DEEP OPERATOR AND SSA COLLABORATION FOR SPACE SUSTAINABILITY

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ABSTRACT

The Space Data Association (SDA) has been providing reliable flight safety products for approximately 30 spacecraft operators for 14 years now. The service provides conjunction warnings and operator points of contact for around 700 spacecraft occupying all orbital regimes. The SDA's Space Data Center (SDC), built by AGI and maintained and operated by COMSPOC Corporation, has a proven track record of providing high availability Space Traffic Coordination (STC) products since becoming operational on 15 July 2010.

Earlier this year, the SDA, and its chief technical consultant, COMSPOC Corporation, supported the U.S. Department of Commerce (DOC) GEO/MEO Pilot project by providing comprehensively fused orbit solutions, ten-day orbit ephemeris and covariance predicts, and smoothed reference ephemerides for 100 active spacecraft. Most of these spacecraft are operated by SDA members and participants, allowing the operators to collaboratively contribute their maneuver plans, GPS NavSol measurements, active ranging, and passive RF observations, and authoritative spacecraft dimensions to the DOC Pilot project. For its part, COMSPOC employed its SSA Software Suite to comprehensively fuse this diverse set of spacecraft operator observations with COMSPOC's own observations from its global network of optical sensors.

The first phase of this collaborative data fusion required the establishment of accounts, data connectivity, file transfer methods, and sensor calibration. This required about one month of technical interchange, provision of operator sensor locations and specifics, and COMSPOC SSS operator calibration of those sensors for each spacecraft.

But once the data flows, sensor calibrations, and maneuver readers were completed, the second phase drew upon a nearly continuous stream of fused observations and maneuvers to yield accurate and timely predictive ephemerides and covariance time histories. These data products are well-suited to the collision avoidance problem.

1. INTRODUCTION

Global space safety guidelines and governance [1] provide guidance and regulations designed to enable space safety and sustainability. But people often ask, "What is the most important thing to get right for [insert any STC, SSA, or Space Domain Awareness (also SDA) concern here]…" While the answers to such questions may help the questioner determine how to prioritize their actions, such questions can be dangerous, because they imply that (a) multiple courses of action are not achievable, and (b) if you address that "most important thing," all will be well. Both are usually incorrect assumptions. Such is the case for how to make Space Situational Awareness (SSA) data truly accurate, timely, comprehensive, available, and effective, or to enable space sustainability. Development of new sensors, new sensor phenomenologies, new algorithms, data fusion tools and approaches, collision probability [2,3], risk, and consequence metrics and thresholds, advances in and application of Artificial Intelligence and Machine Learning, and perhaps the eventual development of consensus Rules of the Road can all play a part in enabling SSA, STC, SDA, space safety, and sustainability (where those acronyms are as in [4]).

That said, we have learned through fourteen years of operations of the Space Data Center that several aspects are essential in order to achieve usable, effective, accurate, and timely SSA: (1) collaboration, both in between the spacecraft operators themselves, and between the Owner/Operator (O/O) community and the commercial and government SSA enterprises; (2) comprehensive exchange of SSA and spacecraft information, including ephemerides, historical and planned maneuvers, metric observations, and spacecraft dimensions; and (3) the comprehensive fusion of all available SSA and spacecraft operator information to achieve effective and actionable risk assessments.

2. MOTIVATION FOR COMPREHENSIVE DATA FUSION

The DOC's stated motivation for conducting the GEO/MEO Pilot was "to assess if commercial SSA and STM capabilities are essentially equivalent or better than the legacy flight safety products provided by

United States Space Force." The DOC's initial strategy for conducting this GEO/MEO Pilot is shown in **Figure 1**, whereby satellite operators would provide the de facto "truth" ephemerides for their spacecraft, incorporating their maneuver plans and including covariance time histories. There were several problems with this strategy, namely that (a) while many spacecraft operators have positional knowledge that is very accurate, this is not universally so; (b) spacecraft operators are typically unable to provide covariance information time histories.

Instead, the strategy shown in **Figure 2** was adopted, whereby authoritative spacecraft operator data was ingested by the COMSPOC SSA Software Suite and fused with COMSPOC optical observations to form a single integrated, fused solution. The benefits of this approach are that (a) all operator ephemerides would adopt a unified ephemeris format; (b) all operator ephemerides would include covariance time histories (which operators are largely unable to provide, but which is required in order to estimate collision probability); (c) automated scripting, once implemented and configured, would minimize disruption of the DOC Pilot on spacecraft operators; (d) a consistent orbit determination approach is used that uses internally-consistent force models, Earth Orientation Parameter (EOP) and Space Weather, statistical modelling, etc, and (e) that the OD could be invoked on the processing and delivery timescales of the DOC Pilot as opposed to spacecraft operator processing, networking, and staffing constraints.

Key challenges in implementing the strategy shown in **Figure 2** are indicated by the circled numbers, i.e.,

① Spacecraft operators obtaining approvals to share data and establish network connectivity via IT rules.

② Operators developing scripting to automate the regular/routine transfer of their sensor observations and planned maneuvers for selected sats at low latency.

③ COMSPOC configuration, including development of O/O tracking data readers based on operator format & frame, development of maneuver plan readers, calibration of all operator sensors before allowing use, and tailoring of spacecraft force models.

In a previous collaborative data fusion demonstration [9], the SDA/COMSPOC/USG team demonstrated that operationally fusing sensor and spacecraft data from a wide variety of disparate sources, sensors, sensor types, and networks greatly improves the accuracy of orbit solutions. Accordingly, our motivation for this campaign was to demonstrate, in the context of an initial DOC pathfinder, the benefits of processing data sourced entirely from the commercial space operator and commercial SSA community to determine what accuracy gains could be obtained by working together to address current SSA gaps [5]. A comparison of the two collaborative data fusion campaigns is shown in **Table 1**.

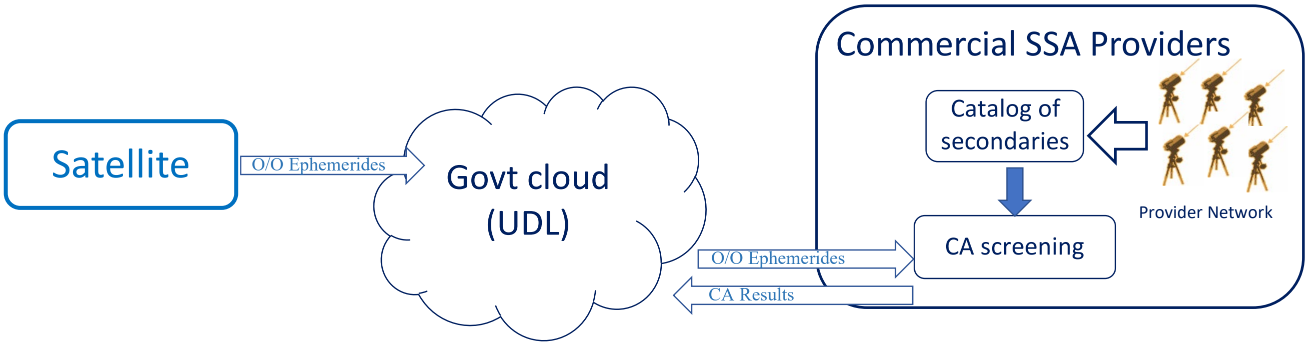


Figure 1: DOC's initial strategy for the GEO/MEO Pilot Program.

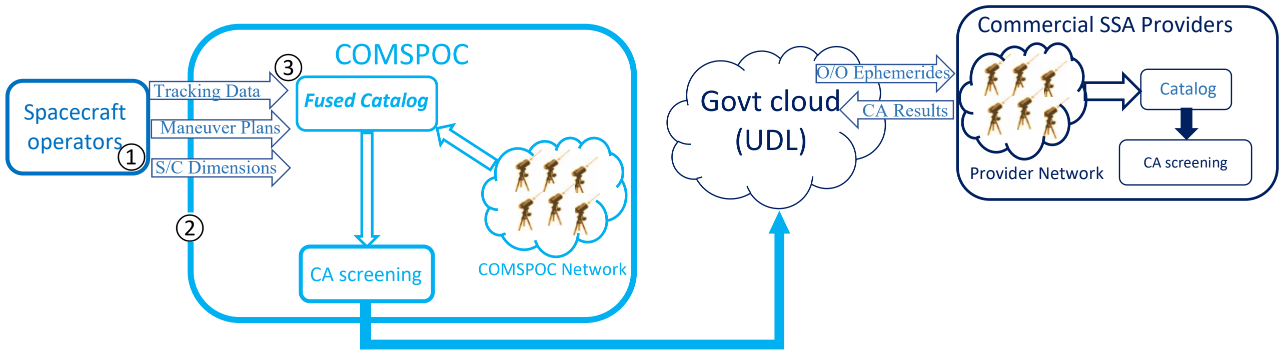


Figure 2: Adopted strategy for the DOC Pilot Program.

Table 1: Comparison of previous and current data fusion campaigns

Data Type	STCM Study (2020)	DOC Pilot (2022-2023)
Number of operators	5	9
Number of spacecraft	17	67**
Study duration (days)	14	60
Commercial SSA optical tracking	☑	☑ (COMSPOC only)
Commercial SSA radar tracking	☑	*
Commercial SSA passive RF	☑	*
Govt SSA (US SSN) radar and optical	☑	*
Operator ranging	☑	☑
Operator passive RF	☑	☑
Operator GNSS	☑ (Used for comparative analyses only)	☑
Operator planned maneuvers	☑	☑

*** DOC opted to exclude use of US Space Surveillance Network sensors for this first Pilot**

**** Initially tried for 100, but not all data flows & calibrations were completed within Pilot timeframe**

3. DOC GEO/MEO PILOT SCHEDULE

The overall schedule DOC GEO/MEO Pilot was:

Jun-Sep 2022	Start discussions and planning regarding potential concepts, framework, and contracting mechanisms for a DOC Pilot.
23 Sep 2022	DOC/SDA GEO/MEO Pilot discussion; SDA suggests 100 spacecraft suitable for the Pilot.
24 Oct 2022	DOC hosts meeting with commercial SSA data and analytics service providers
23 Nov 2022	DOC Pilot Program open solicitation posted on SDA Market Place. Responses due 4 Dec 2022.
4 Dec 2022	SDA and commercial SSA data and analytics service providers awarded roles in DOC Pilot, with SDA responsible to provide active satellite ephemerides including covariance and planned maneuvers.
5 Dec 2022	DOC Pilot Program begins.
4 Feb 2023	Original DOC Pilot termination date.
18 Feb 2023	DOC Pilot extended two weeks to gather more data for the government to evaluate.

4. COMPOSITION OF SDA-LED TEAM

A consortium of nine commercial and government space operators contributed their ephemerides (via the SDA) as well as their raw metric observations (transponder ranging, passive RF, GNSS), planned maneuvers, and spacecraft dimensions to a data fusion system, the SSA Software Suite, operated by COMSPOC for SDA. **Table 2** shows the contributions from each organization.

Table 2: Composition of SDA/COMSPOC team

Who	Eph	Obs	Mnvr Plans	S/C dim.	Data fusion agent	Cust-omer
DOC						✓
Space Data Association (SDA)						✓(sub)
COMSPOC					✓	
Avanti	✓	✓	✓	✓		
Claro	✓	✓	✓	✓		
Eutelsat	✓	✓	✓	✓		
Inmarsat	✓	✓	✓	✓		
Intelsat	✓	✓	✓	✓		
NOAA	✓	✓	✓	✓		
SES	✓	✓	✓	✓		
Telesat	✓	✓	✓			
Viasat	✓	✓	✓	✓		

5. 100 CANDIDATE SPACECRAFT

Today, the 32 spacecraft operators participating in the SDA operate 750 satellites in all orbital regimes (290 GEO and 460 in LEO/MEO). The SDA was asked by the DOC to recommend a diverse set of spacecraft for participation as "primary" spacecraft in support of the DOC Pilot project.

In response, SDA and COMSPOC selected and recommended the satellites shown in **Table 3** to support the DOC Pilot Program. Over the course of the Pilot, the SDA and COMSPOC Team provided approximately 6000 fused ephemerides containing positional knowledge on this set of 100 active spacecraft. Ninety of these spacecraft are operated by spacecraft operators who participate in the SDA (one government and 9 commercial), with an additional 10 spacecraft serving as third-party reference orbit sources operated by Japan, China, and the U.S.

Processing drew upon both the Space Data Center which has been in high availability operations since 2010, as well as recent SDC and SSA Suite enhancements[6] to comprehensively fuse multi-source observations (from spacecraft operators, commercial SSA data providers, and 3rd-party GNSS data) in keeping with the SDA goal to promote and enable crowdsourcing and fusion of diverse datasets to achieve actionable flight safety products.

Data fusion and track processing achieved for these 100 space objects is shown in **Figure 4**, with 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 denote 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.

6. ADOPTED START AND STOP TIMES FOR THIS EVALUATION

Although SDA notified DOC that 30 days would be required to prepare for full DOC Pilot support, DOC started the Pilot with one day's advanced notice. This led to challenges to get data flowing on short notice during a holiday season. The extensive sharing of data which is underpinning the SDA's fusion concept requires involvement of IT staff, modifications to firewalls, creation of automated upload scripts, creation of accounts on the COMSPOC system, in creation of data readers compatible with each submitted data format to normalize the data for ingest and processing.

Spacecraft operators needed slightly more time than the anticipated 30 days to set up the system, as they needed to get the required approvals and the necessary automation scripts in place. As well, the COMSPOC team needed a number of weeks to prepare the computer accounts, configure firewalls, and build data readers for the many different formats that spacecraft operators use. While some configurations and data flows happened much more quickly, it took until early to mid-January for most operators to flow their data. An advantage of this initial configuration effort is the ability to continue these data flows and data fusion mechanisms for future DOC pathfinder and operations support.

As we neared the official completion date of 4 February 2023, the government requested that DOC Pilot participants continue to send DOC their data for two additional weeks. Although DOC Pilot funding ended on 4 Feb 2023, COMSPOC agreed to continue sending data but was not able to staff the data quality monitoring and remediation efforts given that these two additional weeks were unfunded. This meant that for some of the 100 selected spacecraft, covariances and positional knowledge became degraded beyond 4 February.

With those engagement and scheduling realities in mind, we chose in this analysis to perform comparative SSA of DOC Pilot positional knowledge for the three-week period between 15 January to 4 February 2023.

7. THE DATA FUSION PROCESS

The data fusion, orbit determination, and comparative analysis process consisted of the six steps shown in **Figure 5**. In Step 1, we collected disparate, diverse data from spacecraft operators and COMSPOC's commercial SSA optical sensors and ingested those raw measurements into COMSPOC's comprehensive and technically mature data fusion engine. In Step 2, we developed accurate reference orbits for each space object participating in the demonstration. In Step 3 and 4, we gathered and differenced all orbit positional knowledge products with respect to the reference orbit as a function of time. In Step 5, we re-baseline all positional knowledge products to a common "time since OD epoch." And finally, in Step 6 we generated accuracy distribution statistics.

Data fusion is a complex topic that involves many factors. In Chapter 10 of [7], the overall topic of orbit determination is discussed. Many of the factors involved in data fusion are discussed in Sec 10.9 (Practical Considerations). The discussion goes through observation data, availability, quantity, location of observations, types of data, and observability considerations and how they apply to the overall OD accuracy.

The eleven participating organizations, spanning government and commercial arenas, did so with the goal of demonstrating the power of data fusion, and not in diminishing the value of any SSA product. These products all contribute to flight safety, sustainability, and operations. Overall, we found (as shown in Section 11) that comprehensive data fusion using a diverse set of tracking sensors coupled with advanced analytics typically yielded a seven-fold improvement in positional accuracy and timeliness in GEO, consistent with our prior data fusion in GEO of a tenfold improvement.

Table 3: SDA/COMSPOC team delivered both reconstructed and 10-day predict ephemerides and maneuver plans associated with these 100 active spacecraft, 67 of which were statistically evaluated for accuracy. Sorted by orbit regime (GEO/MEO), operator, and spacecraft name.

Sat #	Orbit Regime	SSC	Statistics generated in this analysis	Operator	Sat Name	SDA Participant	Independent third-party "truth" reference
1	GEO	37237	●	Avanti	Hylas 1	●	
2	GEO	38741	●	Avanti	Hylas 2	●	
3	GEO	32768	●	Claro (Embratel Star One)	Star One C2	●	
4	GEO	38991		Claro (Embratel Star One)	Star One C3	●	
5	GEO	40733		Claro (Embratel Star One)	Star One C4	●	
6	GEO	41904		Claro (Embratel Star One)	Star One D1	●	
7	GEO	49055	●	Claro (Embratel Star One)	Star One D2	●	
8	GEO	40425		Eutelsat	Eutelsat 115 WEST B	●	
9	GEO	41589	●	Eutelsat	Eutelsat 117 WEST B	●	●
10	GEO	28924	●	Eutelsat	Eutelsat 174A	●	
11	GEO	41382	●	Eutelsat	Eutelsat 65 WEST A	●	
12	GEO	37816	●	Eutelsat	Eutelsat 7 WEST A	●	
13	GEO	39020	●	Eutelsat	Eutelsat 70B	●	
14	GEO	39163	●	Eutelsat	Eutelsat 7B	●	
15	GEO	44334	●	Eutelsat	Eutelsat 7C	●	
16	GEO	40875	●	Eutelsat	Eutelsat 8 WEST B	●	
17	GEO	29270		Eutelsat	Eutelsat HOTBIRD 13B	●	
18	GEO	33459		Eutelsat	Eutelsat HOTBIRD 13C	●	
19	GEO	28946		Eutelsat	Eutelsat HOTBIRD 13E	●	
20	GEO	45027		Eutelsat	Eutelsat KONNECT	●	
21	GEO	49056		Eutelsat	Eutelsat QUANTUM	●	
22	GEO	23839		Inmarsat	INMARSAT 3-F1	●	
23	GEO	24307		Inmarsat	INMARSAT 3-F2	●	
24	GEO	24674		Inmarsat	INMARSAT 3-F3	●	
25	GEO	28628		Inmarsat	INMARSAT 4-F1	●	
26	GEO	33278	●	Inmarsat	INMARSAT 4-F3	●	
27	GEO	40384	●	Inmarsat	INMARSAT 5-F2	●	
28	GEO	42698		Inmarsat	INMARSAT 5-F4	●	
29	GEO	26107		Intelsat	ASIASTAR	●	
30	GEO	28659	●	Intelsat	DIRECTV 8	●	
31	GEO	29494	●	Intelsat	DIRECTV 9S	●	
32	GEO	26038	●	Intelsat	GALAXY 11 (G-11)	●	
33	GEO	27715		Intelsat	GALAXY 12 (G-12)	●	
34	GEO	28790		Intelsat	GALAXY 14 (G-14)	●	
35	GEO	28884		Intelsat	GALAXY 15 (G-15)	●	
36	GEO	29236	●	Intelsat	GALAXY 16 (G-16)	●	
37	GEO	33376		Intelsat	GALAXY 19 (G-19)	●	
38	GEO	46114	●	Intelsat	GALAXY 30 (G-30)	●	●
39	GEO	43633		Intelsat	HORIZONS-3E	●	
40	GEO	36106		Intelsat	INTELSAT 15 (IS-15)	●	
41	GEO	36397		Intelsat	INTELSAT 16 (IS-16)	●	
42	GEO	37238	●	Intelsat	INTELSAT 17 (IS-17)	●	
43	GEO	37834		Intelsat	INTELSAT 18 (IS-18)	●	

44	GEO	38356		Intelsat	INTELSAT 19 (IS-19)	●	
45	GEO	38098	●	Intelsat	INTELSAT 22 (IS-22)	●	
46	GEO	40271	●	Intelsat	INTELSAT 30 (IS-30)	●	
47	GEO	41581	●	Intelsat	INTELSAT 31 (IS-31)	●	
48	GEO	41748	●	Intelsat	INTELSAT 33E (IS-33E)	●	
49	GEO	42917	●	Japan	QZS-3 (MICHIBIKI-3)		●
50	GEO	41866	●	NOAA	GOES 16	●	
51	GEO	43226		NOAA	GOES 17	●	
52	GEO	38953	●	PRC	BEIDOU 16		●
53	GEO	36287	●	PRC	BEIDOU 3		
54	GEO	41586	●	PRC	BEIDOU-2 G7		●
55	GEO	24315	●	SES	AMC-1 (GE-1)	●	
56	GEO	28446	●	SES	AMC-15	●	
57	GEO	33275	●	SES	AMC-21	●	
58	GEO	24936	●	SES	AMC-3 (GE-3)	●	
59	GEO	25071	●	SES	ASTRA 1G	●	
60	GEO	29055	●	SES	ASTRA 1KR	●	
61	GEO	31306	●	SES	ASTRA 1L	●	
62	GEO	33436	●	SES	ASTRA 1M	●	
63	GEO	37775	●	SES	ASTRA 1N	●	
64	GEO	25462	●	SES	ASTRA 2A	●	
65	GEO	38778	●	SES	ASTRA 2F	●	
66	GEO	40364	●	SES	ASTRA 2G	●	
67	GEO	27414	●	SES	NSS-7	●	
68	GEO	33749	●	SES	NSS-9	●	
69	GEO	37826	●	SES	QUETZSAT 1	●	
70	GEO	36516		SES	SES-1	●	
71	GEO	42967		SES	SES-11 (ECHOSTAR 105)	●	
72	GEO	42709	●	SES	SES-15	●	●
73	GEO	37809		SES	SES-2	●	
74	GEO	37748	●	SES	SES-3	●	
75	GEO	#N/A		Space Logistics	MEV-1 (901)	●	
76	GEO	#N/A		Space Logistics	MEV-2 (10-02)	●	
77	GEO	23553	●	Telesat	AMSC 1	●	
78	GEO	28868	●	Telesat	Anik F1R	●	
79	GEO	39127		Telesat	Anik G1	●	
80	GEO	43611		Telesat	TELSTAR18V(APSTAR 5C)	●	
81	GEO	42740		ViaSat	Viasat-2	●	
82	GEO	29643	●	ViaSat	WildBlue-1	●	
83	MEO	43234	●	SES	O3B FM13	●	
84	MEO	43233	●	SES	O3B FM14	●	
85	MEO	43231	●	SES	O3B FM15	●	
86	MEO	43232	●	SES	O3B FM16	●	
87	MEO	44114	●	SES	O3B FM17	●	
88	MEO	44115	●	SES	O3B FM18	●	
89	MEO	44113	●	SES	O3B FM19	●	
90	MEO	39190	●	SES	O3B FM2	●	
91	MEO	44112	●	SES	O3B FM20	●	
92	MEO	39189	●	SES	O3B FM4	●	
93	MEO	39188	●	SES	O3B FM5	●	
94	MEO	39191	●	SES	O3B PFM	●	
95	MEO	28874	●	US	NAVSTAR 57 (USA 183)		●
96	MEO	29486	●	US	NAVSTAR 58 (USA 190)		●
97	MEO	32260	●	US	NAVSTAR 60 (USA 196)		●
98	MEO	32384	●	US	NAVSTAR 61 (USA 199)		●

