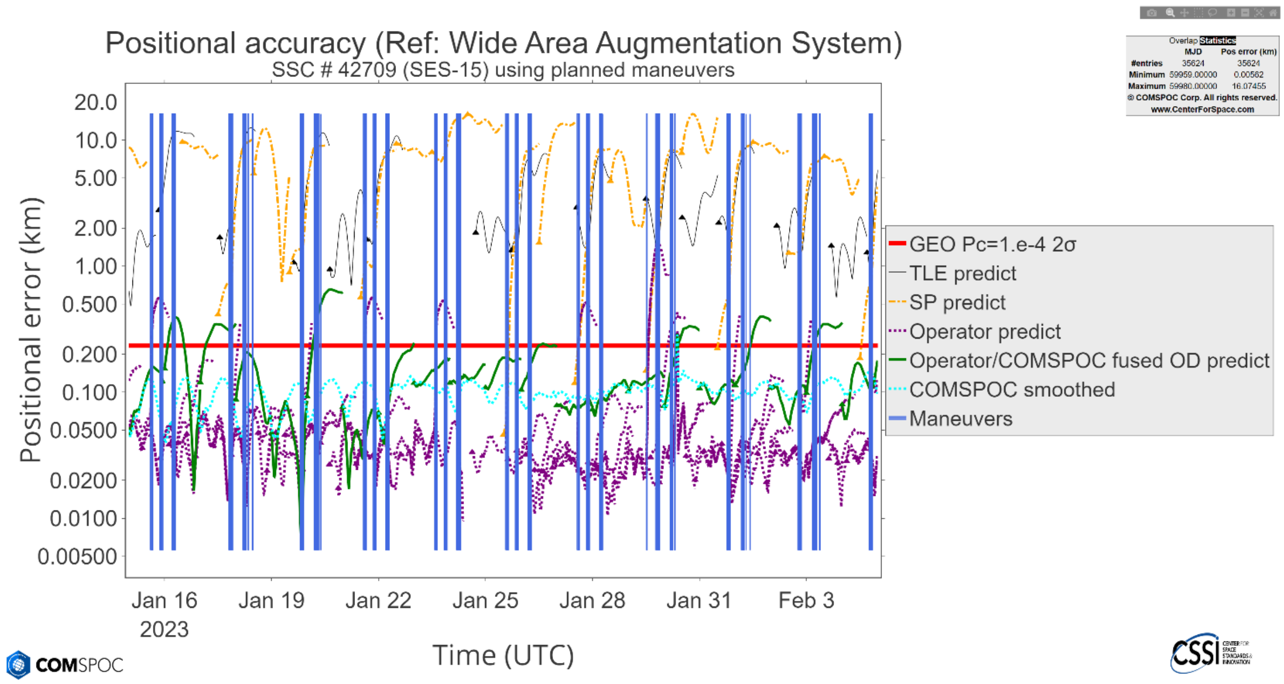

Fig. 32 - Median accuracy for various SSA products for frequently maneuvering SES-15.