99	MEO	32711	●	US	NAVSTAR 62 (USA 201)		●
100	MEO	39533	●	US	NAVSTAR 69 (USA 248)		●

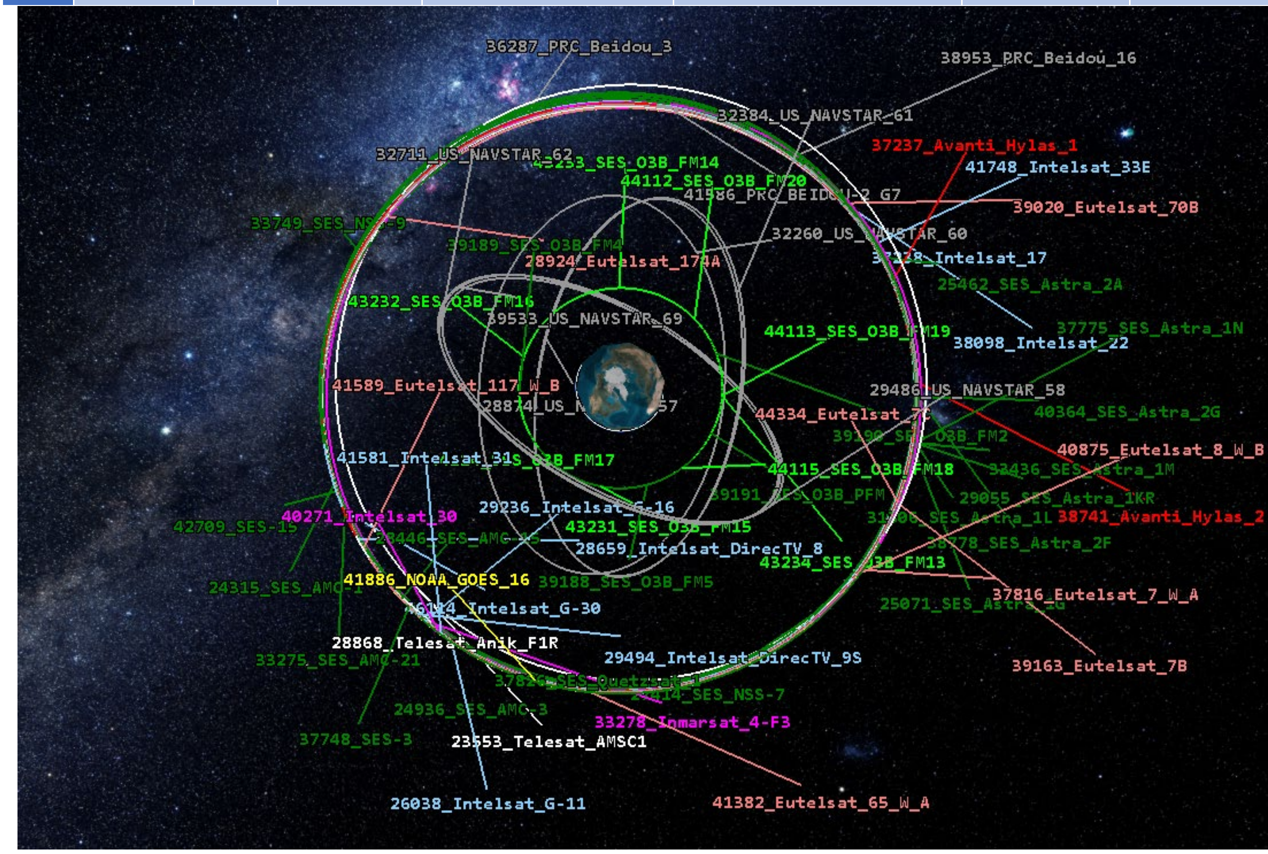


Figure 3: Depiction of 18 MEO and 82 GEO active spacecraft included in the DOC Pilot Program.

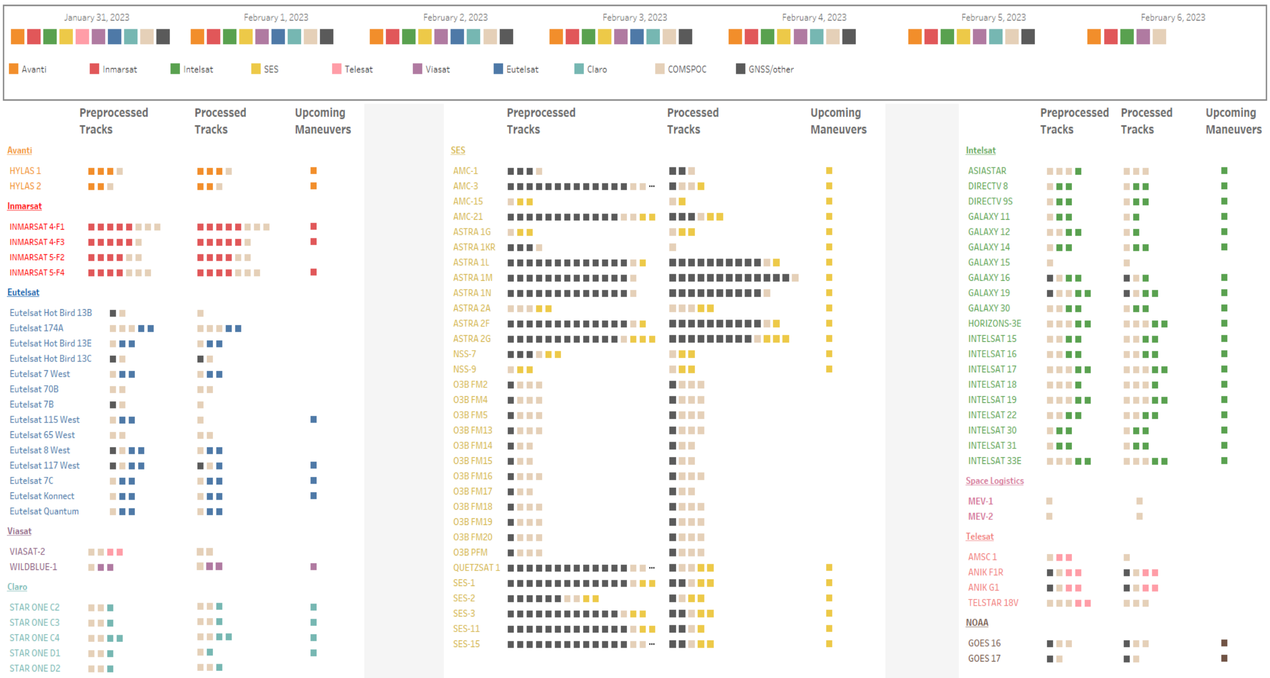


Figure 4: Satellite-specific data fusion achievements in the DOC Pilot Program.

8. REFERENCE ORBIT DEVELOPMENT AND ACCURACY

Absolute positional accuracy of SSA products can be assessed once one has access to an accurate "truth" (or nearly so) reference orbit. Such third-party independent reference orbits are based upon GPS Navigation Solution (NavSol) data, Wide Area Augmentation System (WAAS) data, passive Radio Frequency (RF) observations, and data-rich tracking observations from numerous, diverse sensors. In GEO, the number of available high-accuracy reference ephemerides (step 3 in **Figure 5**) has been declining as WAAS spacecraft have had their WAAS service turned off and not been replaced.

It is important to characterize the estimated accuracy of such reference orbits. The higher accuracy reference orbits are based upon laser ranging, WAAS, GPS and passive RF data. A characterization of the major and minor 2σ error range versus time for a GEO reference orbit is shown in **Figure 6**, which indicates that the 2σ positional knowledge associated with this particular reference ephemeris ranges between 25 and 120 meters, which means that the error is usually well below 120 meters (i.e., such that more than 70% of the time the accuracy is perhaps 40 meters or better when averaged across the three-week DOC Pilot statistical evaluation period and across all viewing orientations). These reference orbits provide a statistically significant set of "truth" data that can be used to conduct positional error assessments (as presented in the next section). Note how maneuvers (vertical blue lines) may introduce uncertainty in one's positional knowledge.

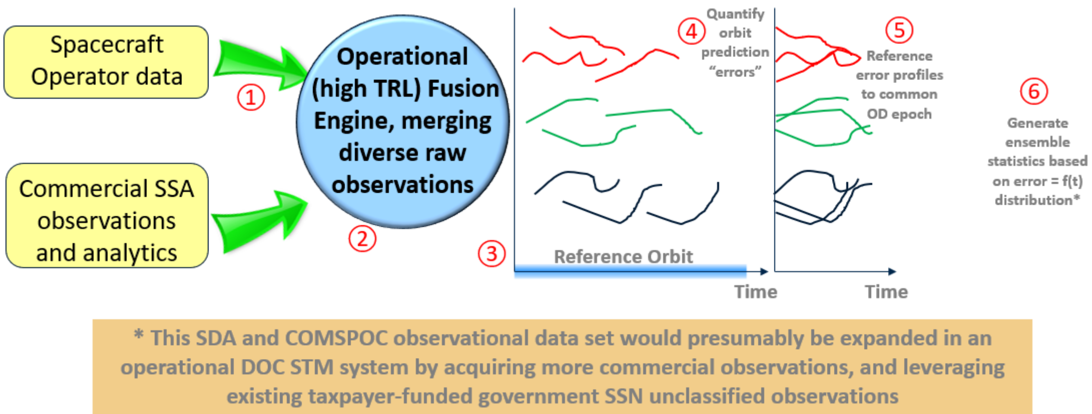


Figure 5: Data fusion and accuracy assessment analysis steps.

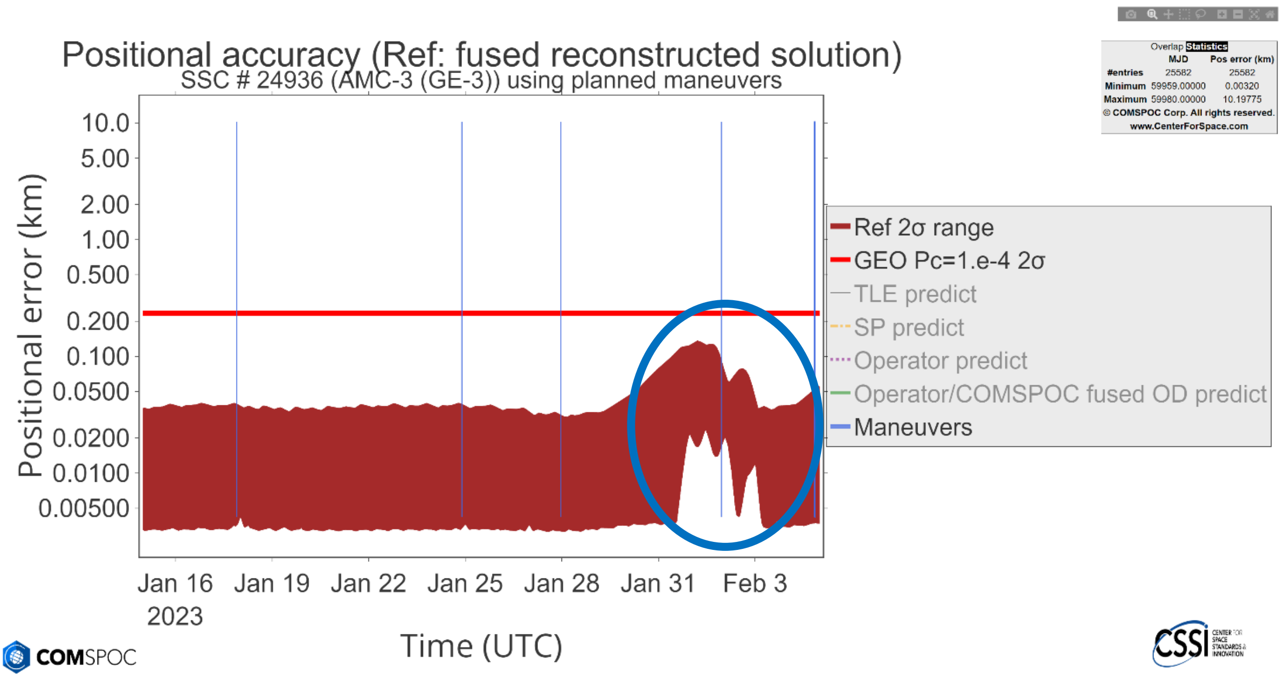


Figure 6: Reference orbit major and minor eigenvalue-based 2-sigma boundaries (in red).

9. SSA DATA TYPES EVALUATED

Four SSA/orbit prediction sources were analyzed in the SDA's data fusion process. They are:

- Two-Line Element sets (or TLEs) that are based on optical and radar but have no planned maneuvers or other data sources incorporated.
- Special Perturbations (SP) ephemerides that use a higher fidelity propagator but are otherwise based upon the same observational data as TLEs (again typically without planned maneuvers).
- Spacecraft operators' ephemerides, which typically draw from a more diverse set of observation types, with some operators combining their ranging measurements with passive RF, GPS (navigation solution or NavSol), and even optical measurements with their planned maneuvers.
- The fused orbit solution incorporated optical, active ranging, passive RF, GPS/NavSol, and planned maneuvers.

10. ASSESSING TLE, SP, OPERATOR, AND FUSED POSITIONAL ACCURACY

With such reference orbits in hand, the accuracy (i.e., positional error) of a variety of SSA and orbit products is shown in **Figure 7** and **Figure 8**, corresponding to Step 4 in **Figure 5**. The smaller the positional error, the better the flight safety alerts will be, and the more actionable and effective the result.

Many accuracy analysis results were generated stemming from this DOC Pilot Program. As these results are voluminous, they have been placed in Appendix 1 (comparisons with third-party reference trajectories) and Appendix 2 (comparisons with COMSPOC's post-reconstruction.

In this section, we want to familiarize the reader with the accuracy plot format (see **Figure 7** as an example) adopted for characterizing accuracy of the MEO and GEO active spacecraft involved in the DOC Pilot Program. 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 [8] of one in ten thousand as a conjunction screening threshold (as derived in [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 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 this maneuver, 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 **Figure 8**. 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.*

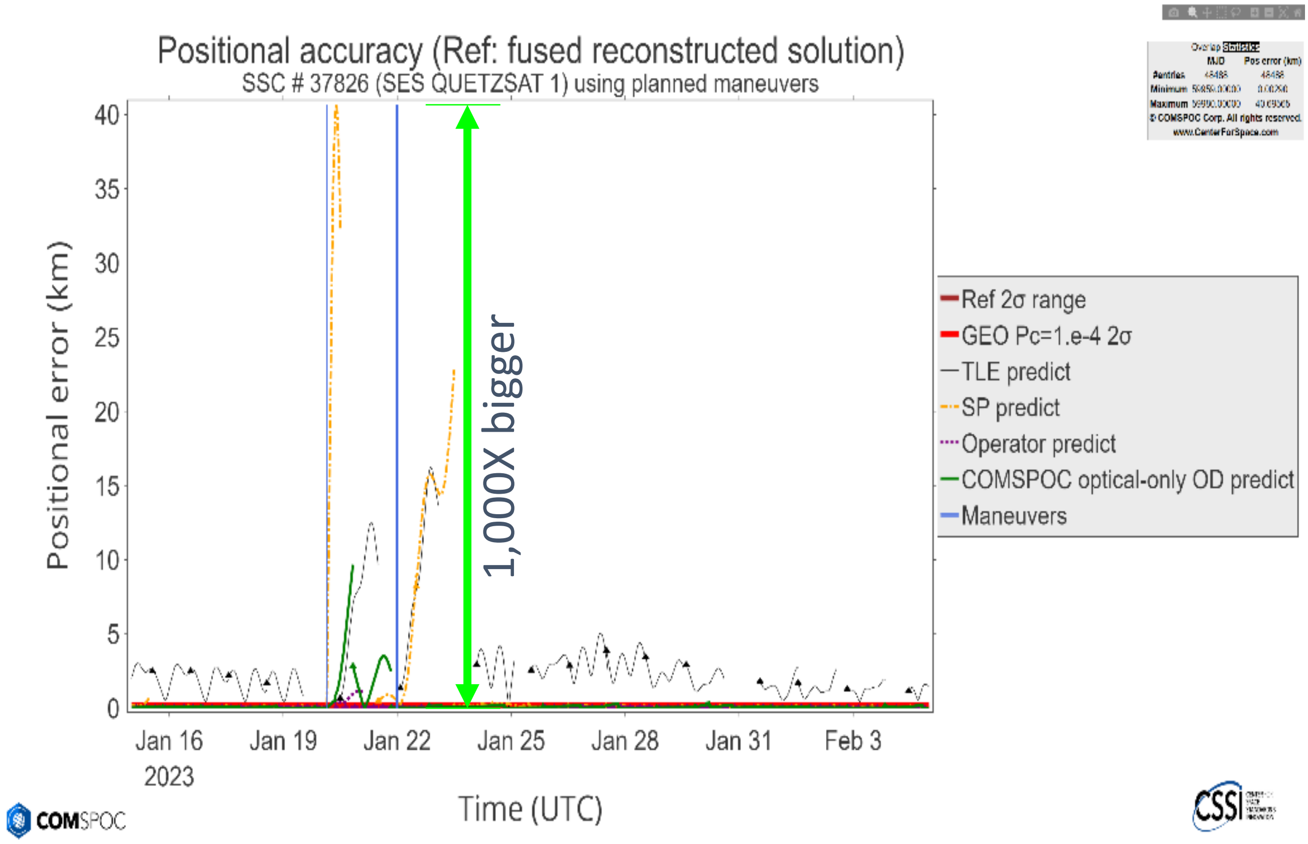


Figure 7: Example of STCM demonstration predict accuracy on a linear y-axis scale.

Using the log scale, the operator's ephemerides (dotted purple) and the SDA/COMSPOC Fused Solution are clearly visible. In this case, it appears that the planned maneuver was incorporated into the fused orbit prediction. But planned maneuvers don't always occur as planned; it is common that some errors will be introduced by a maneuver event.

And finally, we can add the reference orbit's 2σ error ranges from **Figure 6** to obtain the full (and "busy") accuracy plot format as shown in **Figure 9**.

While the SDA/COMSPOC team strove to comprehensively fuse and process the 100 spacecraft listed in **Table 3**, we ended up fully processing and statistically assessing performance for sixty seven spacecraft as indicated by the "•" symbols in column 4 of **Table 3**. A variety of issues (incomplete or sporadic data flows, lack of time to fully calibrate, or delays in obtaining the operator's management approval to share data) caused some spacecraft to not be processed and fused.

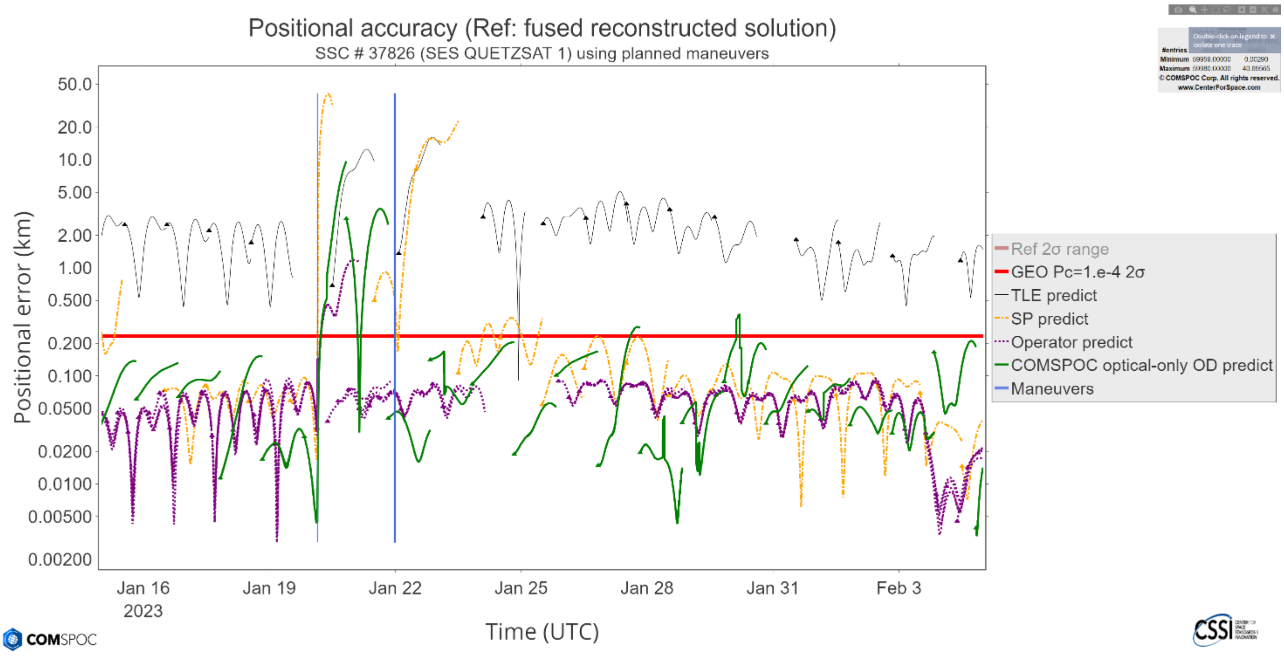


Figure 8: Example of STCM demonstration predict accuracy on a logarithmic y-axis scale.

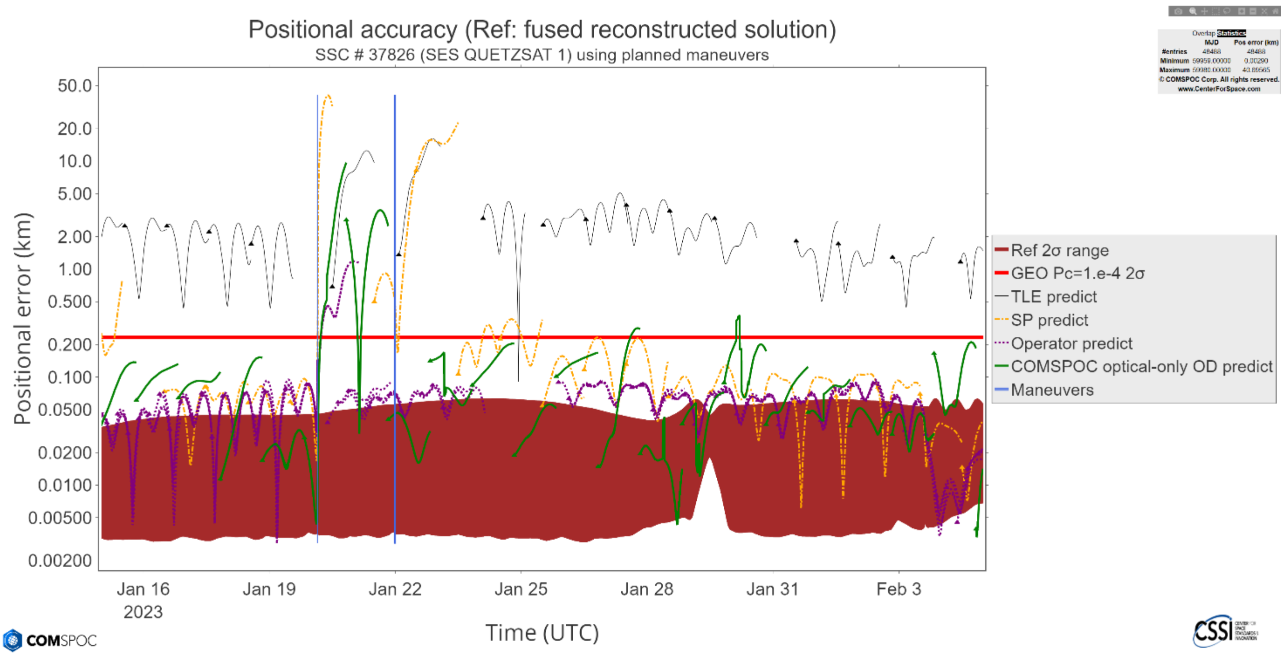


Figure 9: Complete format including major and minor eigenvalue 2-sigma range (in red).

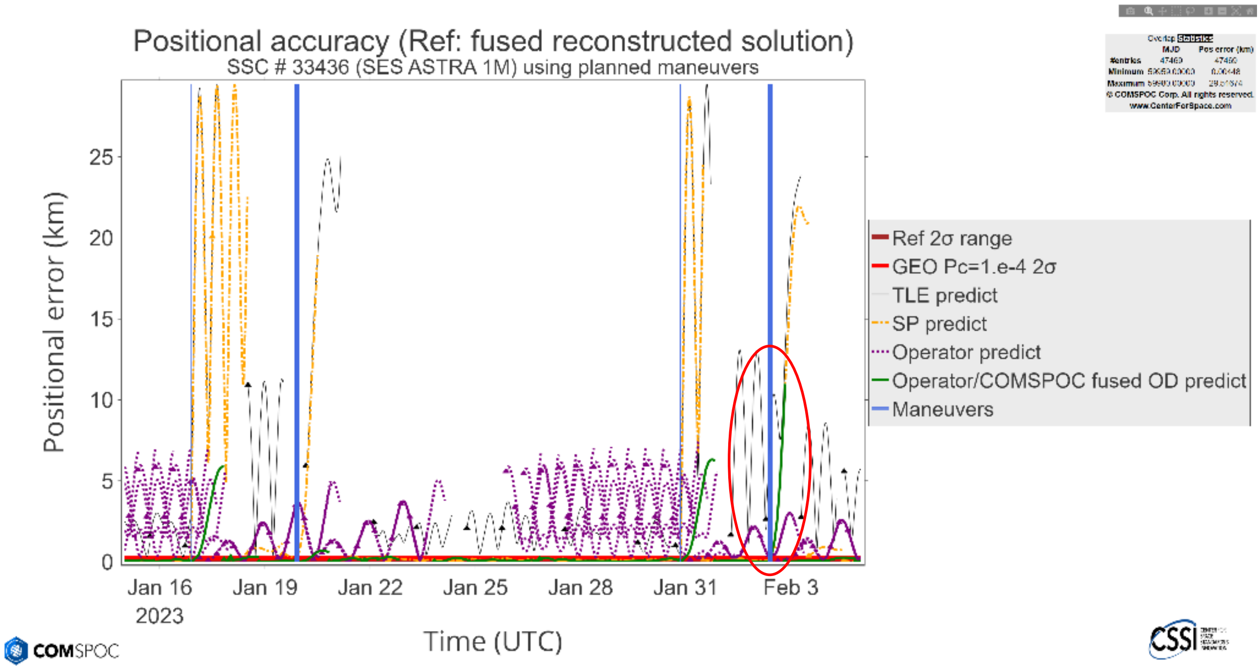


Figure 10: Maneuver adversely impacts SP and Fused solutions; ≈2km operator bias (logarithmic scale).

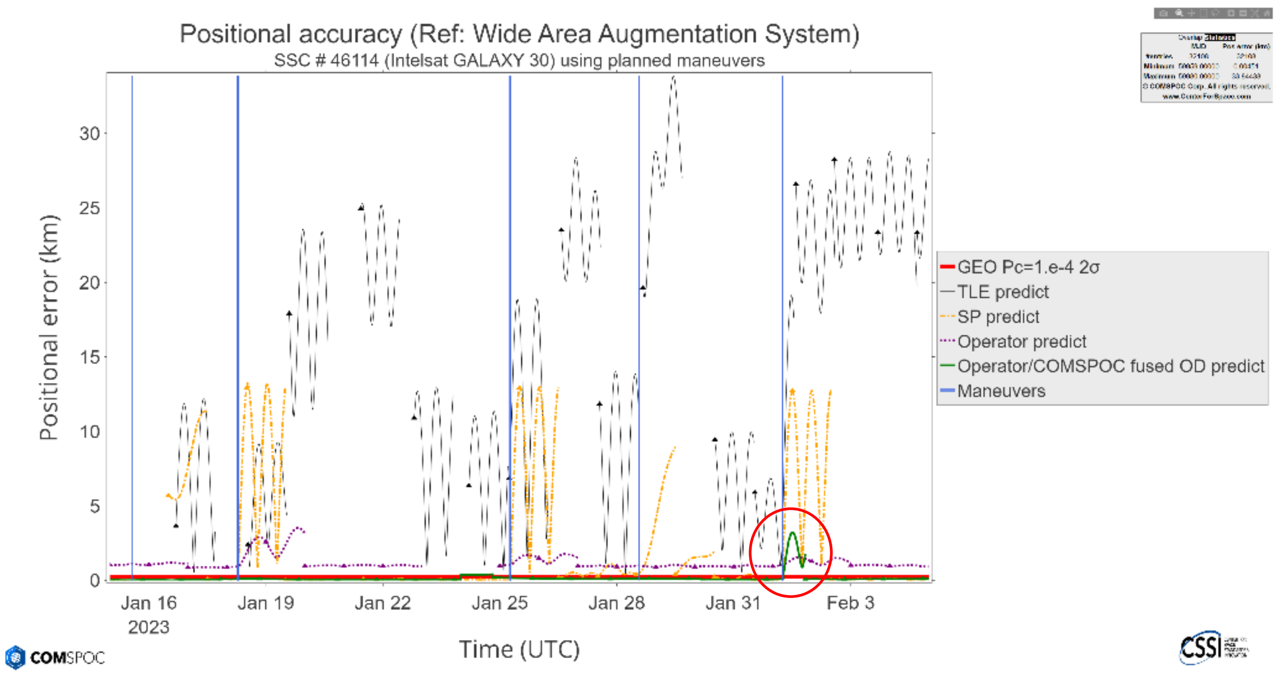


Figure 11: Example of non-cooperative maneuver processing quickly recovering an accurate fused solution.

11. RESULTS

11.1. INDIVIDUAL ACCURACY ASSESSMENTS FOR ALL 67 SPACECRAFT

The full set of accuracy results for these 67 spacecraft during this three-week DOC Pilot demonstration are provided in two appendices. Characterizations of TLE, SP, O/O, and COMSPOC-fused products for the twelve third-party reference spacecraft are provided in Appendix 1 (Figures 28 - 51), whilst characterizations based upon COMSPOC's reconstructed ephemerides for the remaining 55 spacecraft are provided in Appendix 2 (Figures 52 - 161).

While the COMSPOC data fusion team did take steps after the DOC Pilot concluded to see if OD configuration settings and propagation/force models could be better calibrated for each spacecraft, the plots contained in Figures 28 - 161 reflect only the estimated accuracy of the delivered SDA/COMSPOC fused solutions as posted to the UDL.

These plots help identify capability and performance strengths and "gaps" for each of the four SSA data sources analysed in this study. Maintaining accurate positional knowledge on space objects is indeed very challenging, and no system is immune to SSA degradations. We will explore some of the sources of these degradations in a later section.

11.2. STATISTICAL AGGREGATION OF SSA ACCURACY AGAINST 3RD-PARTY "TRUTH"

When the above positional accuracy characterizations are aggregated 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. Relevant to the DOC GEO/MEO Pilot, these 67 spacecraft and this three-week data collection time yielded a plethora of data sets to be statistically analysed.

We begin by aggregating the error distribution shown in **Figure 12** for each SSA provider as a function of time for the twelve spacecraft for which independent third-party reference orbits can be obtained. Such an accuracy assessment against independent "truth" is of particular importance because it alleviates the potential for these statistical accuracy analyses to be somehow biased by using reconstructed ephemerides generated by one of the SSA provider systems (i.e., COMSPOC) used in parallel to generate predicted orbit ephemerides being statistically compared herein. From such distributions, a percentiles-of-accuracy graph can be generated as shown in **Figure 13** and **Figure 14** (linear and logarithmic accuracy scales for GEO) and **Figure 15** and **Figure 16** (linear and logarithmic accuracy scales for MEO).

These four plots are among the most important findings of this paper, characterizing the typical (or median) performance for these various SSA products for the MEO and GEO orbit regimes.

It is not surprising that the limited accuracy of the TLE SGP4 analytic theory (shown in the black line) does not fare as well as the other products at OD epoch. As a mean element theory, SGP4 does "ok" in many applications, but it cannot handle maneuvers either past or future. But a further interesting result is that this TLE accuracy does not appear to degrade as quickly as some other products in longer-term propagations (notably with SP).

In GEO, the SDA/COMSPOC comprehensive data fusion process yielded a substantial accuracy improvement over both TLE and SP products, **with the fused solution typically seven times better in positional accuracy than legacy products at the 50th percentile.**

In MEO, the **SDA/COMSPOC fused products were typically a factor of three better than the SP product**. One might think that this large improvement stems from having spacecraft operator maneuver plans and observations. But for these 6 MEO GPS satellites, no such data was available or incorporated. The accuracy gains were purely driven by using an advanced sequential OD filter with limited COMSPOC observations.

Note that most of the statistical assessments presented in this paper correspond to the median 50th percentile performance. There's nothing magical about the median value, beyond the fact that it represents "typical" performance. At the same time, statistics for all cases for both 3rd party reference and non-reference spacecraft were also generated at the 80th and 95th percentiles as shown in **Figure 17** and **Figure 18** respectively; these were omitted from the paper for space considerations.

11.3. CONCLUSIONS FOR 3RD-PARTY "TRUTH" SPACECRAFT

While the details that underlie these individual and statistical results indicate that every SSA product has strengths and weaknesses, the commercial spacecraft operator and SSA provider fused product typically performs at least as well as legacy SSA products (i.e., TLEs and SP), if not substantially better. Despite only drawing upon COMSPOC's relatively modest global network of optical telescopes combined with spacecraft operator observations, accuracy improvements of between three and seven were seen. This amply meets the DOC's Pilot objective of demonstrating that commercial SSA analytics and orbit determination capabilities are at least equivalent and often superior to legacy SSA projects and are therefore sufficiently mature and ready to be applied to STCM.

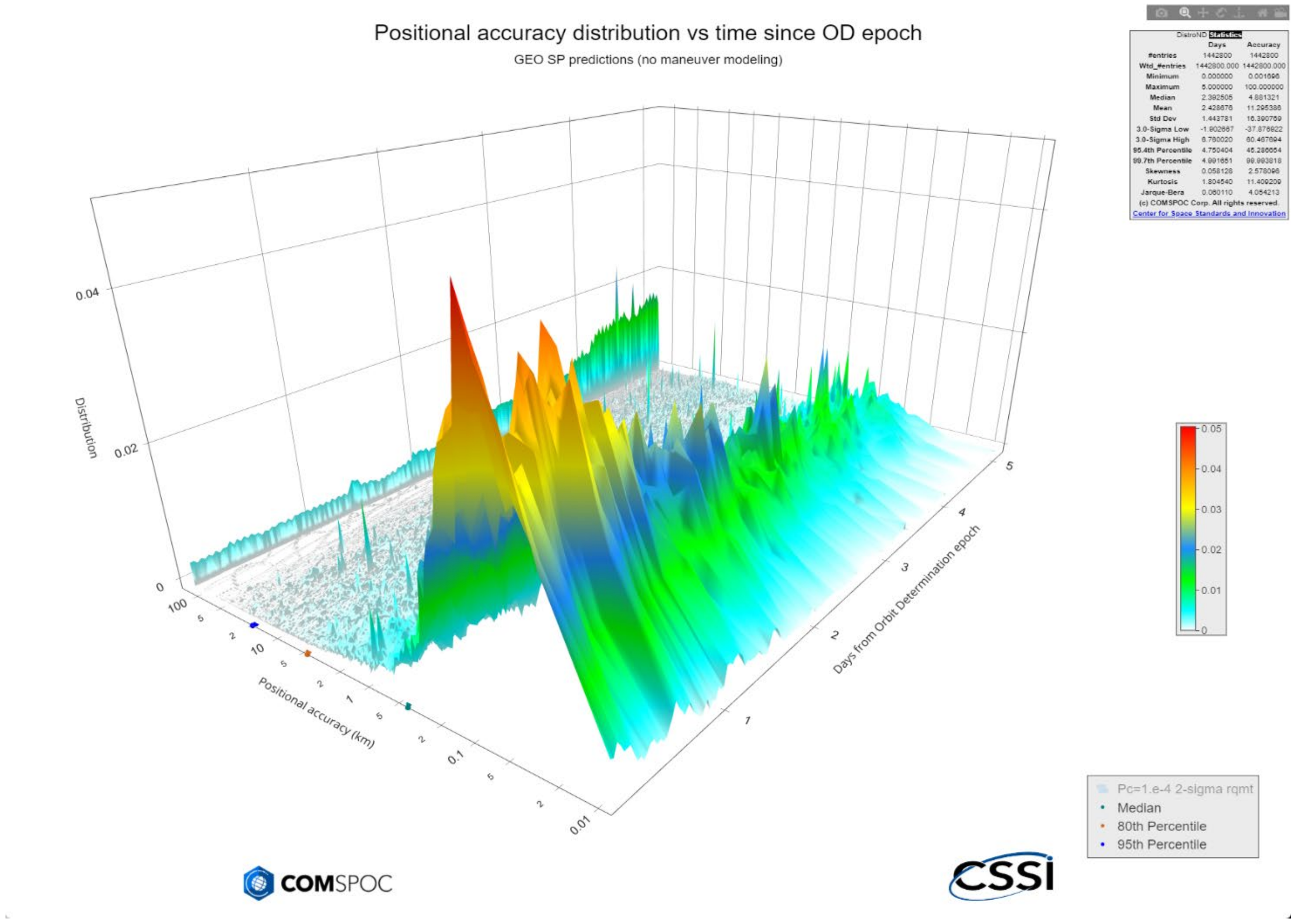


Figure 12: SP accuracy distribution for GEO spacecraft, 15 Jan to 4 Feb 2023 (linear accuracy scale).

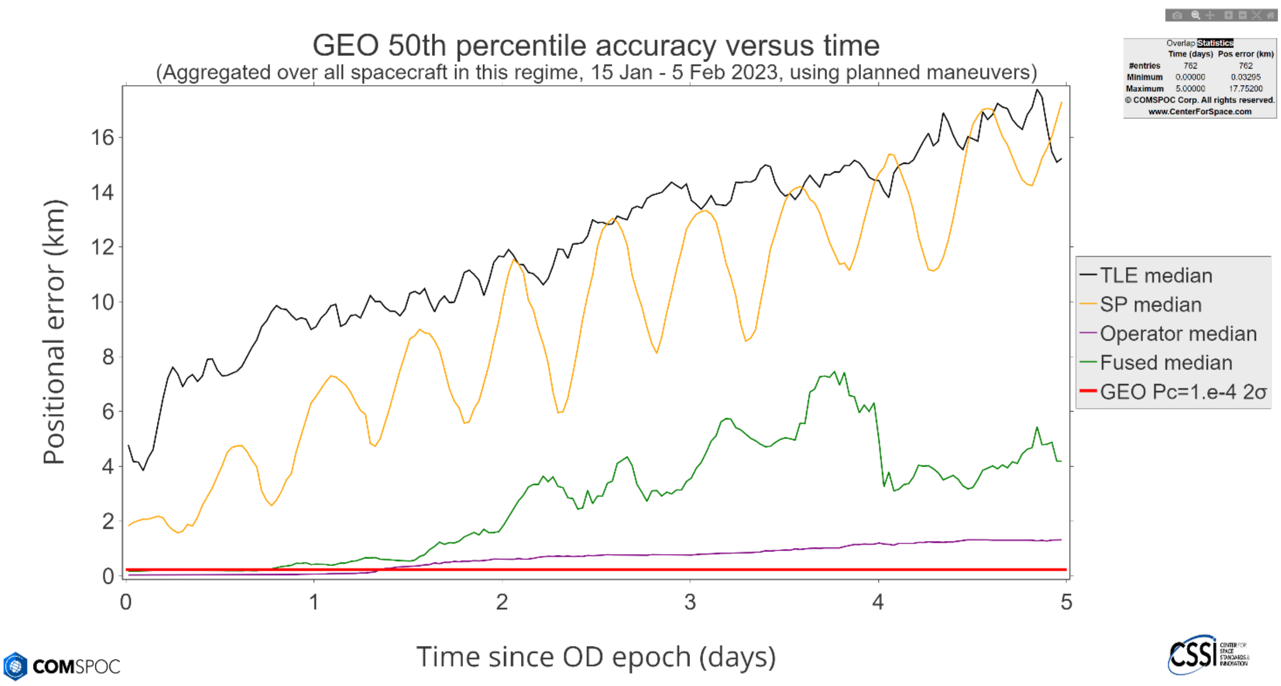


Figure 13: Typical accuracy of a variety of SSA products aggregated across six GEO independent 3rd party reference spacecraft (linear accuracy scale).

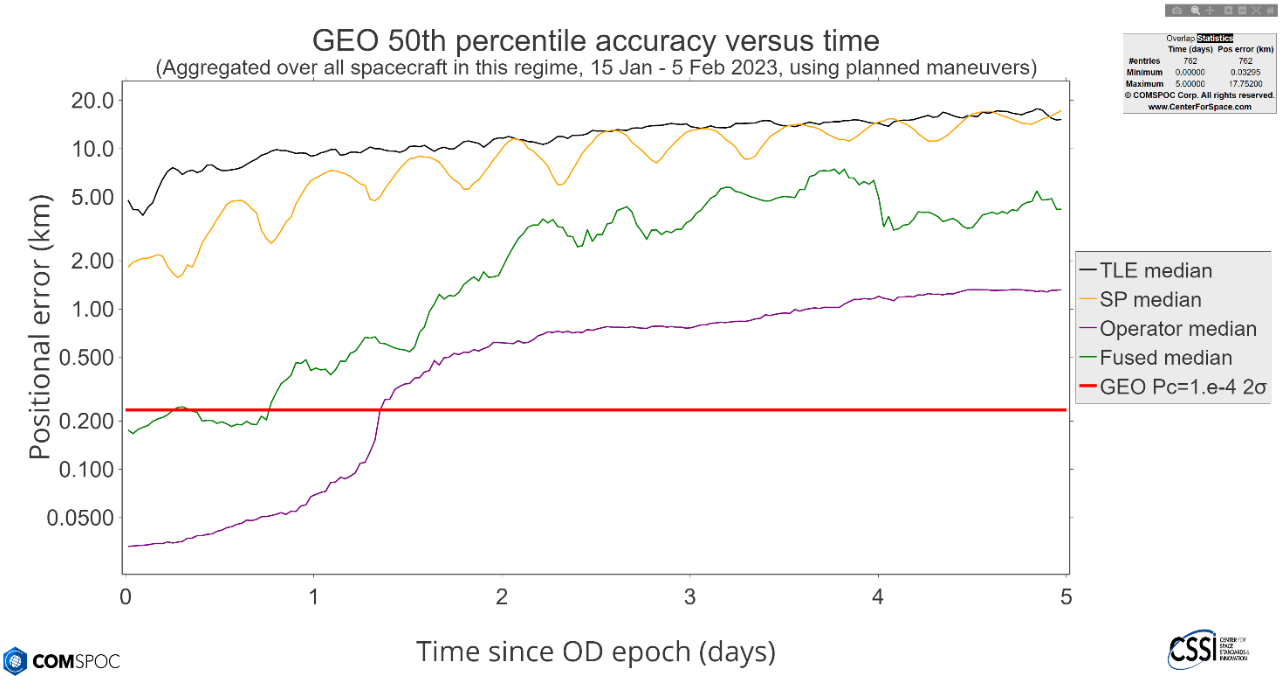


Figure 14: Typical accuracy of a variety of SSA products aggregated across six GEO independent 3rd party reference spacecraft (logarithmic accuracy scale).