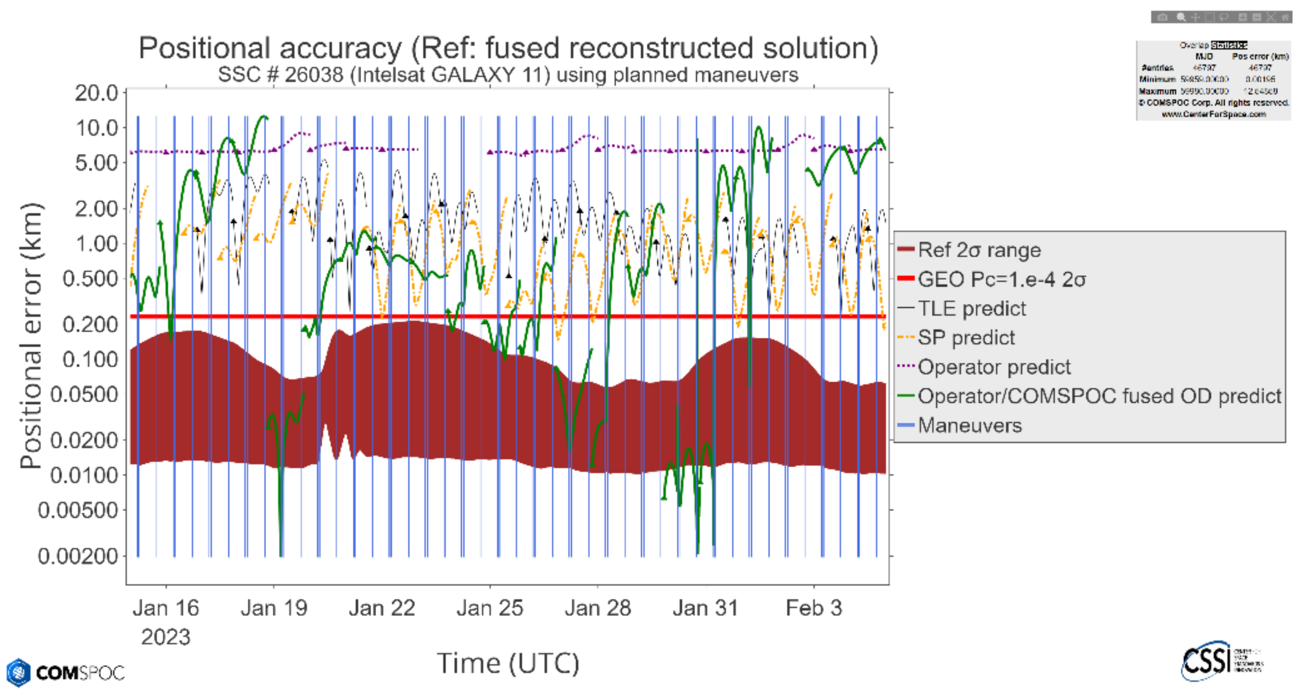

Fig. 33 - Median accuracy for various SSA products for frequently maneuvering Intelsat Galaxy 11.

Some argue that active maneuvering satellites are a small portion of the catalog overall and can be partitioned off as a special part of the catalog which gets advanced maneuver detection and estimation processing. Yet from both national security and space safety perspectives, some space objects that were classified as "space debris" turned out to be maneuver-capable satellites masquerading as debris, suddenly "awakening" and maneuvering to observe and/or passively or actively interfering with another satellite. This indicates that comprehensive SSA systems should avoid any preconceived notions that a resident space object is or is not debris or that it can or cannot maneuver.

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Furthermore, the same data fusion across government and commercial SSA systems is of direct benefit even for debris.

9.3 PROACTIVE APPROACHES TO ADDRESS MANEUVER-INDUCED SSA DEGRADATION VIA DEEP COLLABORATION

As discussed in Section 8, it is vital from an SDA perspective to know when and where chaser/interceptors pose imminent threats to one's assets. To enable this critical awareness step, maps of maneuver magnitude and direction and subsequent Time of Flight (ToF) to intercept can be made as shown in **Fig. 34** (produced by [Ref. 16]).