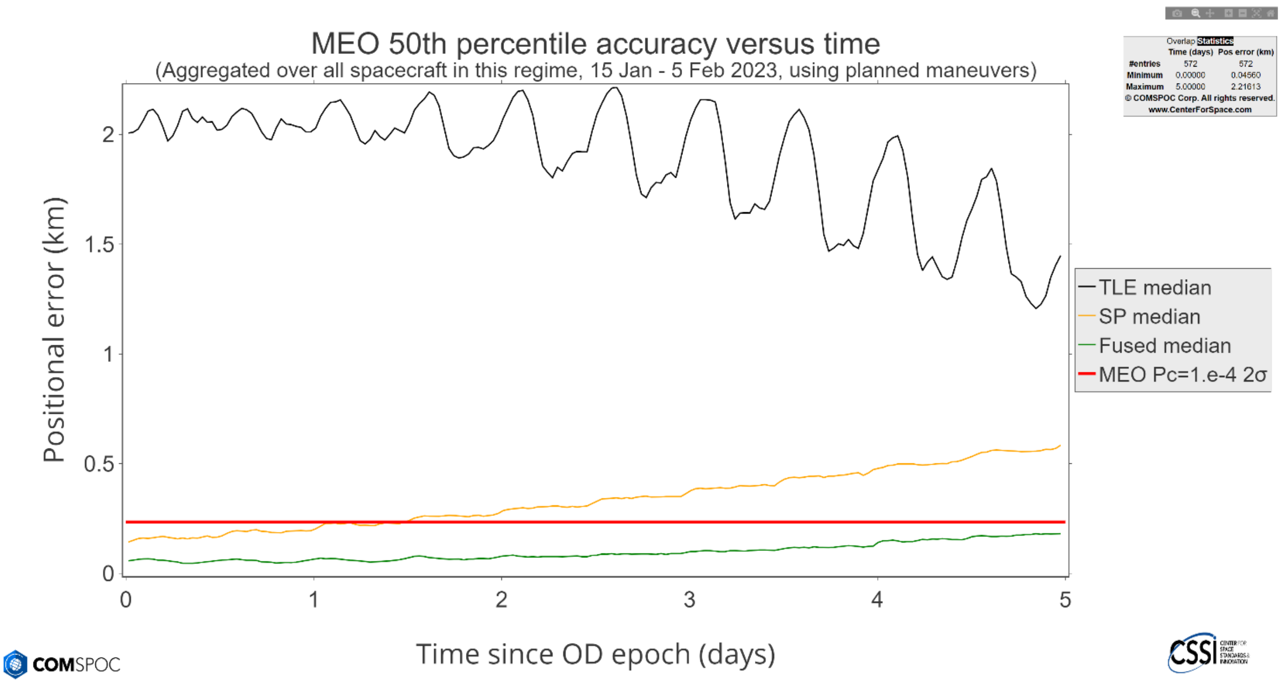


Figure 15: Typical accuracy of a variety of SSA products aggregated across six MEO independent 3rd party reference spacecraft (linear accuracy scale).

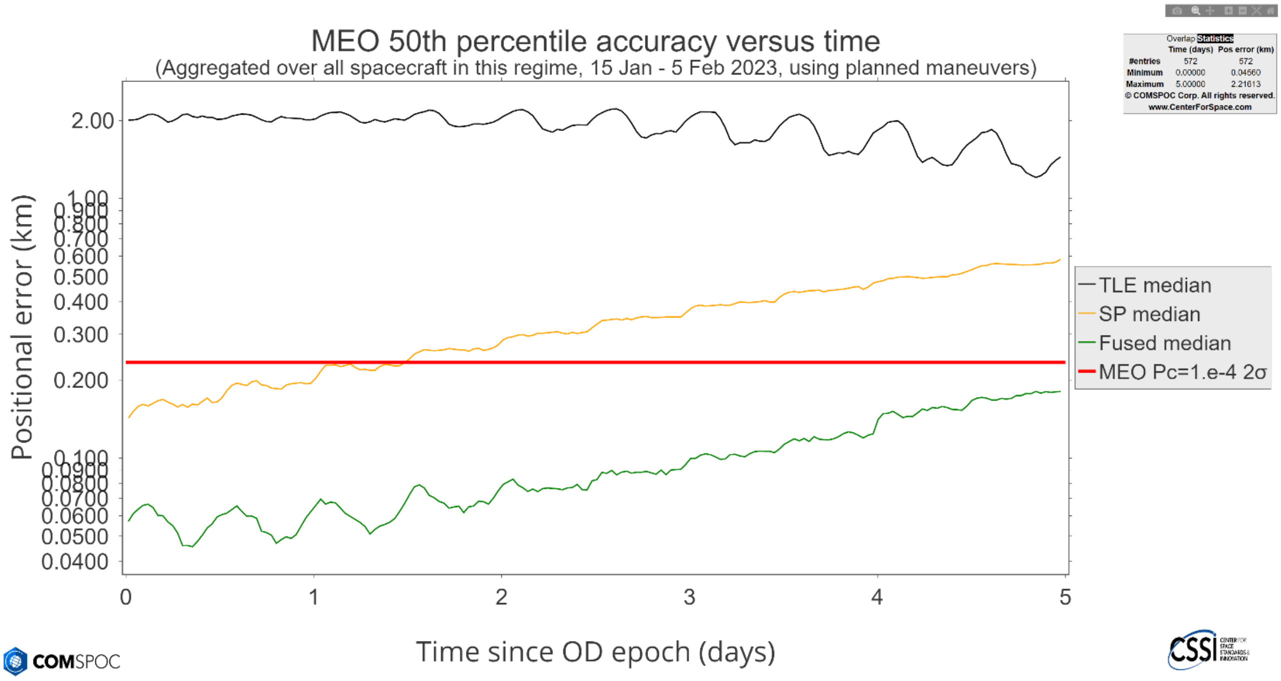


Figure 16: Typical accuracy of a variety of SSA products aggregated across six MEO independent 3rd party reference spacecraft (logarithmic accuracy scale).

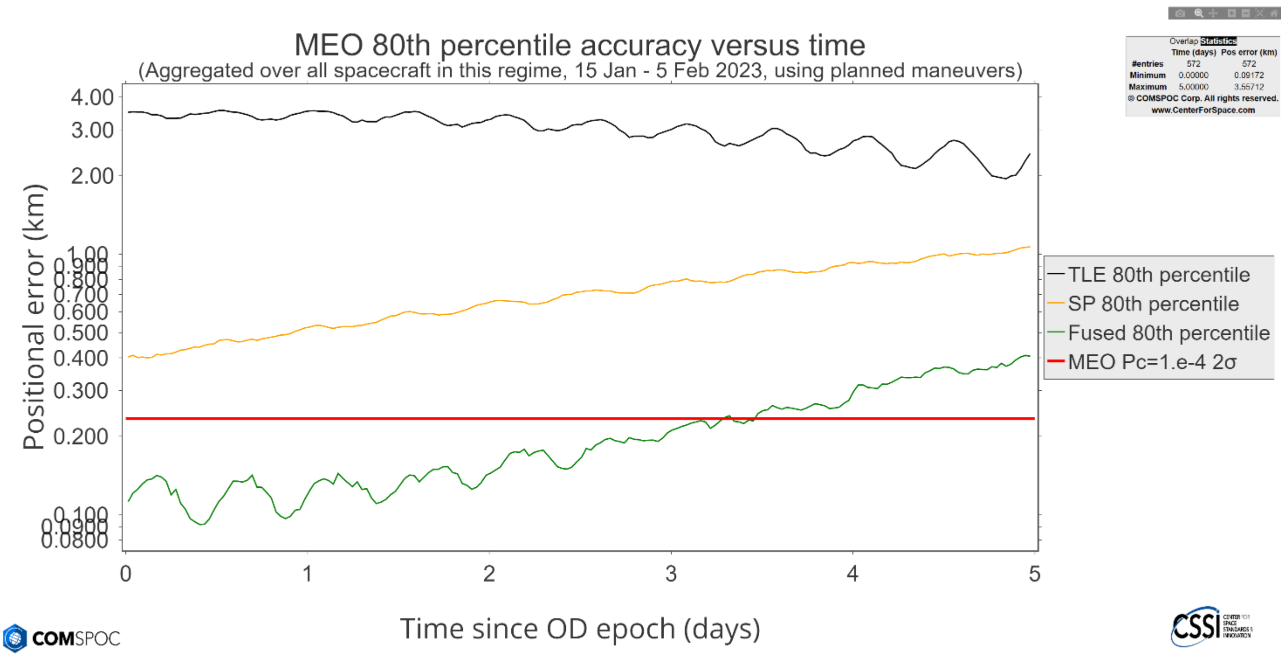


Figure 17: 80th percentile accuracy of a variety of SSA products aggregated across six MEO independent 3rd party reference spacecraft (logarithmic accuracy scale).

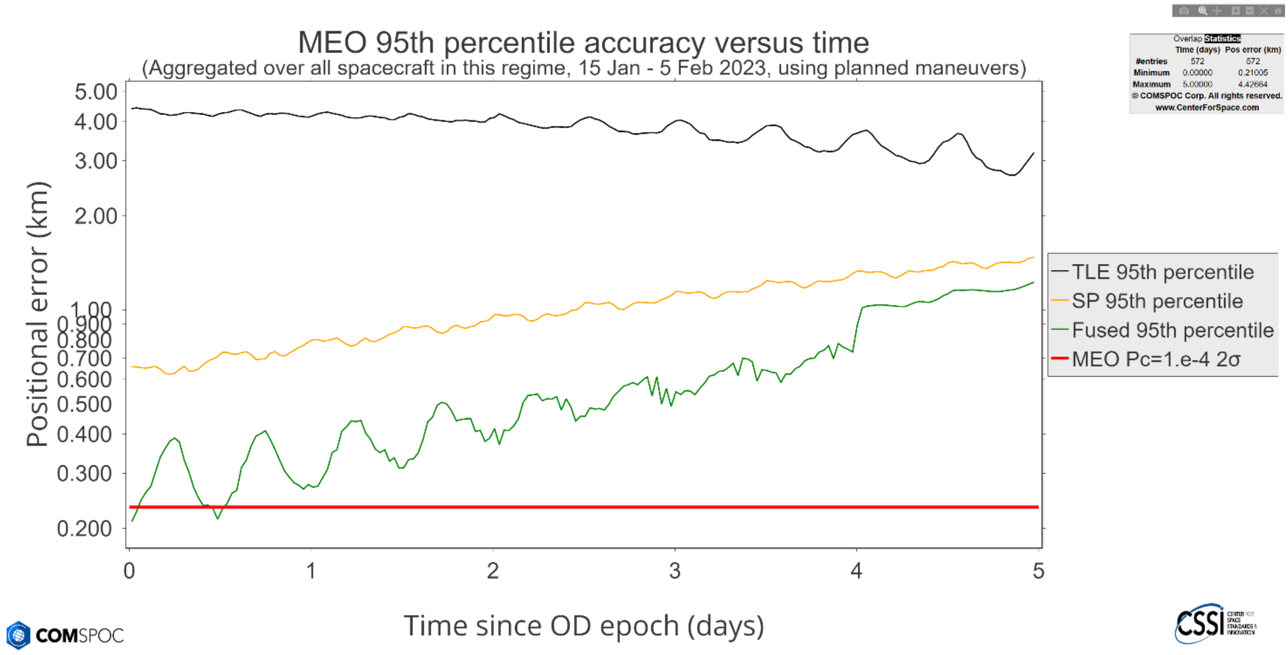


Figure 18: 95th percentile accuracy of a variety of SSA products aggregated across six MEO independent 3rd party reference spacecraft (logarithmic accuracy scale).

11.4. STATISTICAL AGGREGATION OF SSA ACCURACY VERSUS RECONSTRUCTED/ "SMOOTHED" EPHEMERIS

For spacecraft for which a 3rd-party independent reference orbit is unavailable, it can be useful to compare the TLE, SP, O/O, and SDA/COMSPOC fused positional SSA products against a reconstructed or "smoothed" reference ephemeris generated by COMSPOC. This was done for the 55 spacecraft, and the individual plots for these comparisons are contained in in Appendix 2 (Figures 52 - 161) as noted above.

After statistical processing, median percentiles-of-accuracy graph were generated as shown in **Figure 19** and **Figure 20** (linear and logarithmic accuracy scales for GEO) and **Figure 21** and **Figure 22** (linear and logarithmic accuracy scales for MEO).

IN GEO, a substantial improvement in accuracy is once again observed, as statistically aggregated across these 43 GEO spacecraft for which no independent third-party reference orbits were available. While fused solution performance varied for several GEO spacecraft (e.g., SES-15), the COMSPOC team determined that by calibrating the force model and OD settings to the spacecraft, demonstrating that even for a spacecraft that frequently maneuvers, nearly a hundredfold accuracy gain over SP accuracy could be achieved as shown in **Figure 23** (as compared to its pre-calibration plot in **Figure 43**). Similarly, post-Pilot calibration of the Claro Star One D2 settings also yielded almost a hundredfold accuracy gain as compared to SP (**Figure 24**) (as compared to its pre-calibration plot in **Figure 149**).

In MEO, all the COMSPOC-smoothed/reconstructed reference orbits corresponded to the twelve O3B spacecraft. The operator, SP, and fused products were roughly on par at OD epoch, but the fused solution accuracy drifted away approximately five times faster than for SP). This indicated that the fusion force modeling for O3B spacecraft was not properly tuned during this short DOC Pilot demonstration. After the Pilot concluded, the orbit determination settings and force models were more carefully examined. It was determined that for these O3B spacecraft, the mass and coefficient of reflectivity (inputs to Solar Radiation Pressure or SRP modeling) were still set to default values that were inappropriate for these vehicles, and that an OD setting (white noise sigmas) had been incorrectly set or not properly calibrated/changed from its default value.

When the SRP input parameters and white noise sigma settings were corrected, O3B performance was substantially improved (as a representative example, see the SDA/COMSPOC fused solution accuracies for O3B FM15 shown in **Figure 25**, as compared to the previous fused solution accuracies shown in **Figure 154**). Note that the SDA/COMSPOC fused solution surpasses the spacecraft operator's accuracies as well.

The SRP input parameters and white noise sigma updates yielded the statistical accuracies shown in **Figure 26**. Note that the error growth rate in the fused solution still exceeds the operator's rate; when the DOC fully funds and prioritizes fused OD operations, the team is confident that still more force model calibrations can be accomplished that will yield even better O3B accuracies.

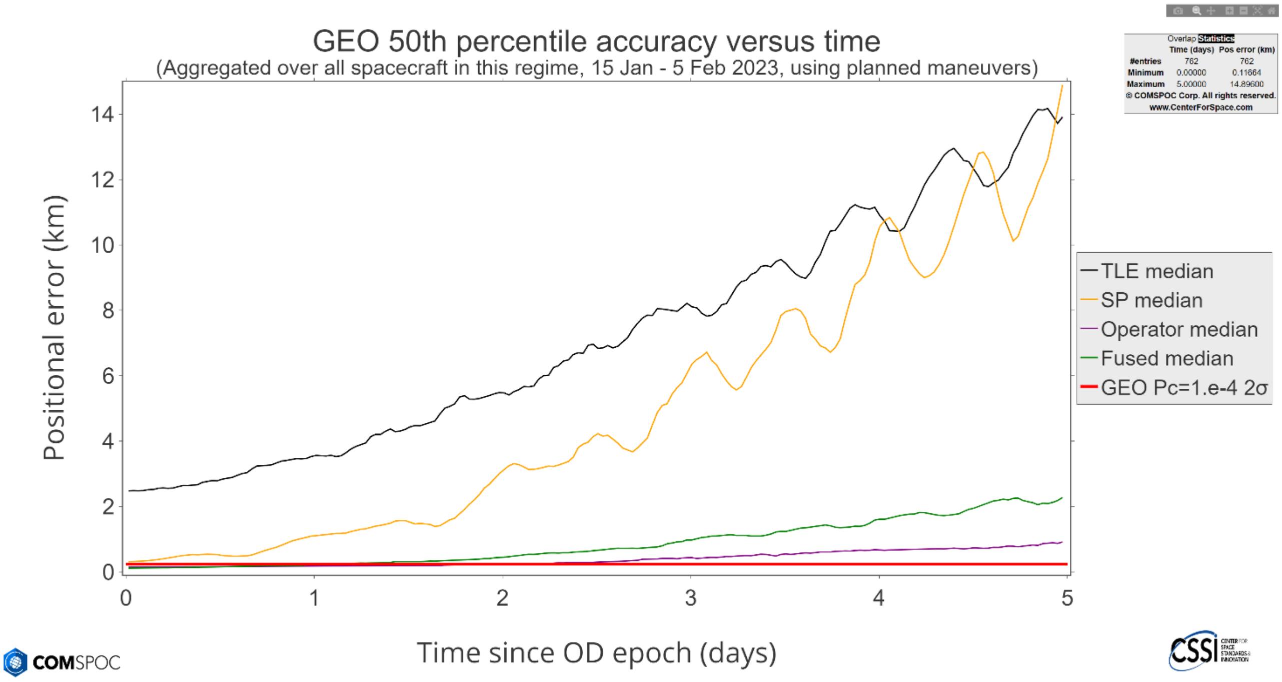


Figure 19: Typical accuracy of a variety of SSA products aggregated across 43 GEO COMSPOC-reconstructed spacecraft (linear accuracy scale).

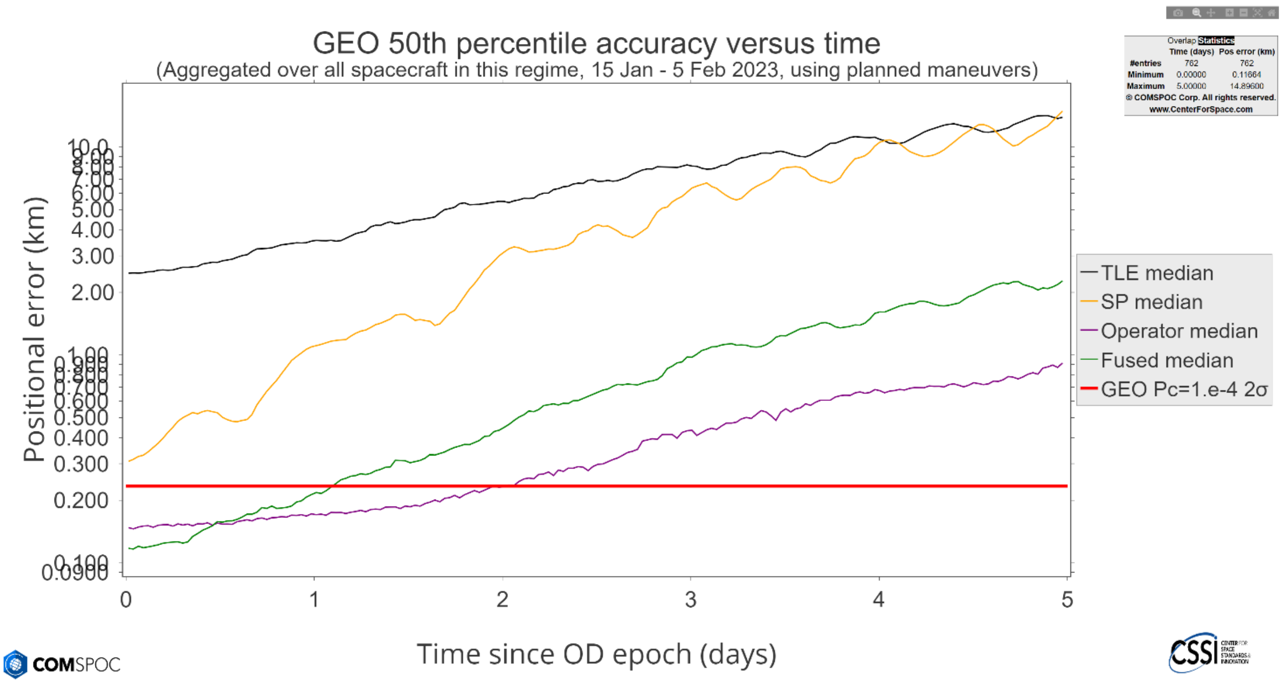


Figure 20: Typical accuracy of a variety of SSA products aggregated across 43 GEO COMSPOC-reconstructed reference spacecraft (logarithmic accuracy scale).

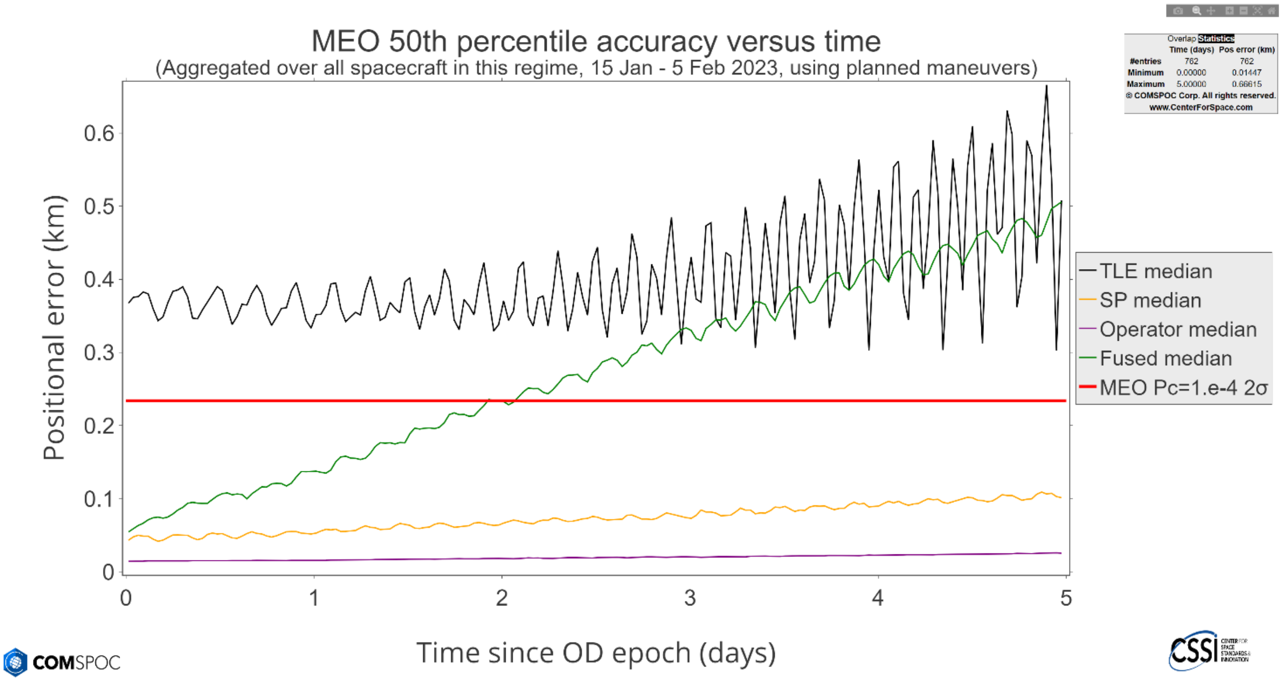


Figure 21: Typical accuracy of a variety of SSA products aggregated across 12 MEO (O3B) COMSPOC-reconstructed reference spacecraft (linear accuracy scale).

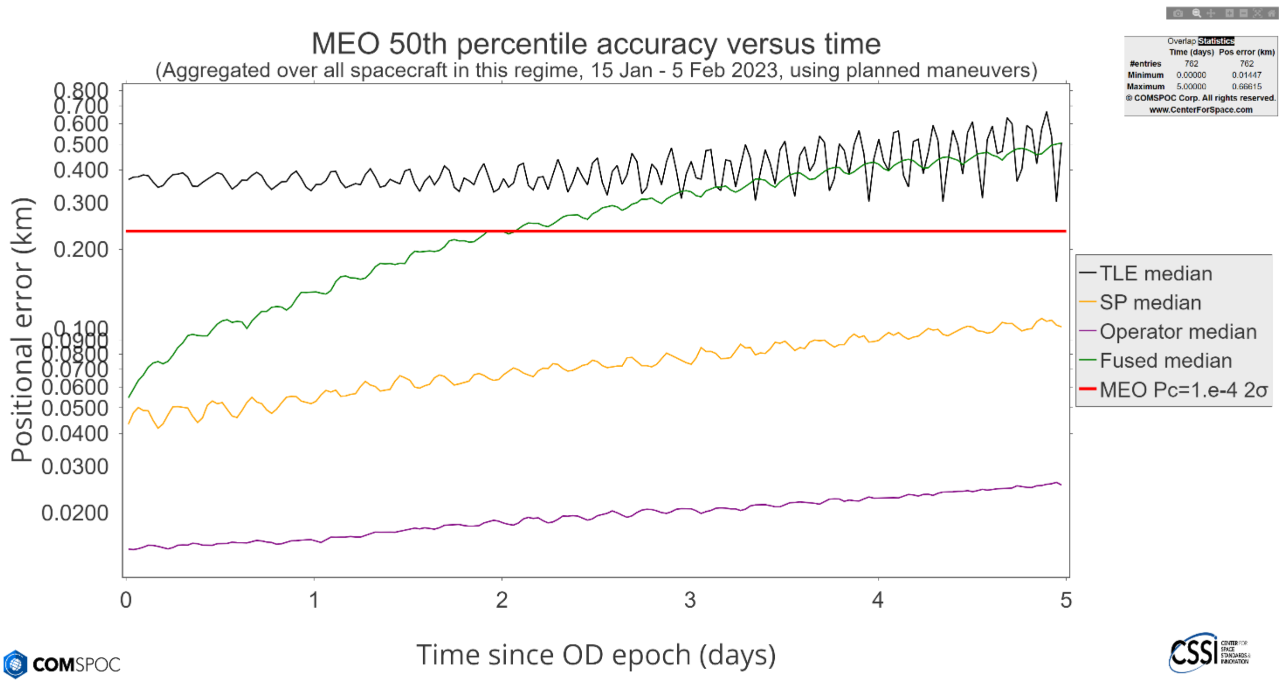


Figure 22: Typical accuracy of a variety of SSA products aggregated across 12 MEO (O3B) COMSPOC-reconstructed reference spacecraft (logarithmic accuracy scale).

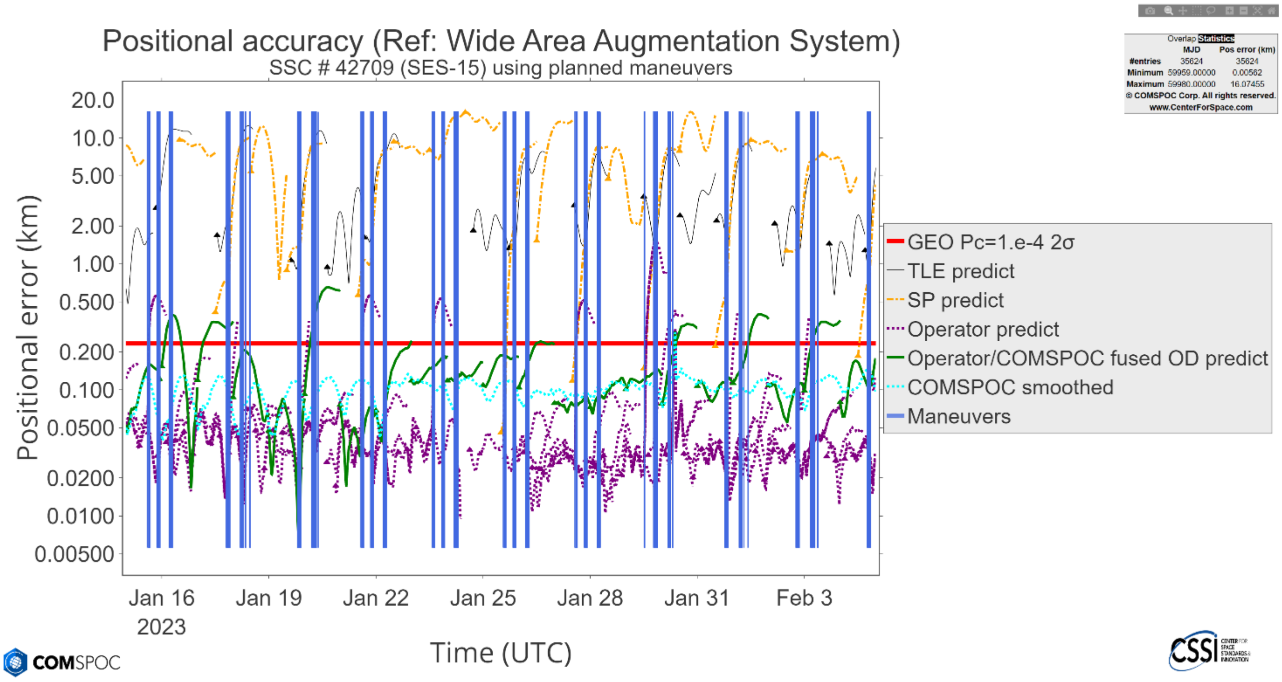


Figure 23: Following Post-Pilot tailoring of OD settings and orbit propagation force model, shows Log (median accuracy) versus time for SSC #42709 (SES-15).

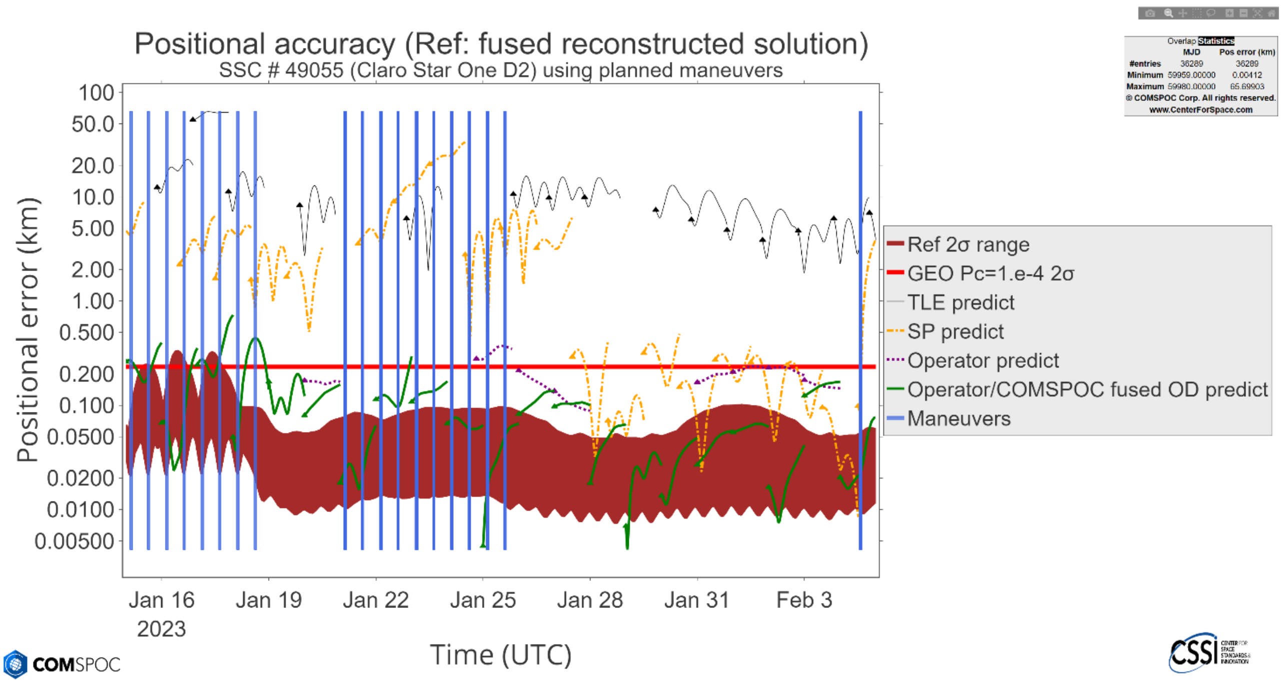


Figure 24: Following Post-Pilot tailoring of OD settings and orbit propagation force model, shows Log (median accuracy) versus time for SSC #49055 (Claro Star One D2).

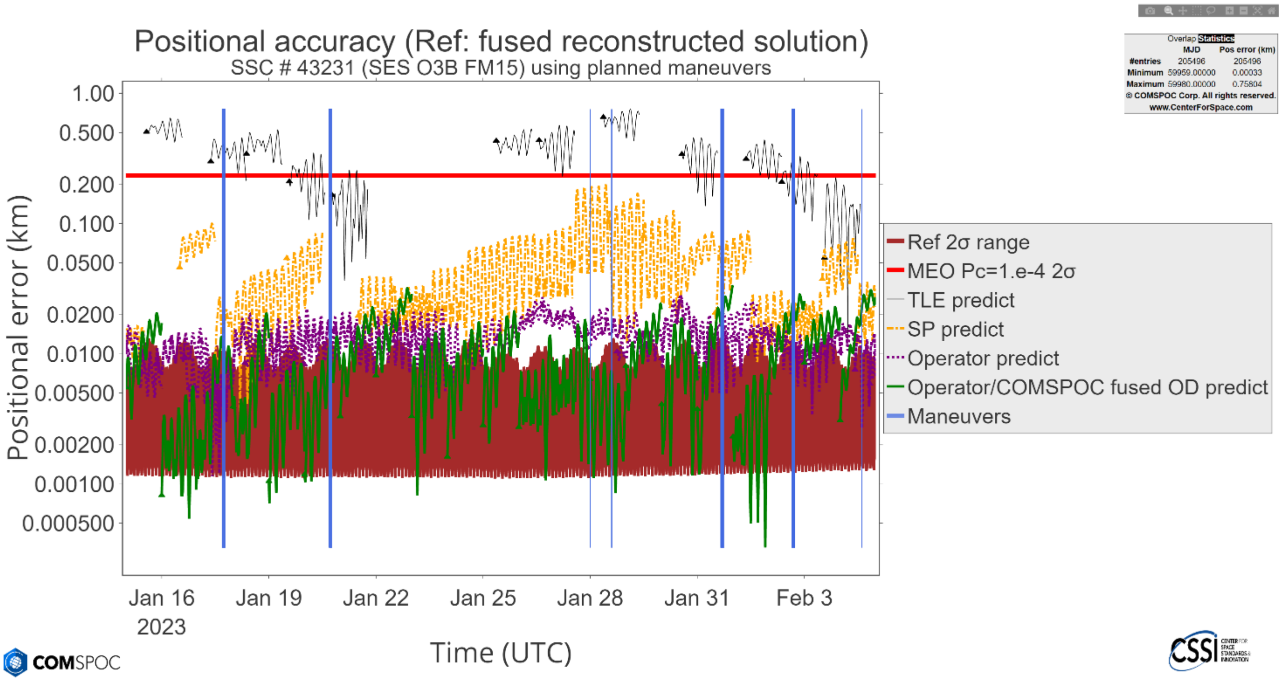


Figure 25: Following Post-Pilot tailoring of OD settings and orbit propagation force model, shows Log (median accuracy) versus time for SSC #43231 (SES O3B FM15).

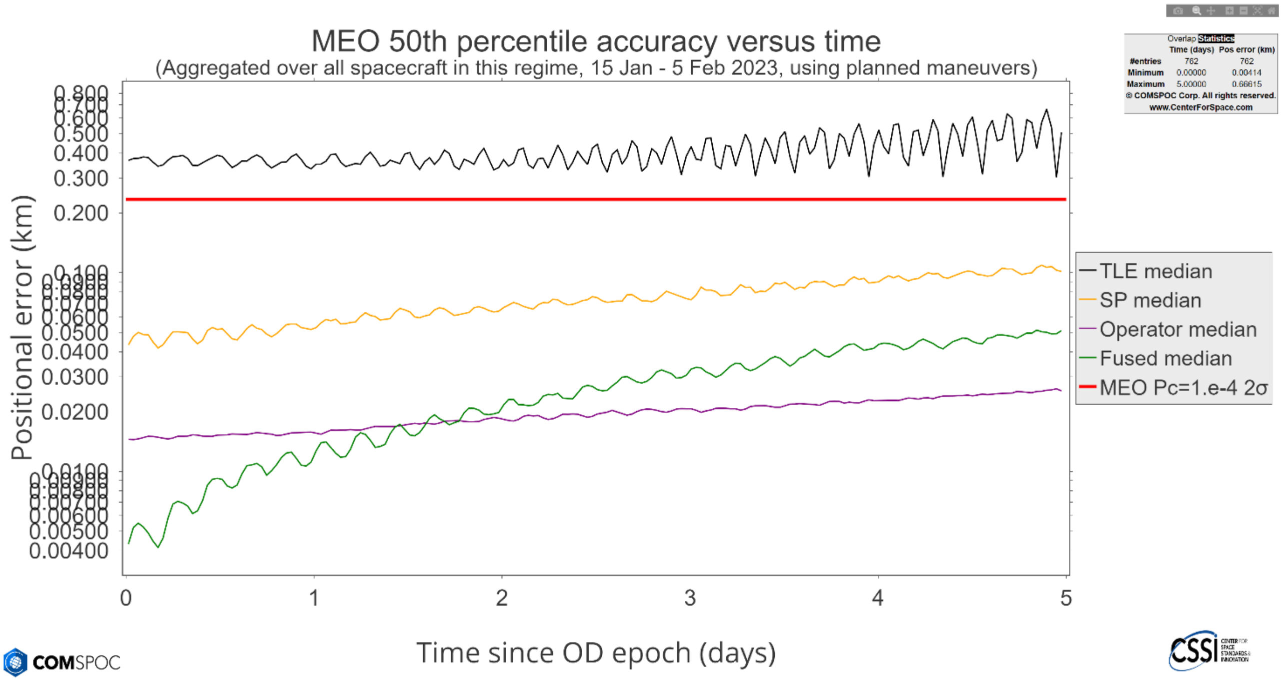


Figure 26: Following Post-Pilot tailoring of OD settings and orbit propagation force model, shows typical accuracy of a variety of SSA products aggregated across 12 MEO (O3B) COMSPOC-reconstructed reference spacecraft (logarithmic accuracy scale).

12. RECURRING SSA DEGRADATION CAUSES

By carefully reviewing the accuracy plots for these 67 MEO and GEO spacecraft, patterns emerge regarding why TLE, SP, O/O, and SDA/COMSPOC fused solution accuracy can be degraded. Common SSA accuracy degradation causes, and suggested mitigation strategies, have been summarized in **Table 4**. Each of these four SSA sources reacts differently to such SSA degradations.

13. LESSONS LEARNED

The data fusion component of the DOC Pilot activity was certainly a learning experience for all involved. Here are some suggested lessons learned for consideration by the community, grouped by category:

13.1. DOC

1) From the standpoint of determining whether commercial SSA tracking observation data providers can perform on par with domestic legacy flight safety services, it was reasonable to constrain the set of tracking observations to those obtained commercially (i.e., no SSN observations from the Space Surveillance Network).
2) Conversely, from the standpoint of determining whether commercial OD and data fusion systems can perform equivalently or better than legacy products, the DOC Pilot did not allow or facilitate leveraging of the rich set of SSN or other commercial SSA observations that would be possible in a future DOC-hosted STCM system. This prevented a true "apples-to-apples" comparison of TLE and SP accuracy versus the commercially fused solution, because the sheer quantity of SSN sensors and resulting observations likely helped the TLE and SP accuracies to be better than they would have been if confined to the set of commercially sourced DOC Pilot observations. Such undersampling was evident for the Beidou reference spacecraft, where COMSPOC's night optical tracking yielded 20m accuracies at night but degraded to 400m in daylight viewing.
3) While the DOC Pilot was focused on comparing results from individual SSA data and analytics providers with each other, the SDA/COMSPOC vision is that comprehensive commercial collaboration, incorporating government and commercial raw observational tracking data from multiple providers, is required to achieve effective flight safety and sustainability.
4) The SDA/COMSPOC team had a very short timeline to set up data flows, ingest and normalize the data, and generate results. Many of the issues faced during this rapid setup would fade away if such an approach was operationally deployed in a methodical manner.

13.2. United States Space Force 19 SDS

1) Some SP ephemerides contained far too large a step size (specifically, a 15-minute step for O3B spacecraft), causing interpolation issues that degraded comparative SSA statistics and could potentially seriously degrade flight safety products based upon SP ephemerides.

13.3. SDA's SPACECRAFT OPERATORS

2) For some spacecraft operators, delivery of their sensor observations and maneuver plans was sporadic and/or delayed, often associated with network and security issues. These issues were not able to be fixed "in the moment" of the DOC Pilot but could readily be addressed when going operational with this construct. These would improve the accuracy of the fused solution still further.
3) Some O/O ephemerides contained far too large a step size (e.g., O3B's 15-minute step), causing interpolation issues that degraded comparative SSA statistics.
4) A few operators plan their upcoming maneuvers over a fixed planning cycle time interval but don't plan or share information on any subsequent maneuvers until the current cycle is completed. This can introduce gaps near the end of the current cycle where maneuvers that will be conducted soon after this cycle is completed are not yet known and/or shared.
5) Though not always available or perfectly calibrated, incorporation of spacecraft operator planned maneuvers into OD data fusion and SSA products proved to be invaluable in substantially improving SSA accuracy.

13.4. COMSPOC OD AND DATA FUSION

Given the collaborative nature of the spacecraft operator/COMSPOC data fusion and incorporation of maneuvers, it would be natural to wonder why that fused product was not found to be better than the TLE and SP products in most, if not all, cases. Some of our lessons learned include the :

1) The COMSPOC team needed to spend more time fully calibrating OD settings and force models for space objects. Default settings for mass, SRP reflectivity coefficient, white noise sigmas, etc. should be refined and, where possible, aligned with existing databases (e.g., ESA's DISCOS database).Sensor calibration, weights, and biases for one orbital regime may not be relevant in other orbital regimes. This is an area for further investigation.
2) Unknown or mis-modelled maneuvers degrade SSA knowledge more than almost all other modelling aspects combined. Consider that the

Iridium/Cosmos collision was at first assessed at a one in a tredecillion (that's a "1" digit followed by 42 zeros!). A small maneuver left unmodeled raised the collision probability to one in a thousand, resulting in an environmentally harmful collision and fragmentation event.

3) Lagrange interpolation, while necessary for positional ephemerides that don't contain first derivative (velocity) information, can be sensitive to overshoots near endpoints or when fitting short maneuvering flight segments. Third-order Hermitian interpolation worked quite well and all but eliminated such overshoots.