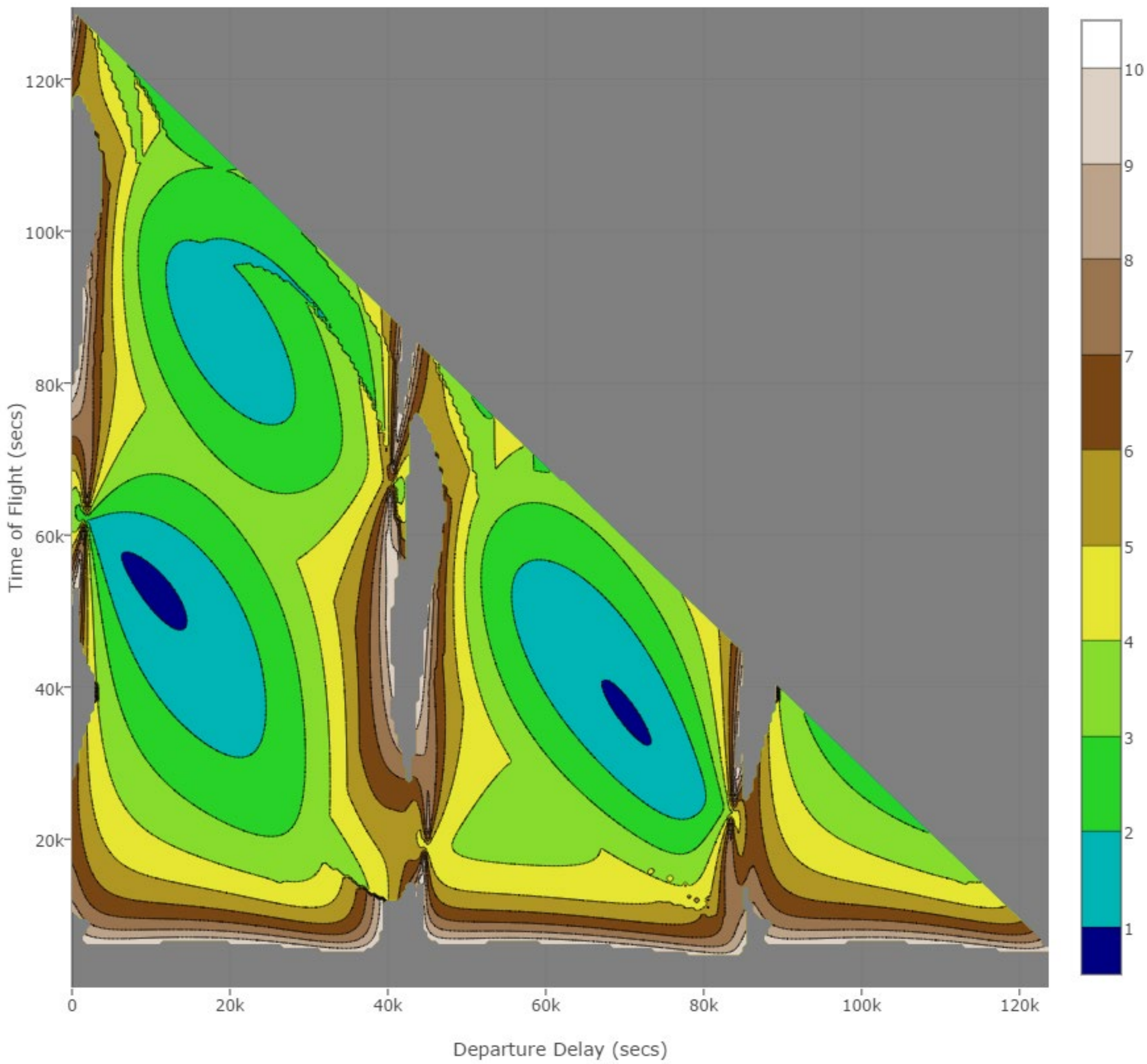

Fig. 34 – Vulnerability map of maneuver magnitude, direction, and subsequent ToF.

By maintaining these accurate maps for all chaser/target pairings of concern, one can observe whether any maneuvers conducted by an adversary's spacecraft are within family with one of its target opportunity windows, thereby allowing appropriate mitigation steps to be taken by the relevant asset(s). Such vulnerability analyses quickly and simultaneously provide mission assurance for any space-based system.

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10. CONCLUSION

This paper examined the SSA accuracy, timeliness, and safety degradations caused by maneuvers, maneuver uncertainties, and outdated orbit determination systems' inabilities to accommodate maneuvers in both Rendezvous and Proximity Operations (RPO) and normal spacecraft operations. Categories of SSA degradations caused by maneuvers that were discussed include:

- Unmodeled/mismodeled maneuvers
- Orbit determination through maneuvers
- Post-maneuver OD recovery challenges
- Position and covariance uncertainties predicted through future maneuvers
- Risk from unannounced spacecraft RPO and proximity stationkeeping maneuvers
- Vulnerabilities and Space Domain Awareness degradation from adversary spacecraft maneuvers

To address these SSA degradations and vulnerabilities, both cooperative and non-cooperative maneuver processing systems and concepts of operation are needed.

Non-cooperative systems have no knowledge of maneuvers and must therefore continually check for possible maneuvers – a very expensive computational operation. Effective maneuver processing tools in non-cooperative systems may miss numerous maneuvers due to observation timing, types of available data, etc. Obviously, an SSA system must have a rapid recovery capability to quickly react to unknown or mismodeled/unmodeled maneuvers. National security, flight safety, and sustainability all depend upon a non-cooperative maneuver detection, characterization, recovery, and refinement capability. But evidence provided here and in the referenced papers indicates that today's national systems cannot react quickly enough.

Cooperative systems have the advantage of knowing when maneuvers "may" occur, and experience significantly reduced computational burdens. Spacecraft operators are typically the best source for planned maneuvers, spacecraft characteristics, and potentially even raw observations. Our experience is that the vast majority (95% or more) of planned maneuvers occur as predicted, including low and electric thrust maneuvers. This can save considerable computational resources in operations over a non-cooperative system where considerable computational effort is required to constantly try to determine if a maneuver occurred.

In cases where advanced SSA service organizations and spacecraft operators can establish a deeply collaborative data sharing relationship, one can additionally foster:

a) Sharing of ephemerides, maneuver plans, astrometric observations, and spacecraft characteristics by spacecraft operators.
b) Incorporation of commercial SSA and government observational data.
c) Curation and fusion of such data by commercial SSA.
d) Orbit determination algorithms that recover quickly from maneuvers and support maneuver calibration.
e) Orbit propagation tools that can predict through planned maneuvers.
f) Data sharing standards development and widespread adoption.

From a technical perspective, existing high Technical Readiness Level (TRL) SSA systems can help gather the necessary input data and produce and maintain actionable SSA/SDA knowledge, allowing decisionmakers to mitigate SSA degradations caused by maneuvers and get the SSA data they need to make informed space safety and sustainability decisions.

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