4) While the default force models employed by COMSPOC are typically quite suitable, force model tuning will further improve the fused solution. Spacecraft operators and 18 SDS (now transitioned to 19 SDS) have in general had decades to tune their force models to their specific spacecraft, and the COMSPOC team would have benefited from more time than the short DOC Pilot allowed.

14. SSA STRENGTHS AND WEAKNESSES

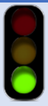
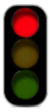
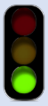
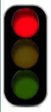
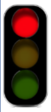
As demonstrated, sources of SSA information vary widely in their accuracy, latency, transparency, and completeness. Based in part upon the statistical findings of this paper, sources of SSA data are compared in **Table 5**.

Table 4: Recurring SSA degradations

SSA degradation source	Figures illustrating this effect {Linear, Log} Figure #s	Mitigation strategies
1) Unknown/unreported maneuvers	{59,114}, {73,128}, {84,139}, {88,143}, {93,148}	Take a methodical "on-boarding" approach to new spacecraft operators and commercial SSA service providers
2) Ephemeris interpolation "ringing" issues at start and stop of segment boundaries	{57,112}, {65,120}, {75,130}, {80,135}, {85,140}, {87,142}, {91,146 }	These "spikes" are not real, but an artifact of the step size used by ephemeris producers (step size should adhere to guidelines in [10]) AND/OR the interpolation method used in this SSA comparative analysis, particularly within maneuver segment boundary intervals. Likely not an operational concern.
3) OD biases	{33,45}, {57,112}, {60,115}, {64,119}, {65,120}, {80,135}, {90,145}, {91,146}	Bring in more sensor observations, sensor phenomenologies, diverse geographical sensor locations, more commercial SSA and USG (SSN) observations.
4) Maneuvers, even if SSA system is notified, can introduce large uncertainties (including the case where a planned maneuver gets cancelled).	{60,115}, {62,117}, {69,124}, {77,132}, {86,141}	Further refine calibration of spacecraft maneuver system, increase frequency of maneuver plan updates and cadence of maneuver plans (some plan maneuvers once per week, and at the end of the week, there is no "carry-over" to the next).
5) Some spacecraft maneuver very frequently, which while efficient, makes it difficult for SSA systems to keep up.	{30,42}, {31,43}, {57,112}, {87,142}, {90,145}, {92,147}, {94,149}	Further refine calibration of spacecraft maneuver system, increase frequency of maneuver plan updates and cadence of maneuver plans. We learned a lot in this Pilot about how to work well with operator maneuver plans; they are generally very accurate and useful.
6) Some reference orbits are insufficiently accurate to serve as a "truth" reference.	{57,112}, {73,128}, {87,142}	Run operation for a longer time, as these generally can be improved by operator OD and force model adjustment
7) Third-party reference ephemerides may have gaps, introducing interpolation errors	{32,44}	"Mind the Gap"
8) Filter initialization and resolution of cross-tagged	{32,44}, {35,47}, {55,110}, {63,118},	Run operation for a longer time, as these generally can be improved by operator OD and force model adjustment

observations may take several weeks to fully settle in	{64,119}, {75,130}, {102,157}	

Table 5: Comparison of relative strengths and weaknesses of SSA information sources

Item	Govt system (e.g., space-track.org)	Commercial SSA (w/o operator ephemerides or planned maneuvers)	Owner/Operator Ephemerides	Fused Commercial SSA (O/O obs, planned maneuvers, s/c dimensions)
Planned maneuvers	 Not included	 Not included	 Included	 Included
Includes covariance	 SP covariance unavailable; CDM covariance only at TCA	 Varies by SSA provider	 None or Only at epoch	 Included
General-purpose OD processing of maneuvers and any type of observations.	 3x/day[1]	 Regular	 Varies from 12x/day to 1x/10days or longer	 Every 2 hours, based on data availability
OD Frequency	 3x/day[1]	 Regular	 Varies from 12x/day to 1x/10days or longer	 Every 2 hours, based on data availability
Ephemeris Quality – cooperative operators	 Degraded for maneuvering s/c	 Degraded for maneuvering s/c	 Varies by operator	 Good – incorporates operator plans and solves
Ephemeris Quality – non-cooperative operators	 Degraded for maneuvering s/c	 Depends on maneuver detection/solve capability	 n/a	 Good – rapidly detects/solves for maneuvers
Operator Biases	 n/a	 n/a	 Varies by satellite; difficult for operators to observe	 n/a
Orbit Accuracy (Pilot results)	 Typically inadequate	 Typically good	 Typically good	 Typically good[2]; Seven-fold accuracy improvement seen for one-day predict
Force models properly calibrated	 Mostly	 Can be accomplished with full funding	 Mostly	 Not yet dialed in, but would be given proper funding.

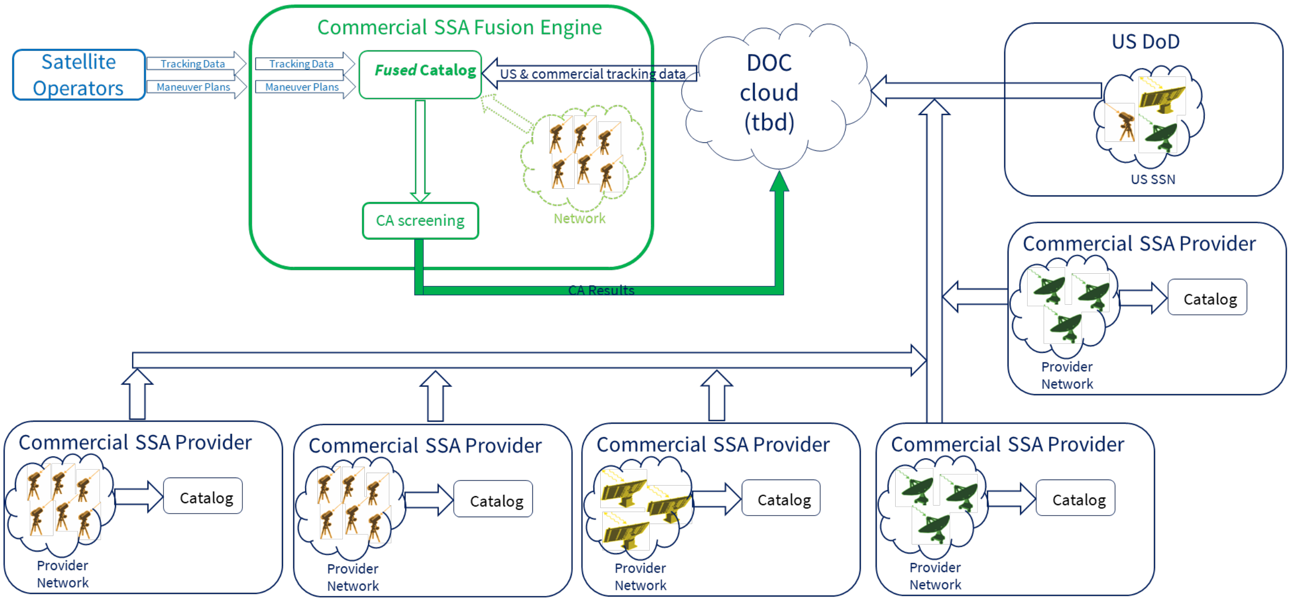


Figure 27: Suggested enterprise DOC STCM system incorporating a commercial data fusion engine and multiple commercial and government SSA data providers.

15. SUMMARY

What is clear in reviewing the many accuracy assessments in Annex A (linear scale) and Annex B (logarithmic scale) is that there is no single SSA source or provider or even spacecraft operator who has a "perfect" scorecard, at least at some time or for certain spacecraft. Said differently, every SSA provider has gaps in capability in certain circumstances. That said, what's more important is what an SSA provider's typical performance is.

The spacecraft operator solutions included in this comparative SSA statistical analysis were incorporated primarily to get a relative sense of their accuracy. But they largely lack covariance information, which led the DOC to take a different approach to obtaining ephemerides for active spacecraft (namely, the construct shown in **Figure 2**). In addition to not containing covariance information, while spacecraft operator ephemerides can have very good accuracy, this is not necessarily the case, and the lack of sensor diversity for some operators can lead to inaccuracies and unknown biases in O/O orbit solutions.

Despite only receiving observations from COMSPOC's optical network and from spacecraft operators, on a statistical basis, the fused solutions obtained in this study are clearly at least equivalent and often superior to current legacy government SSA information. These results reinforce the findings of our earlier DOC/commercial collaborative STCM study, which is that the accuracies needed for STCM typically require the fusion of all available tracking data using best available data fusion algorithms.

This statistical assessment of the data fusion achievements highlights the fact that predictive positional products that fail to incorporate planned maneuvers can be substantially degraded. SSA products must include the spacecraft operators' planned maneuvers whenever possible, and for those cases where accurate planned maneuvers are unavailable, the STCM processing system must be capable of non-cooperatively detecting, characterizing, processing, and recovering from unknown and/or mismodeled maneuvers.

Based upon this favourable finding, the rapid expansion of **Figure 2** into a DOC enterprise framework is suggested as shown in **Figure 27**. The data fusion engine is fed on the left-hand side by spacecraft operator data (maneuvers, spacecraft dimensions, mass, raw metric observations, and active status), and on the right-hand side by raw metric observations from both government and commercial SSA Data Providers.

The key elements of this technical support to the DOC Pilot Program are the comprehensive data fusion capability, advanced quality control and comparative SSA analytics, government SSA observations, and spacecraft operator contributions of spacecraft ephemerides, maneuver plans, and especially raw observation data. Once fully funded by DOC, the commercial SSA community and rapid innovation will provide a step change in SSA performance for commercial spacecraft operators.

16. REFERENCES

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Appendix 1. Accuracy measured against independent "truth" reference trajectories

A1.1. Linear-scale accuracy stats (referenced to independent "truth" reference trajectories; sorted by GEO/MEO regime and then by SSC #)

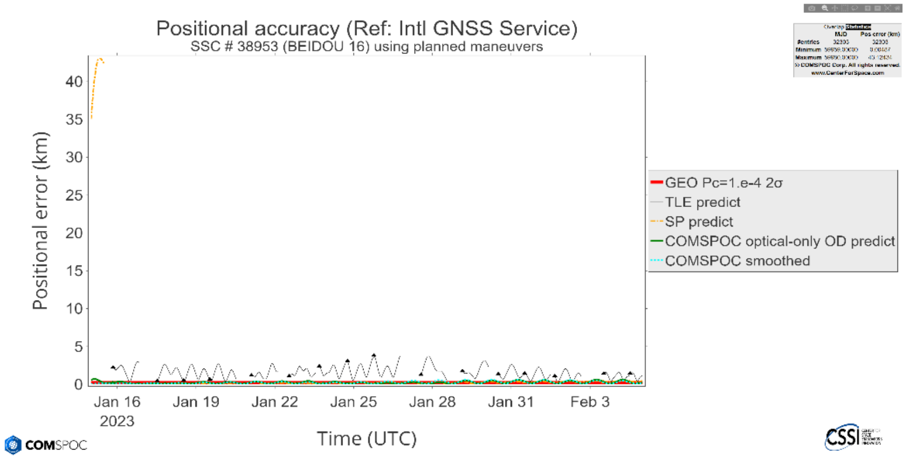

Figure 28: Median accuracy vs. time for SSC #38953 (China BEIDOU-16 G6)

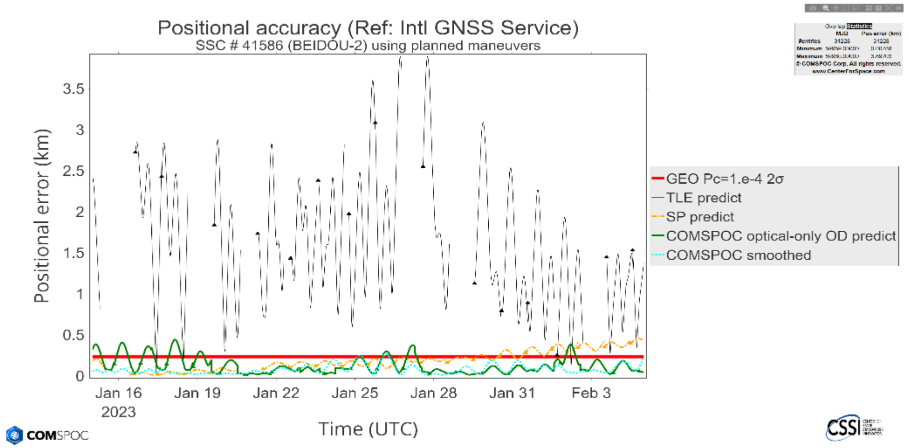

Figure 29: Median accuracy vs. time for SSC #41586 (China BEIDOU-2 G7)

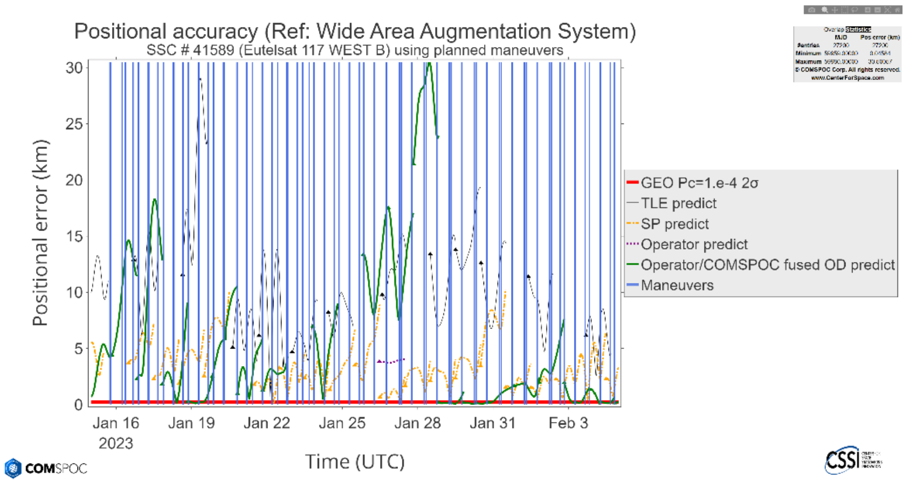

Figure 30: Median accuracy vs. time for SSC #41589 (Eutelsat 117 West B)

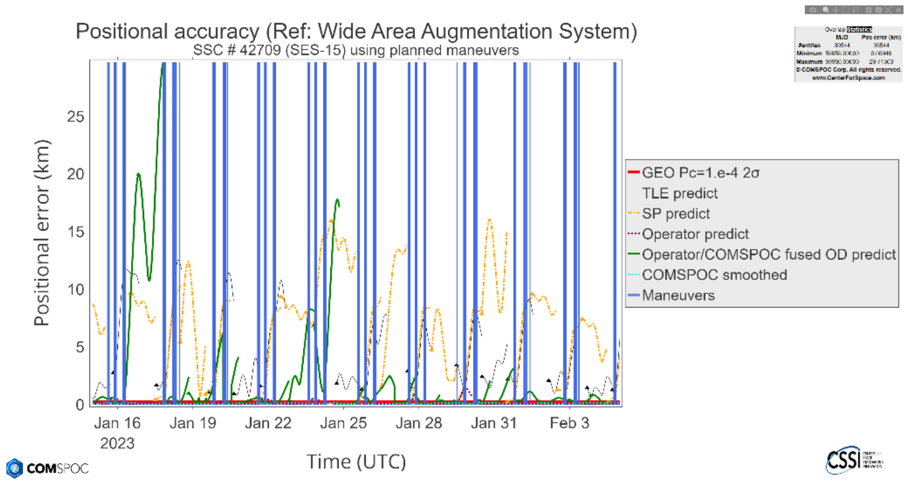

Figure 31: Median accuracy vs. time for SSC #42709 (SES-15)

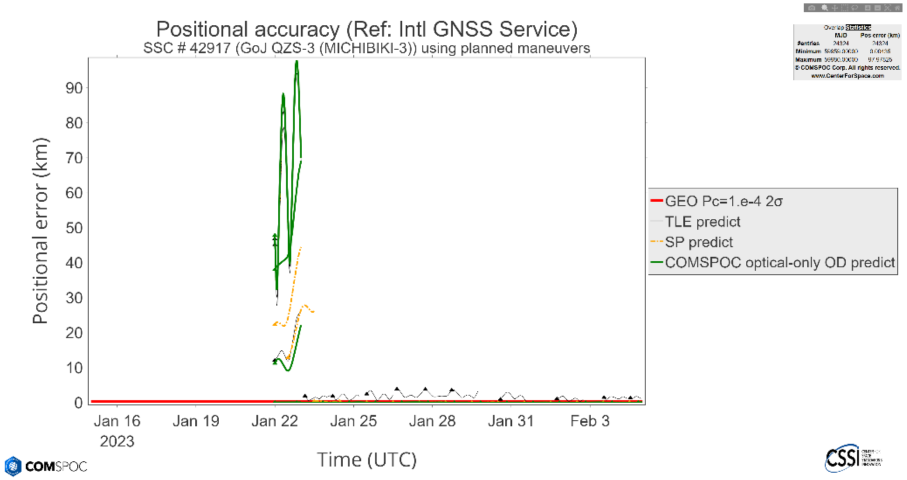

Figure 32: Median accuracy vs. time for SSC #42917 (GoJ QZS-3)

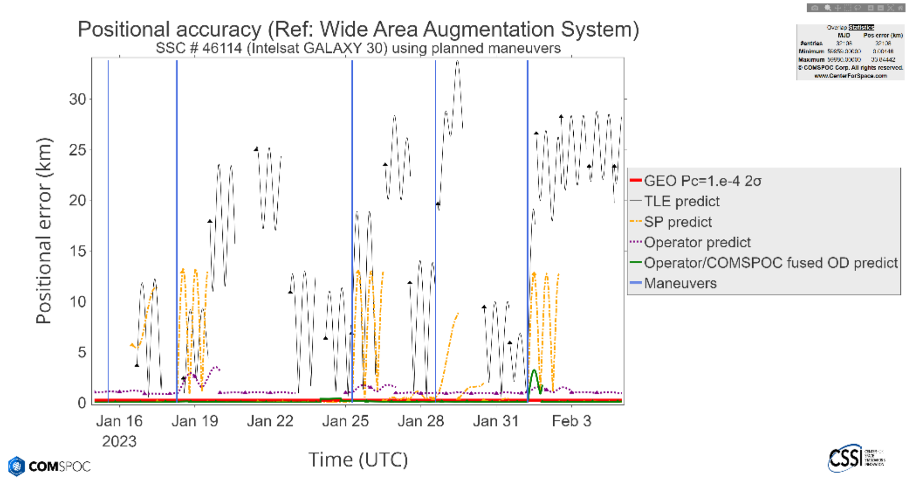

Figure 33: Median accuracy vs. time for SSC #46114 (Intelsat Galaxy 30)

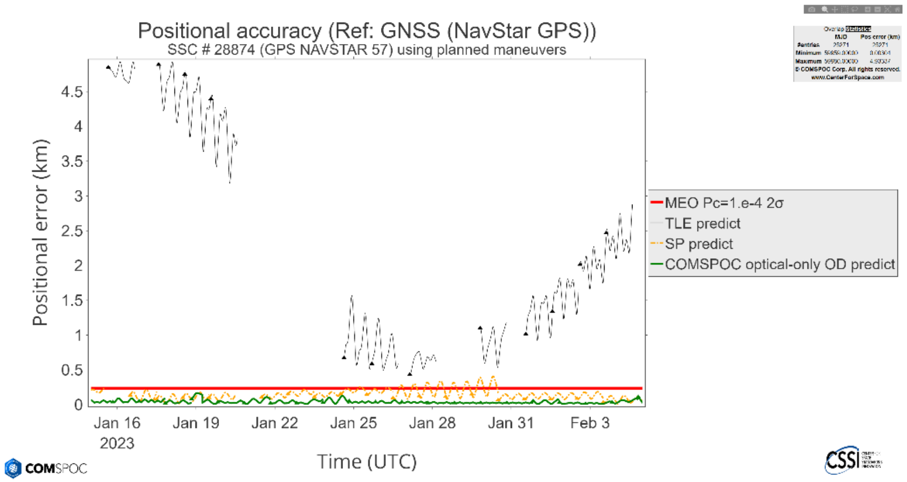

Figure 34: Median accuracy vs. time for SSC #28874 (NAVSTAR 57)

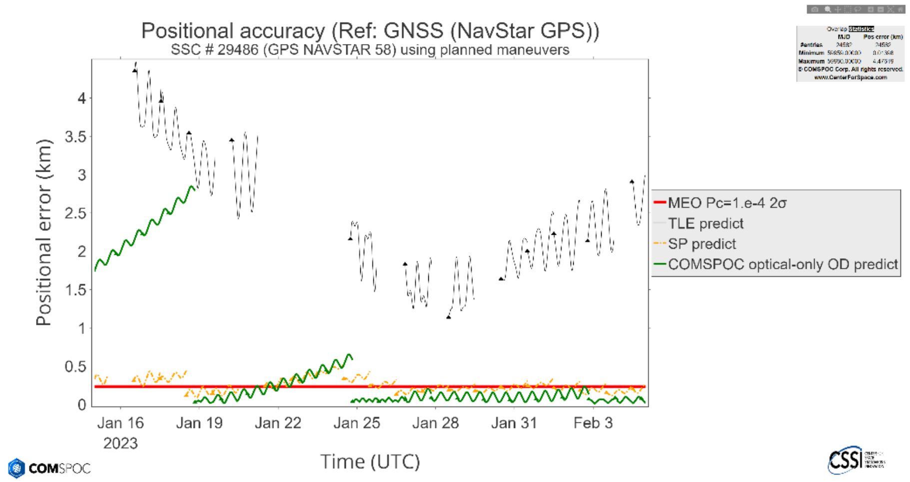

Figure 35: Median accuracy vs. time for SSC #29486 (NAVSTAR 58)

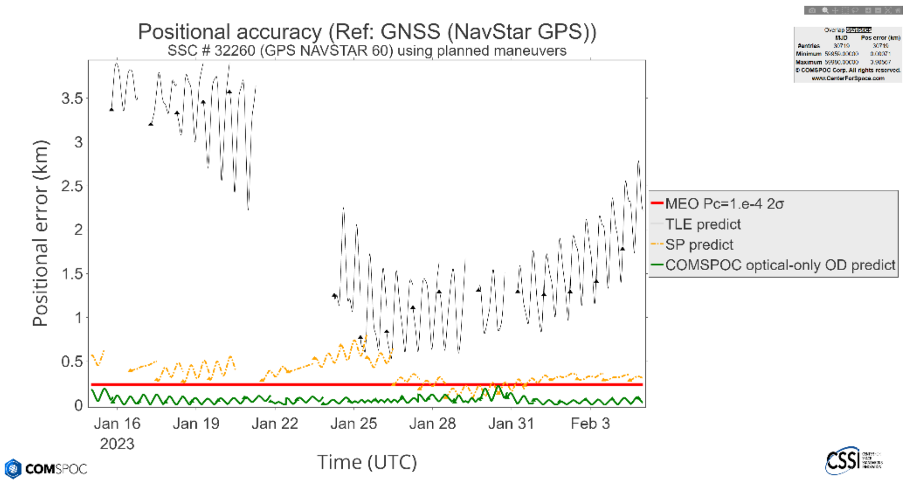

Figure 36: Median accuracy vs. time for SSC #32260 (NAVSTAR 60)

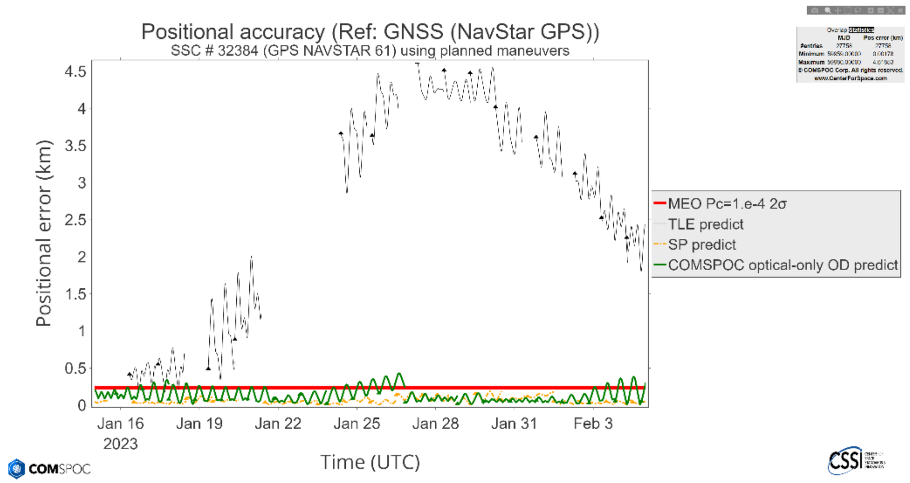

Figure 37: Median accuracy vs. time for SSC #32384 (NAVSTAR 61)

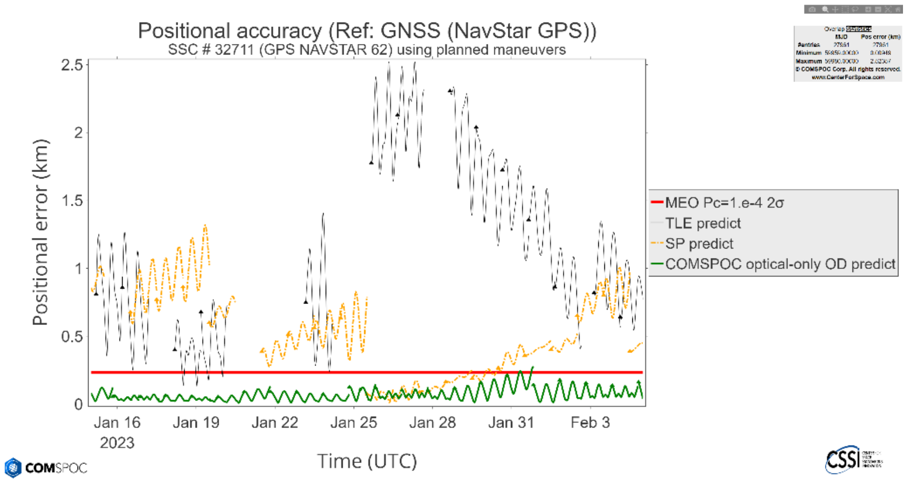

Figure 38: Median accuracy vs. time for SSC #32711 (NAVSTAR 62)

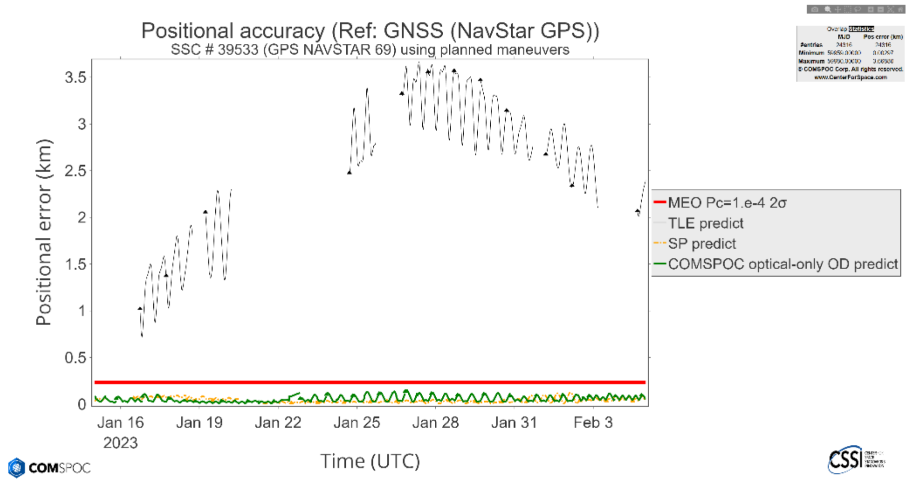

Figure 39: Median accuracy vs. time for SSC #39533 (NAVSTAR 69)

A1.2. Log-scale accuracy stats (referenced to independent "truth" reference trajectories; sorted by GEO/MEO regime and then by SSC #)

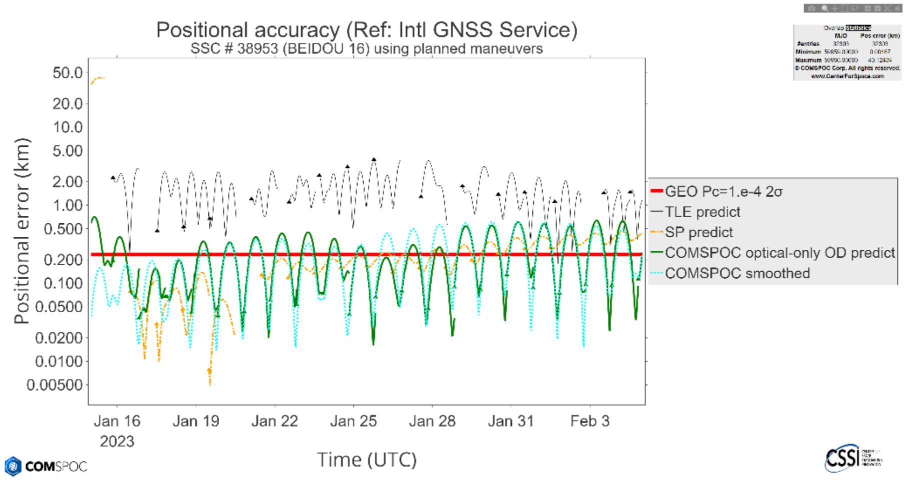

Figure 40: Log(Median accuracy) vs. time for SSC #38953 (China BEIDOU-16 G6)

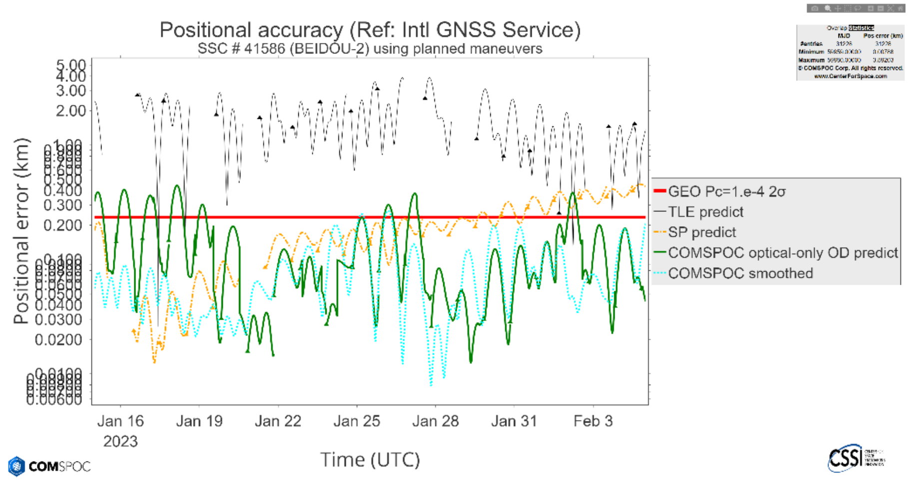

Figure 41: Log(Median accuracy) vs. time for SSC #41586 (China BEIDOU-2 G7)

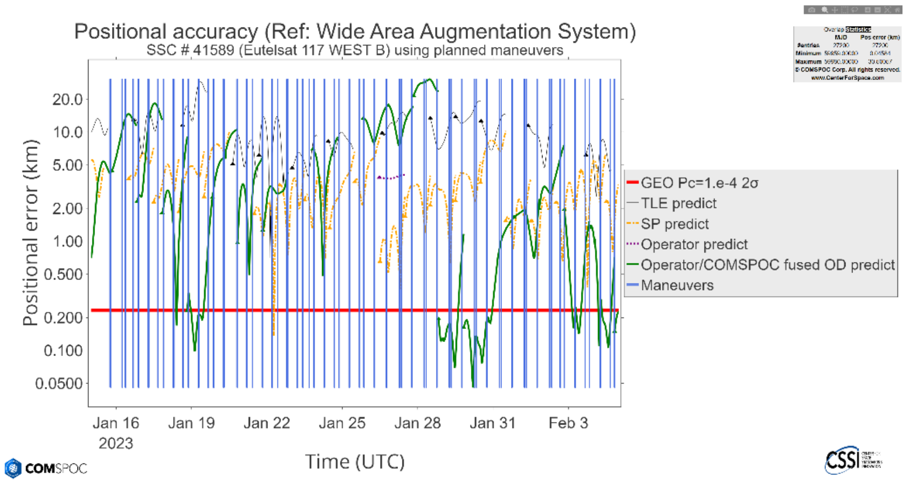

Figure 42: Log(Median accuracy) vs. time for SSC #41589 (Eutelsat 117 West B)

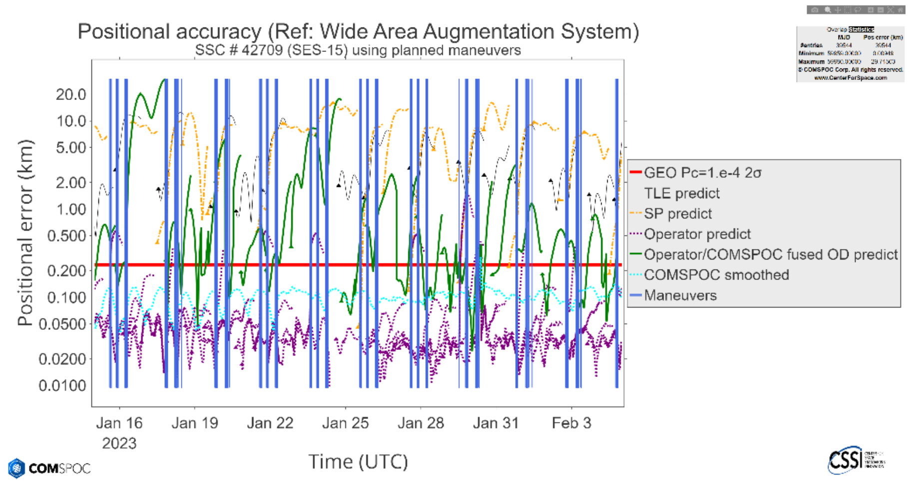

Figure 43: Log(Median accuracy) vs. time for SSC #42709 (SES-15)

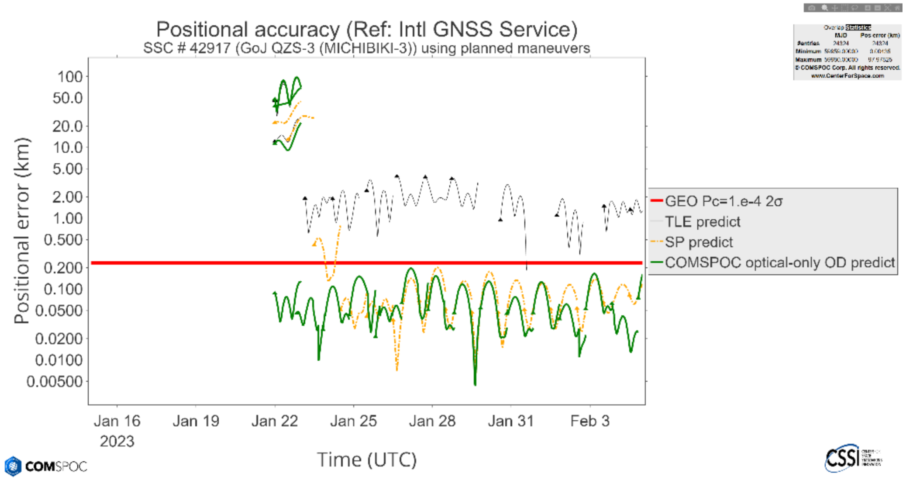

Figure 44: Log(Median accuracy) vs. time for SSC #42917 (QZS-3)

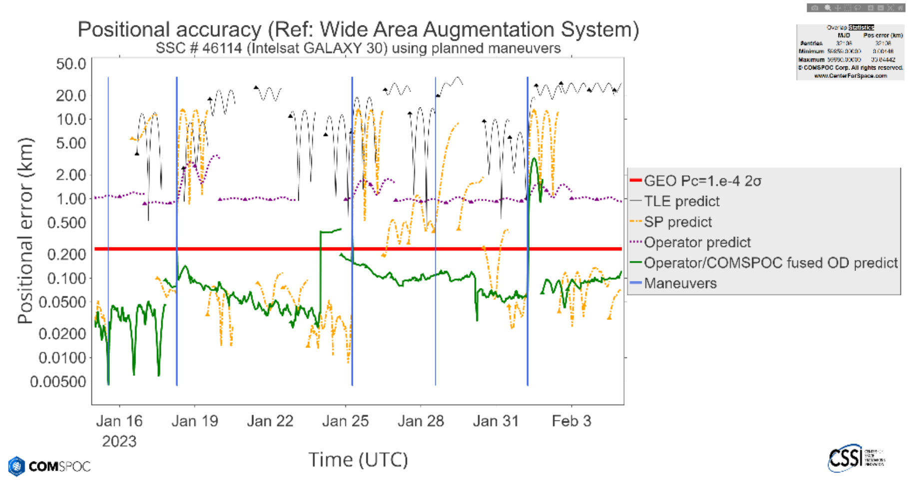

Figure 45: Log(Median accuracy) vs. time for SSC #46114 (Intelsat Galaxy 30)

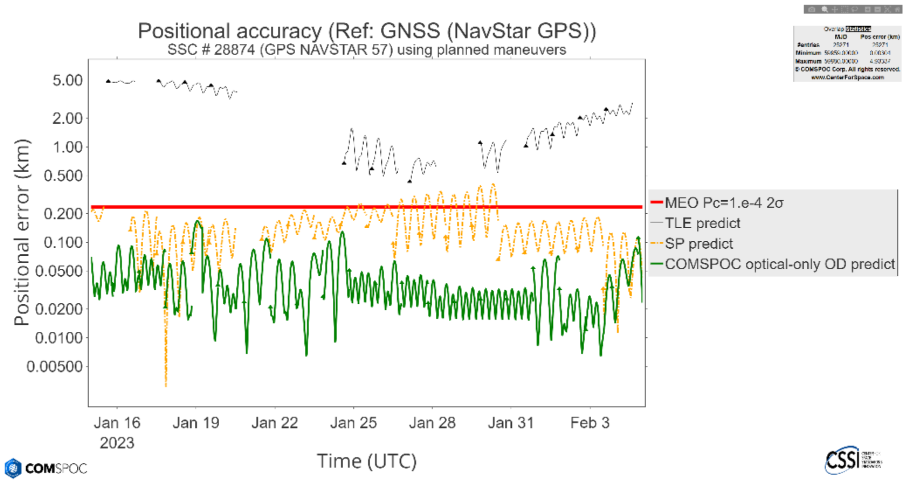

Figure 46: Log(Median accuracy) vs. time for SSC #28874 (NAVSTAR 57)

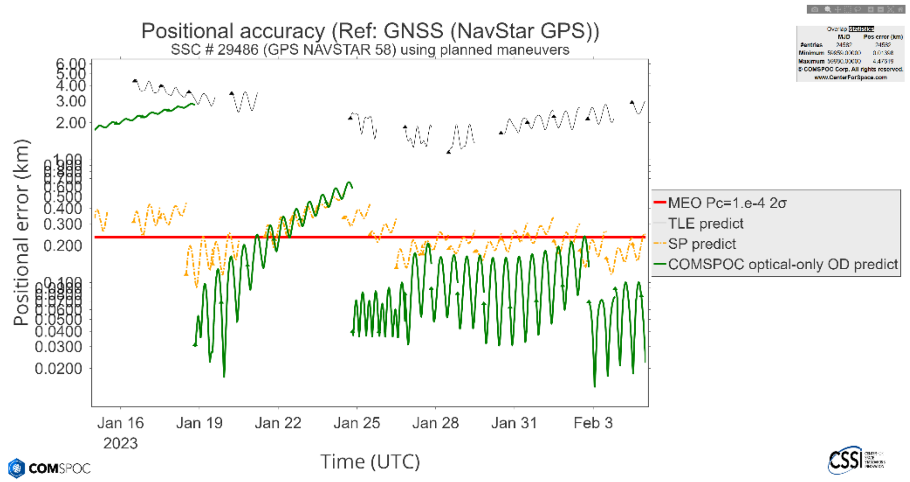

Figure 47: Log(Median accuracy) vs. time for SSC #29486 (NAVSTAR 58)

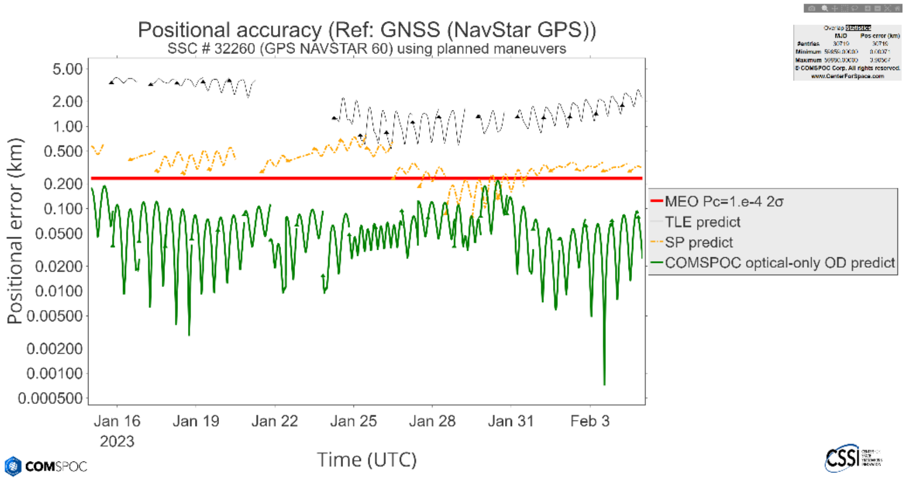

Figure 48: Log(Median accuracy) vs. time for SSC #32260 (NAVSTAR 60)

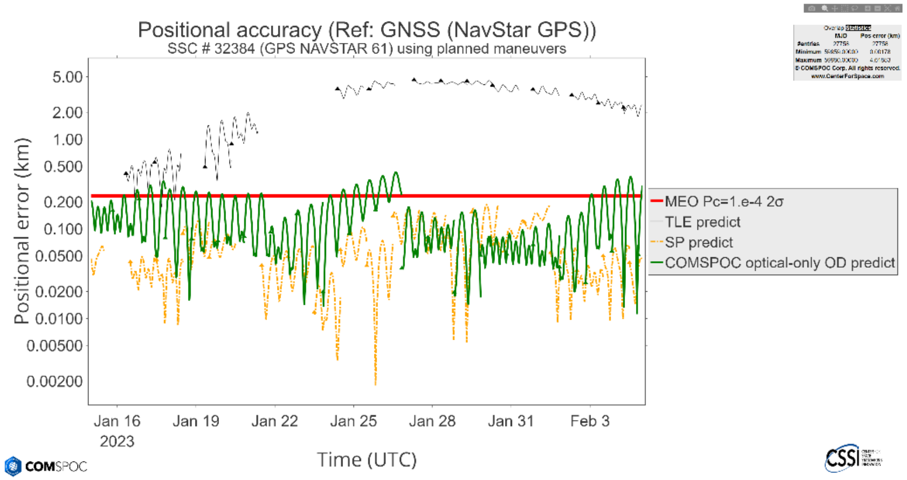

Figure 49: Log(Median accuracy) vs. time for SSC #32384 (NAVSTAR 61)

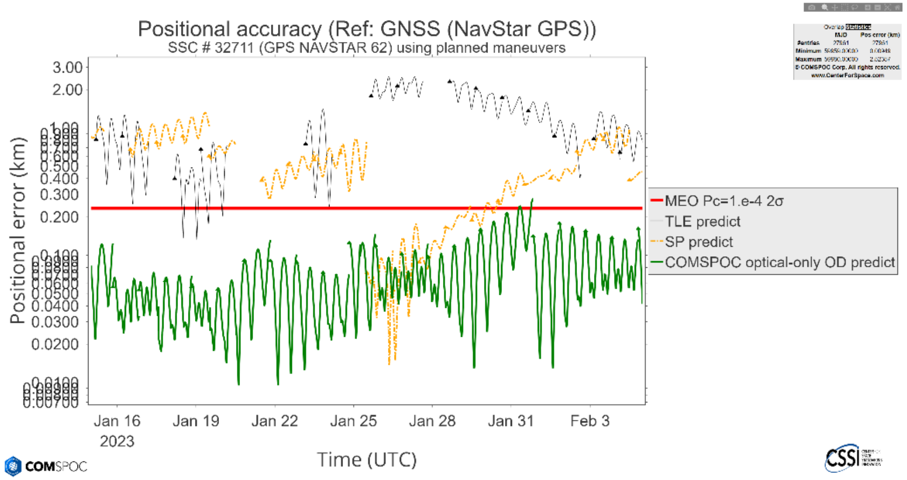

Figure 50: Log(Median accuracy) vs. time for SSC #32711 (NAVSTAR 62)

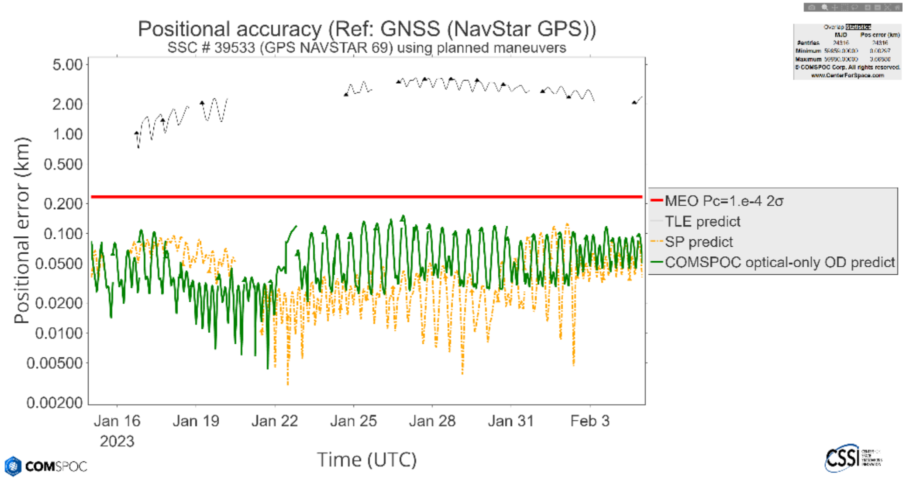

Figure 51: Log(Median accuracy) vs. time for SSC #39533 (NAVSTAR 69)

Appendix 2. Accuracy measured against COMSPOC smoothed ephemerides

A2.1. Linear-scale accuracy stats (referenced to COMSPOC smoothed ephemerides; sorted by GEO/MEO then by SSC)

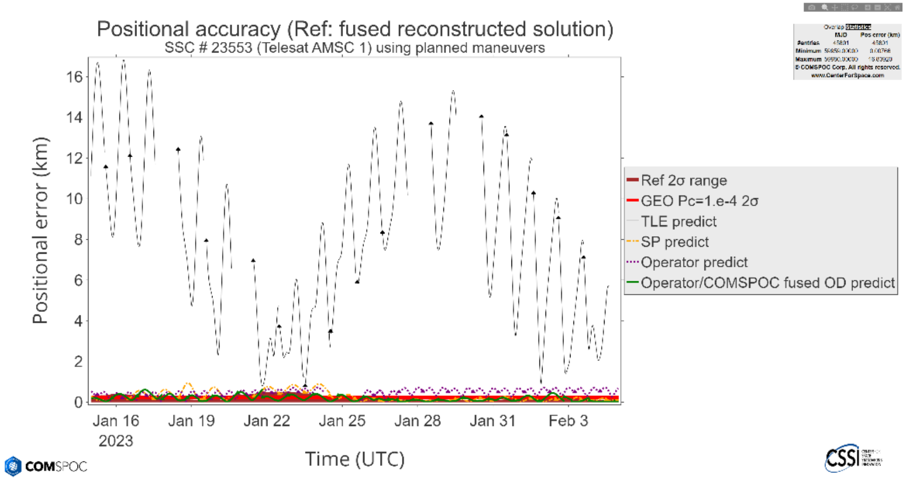

Figure 52: Median accuracy versus time for SSC #23553 (Telesat AMSC-1)

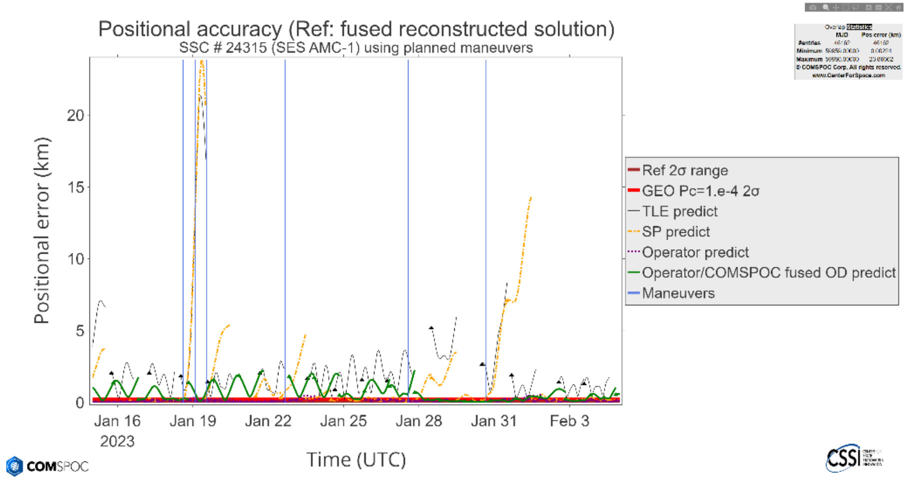

Figure 53: Median accuracy versus time for SSC #24315 (SES AMC-1)

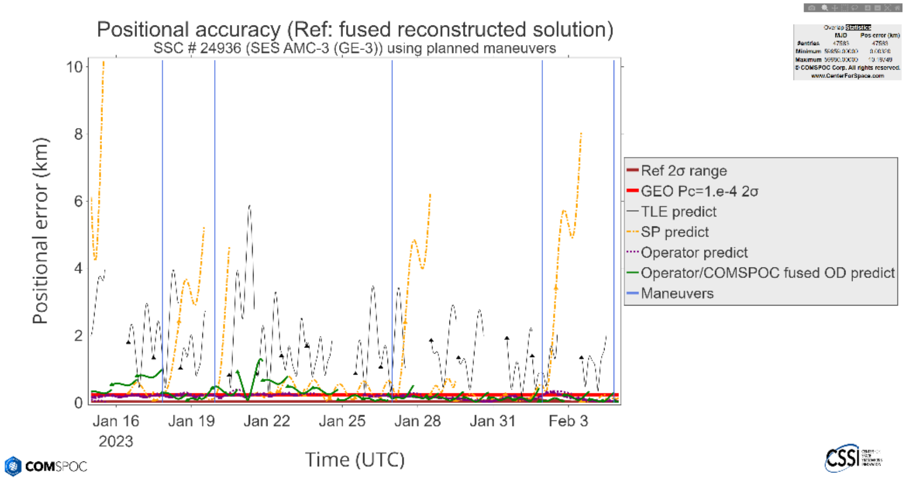

Figure 54: Median accuracy versus time for SSC #24936 (SES AMC-3)

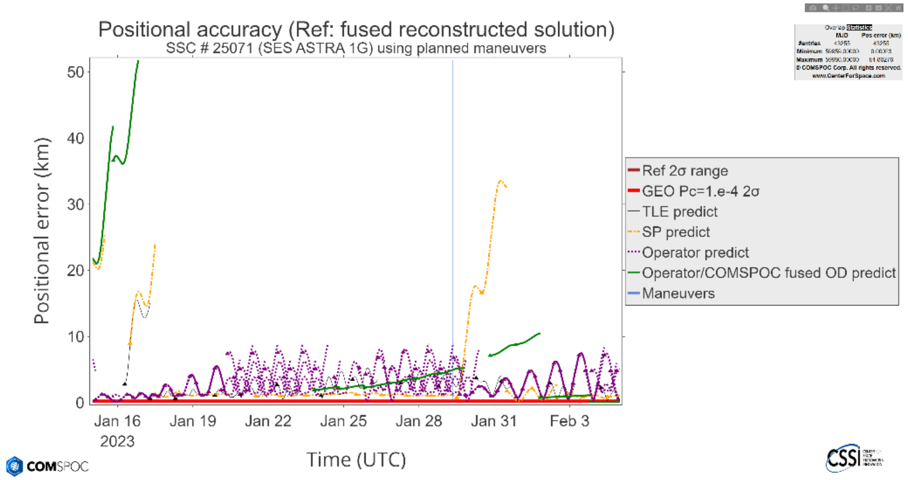

Figure 55: Median accuracy versus time for SSC #25071 (SES Astra 1G)

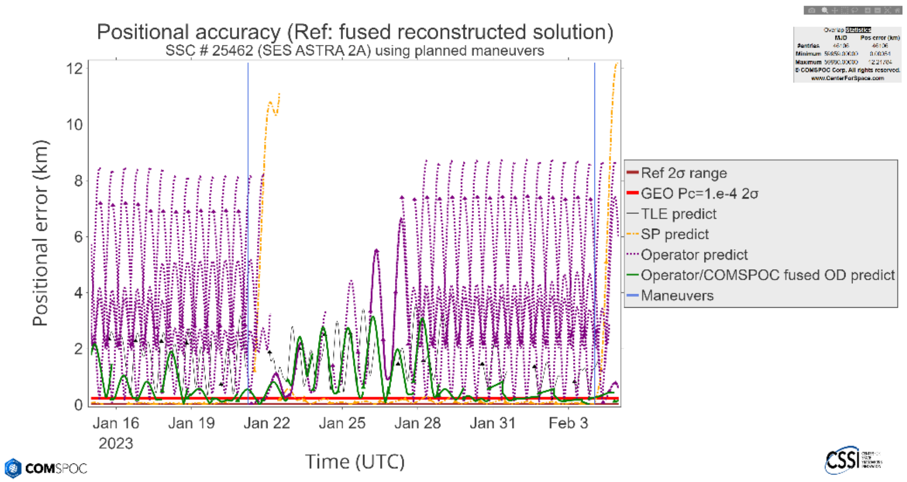

Figure 56: Median accuracy versus time for SSC #25462 (SES Astra 2A)

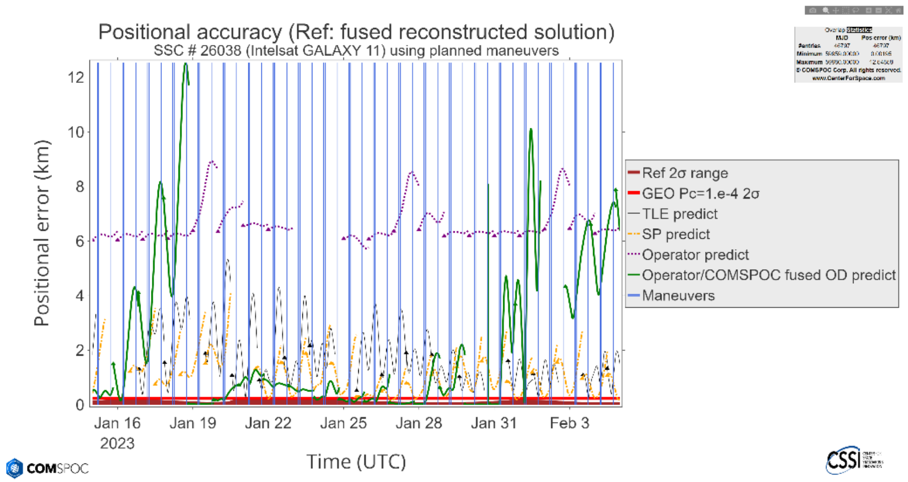

Figure 57: Median accuracy versus time for SSC #26038 (Intelsat Galaxy 11)

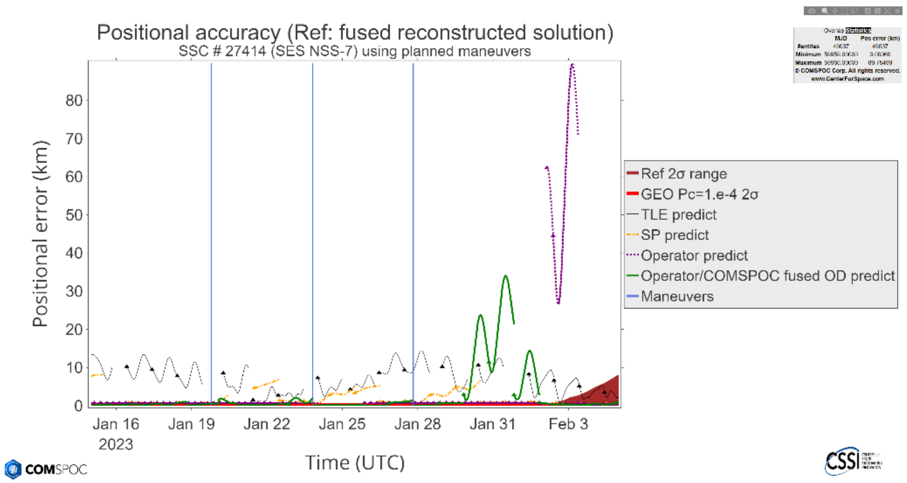

Figure 58: Median accuracy versus time for SSC #27414 (SES NSS-7)

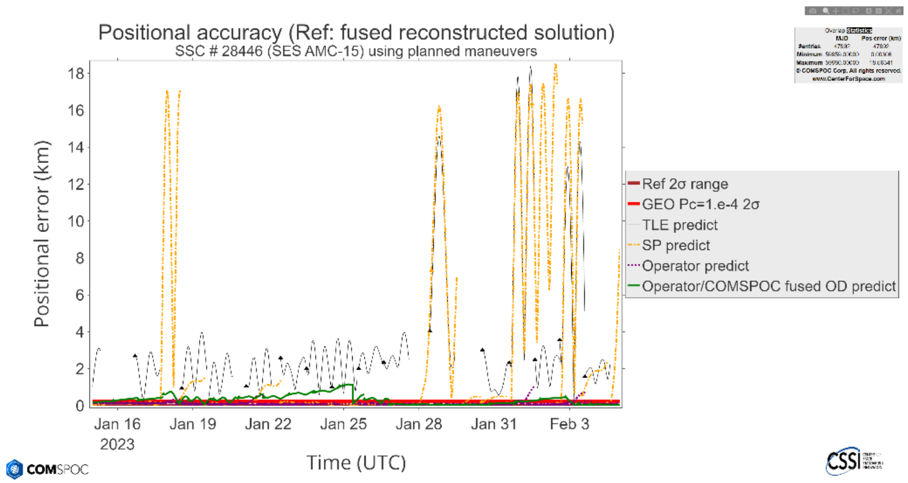

Figure 59: Median accuracy versus time for SSC #28446 (SES AMC-15)

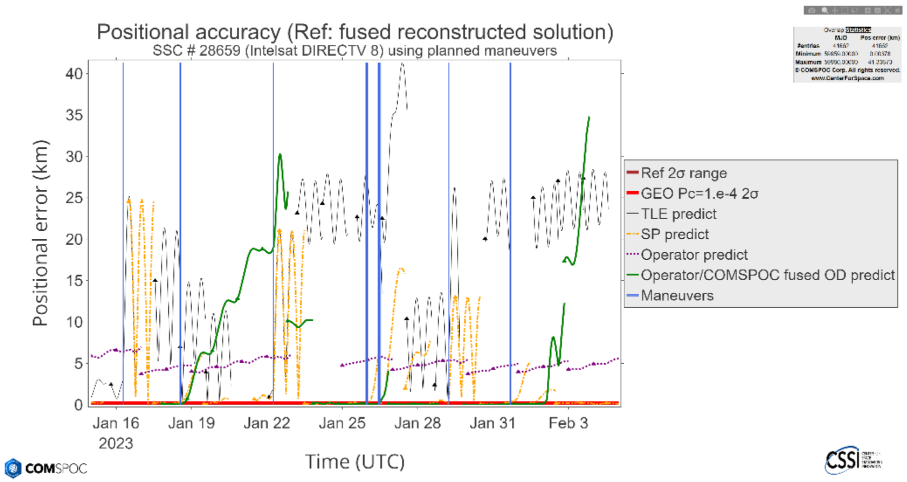

Figure 60: Median accuracy versus time for SSC #28659 (Intelsat DirecTV 8)

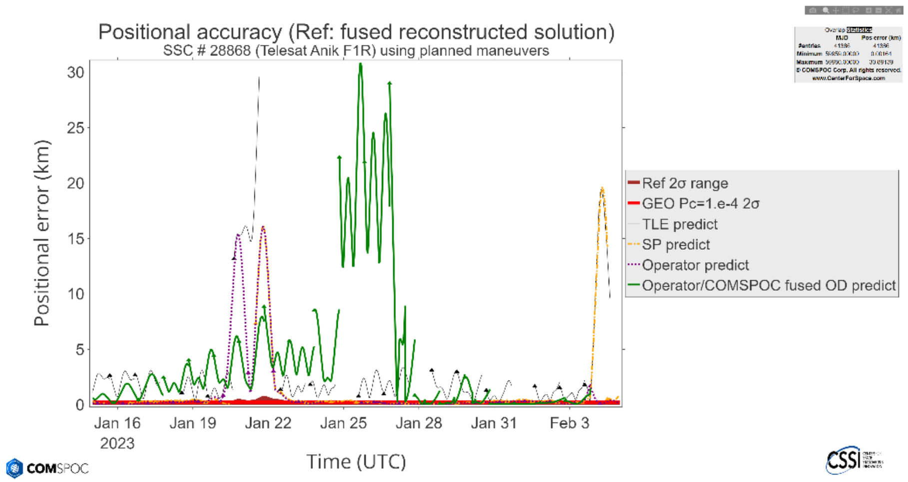

Figure 61: Median accuracy versus time for SSC #28868 (Telesat Anik F1R)

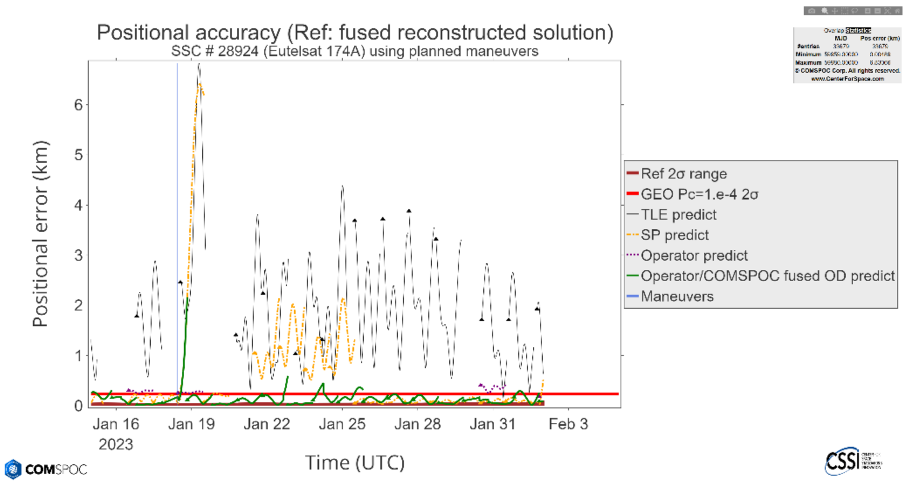

Figure 62: Median accuracy versus time for SSC #28924 (Eutelsat 174A)

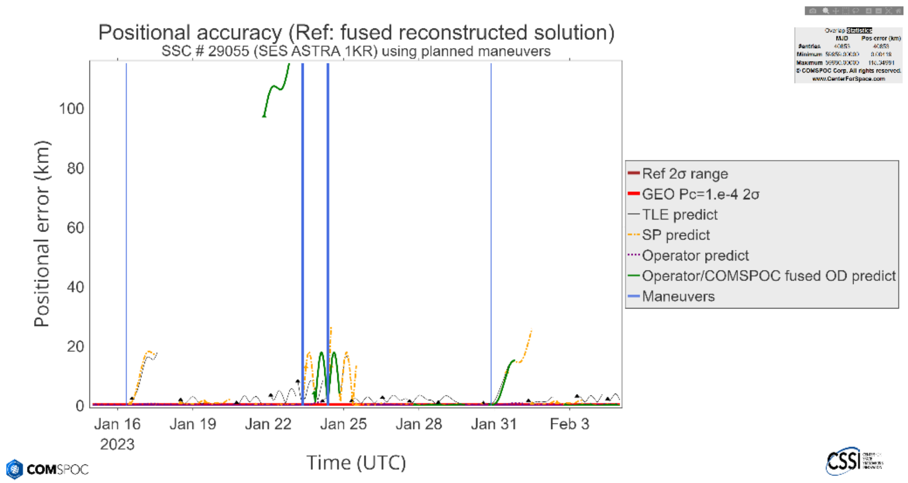

Figure 63: Median accuracy versus time for SSC #29055 (SES Astra 1KR)

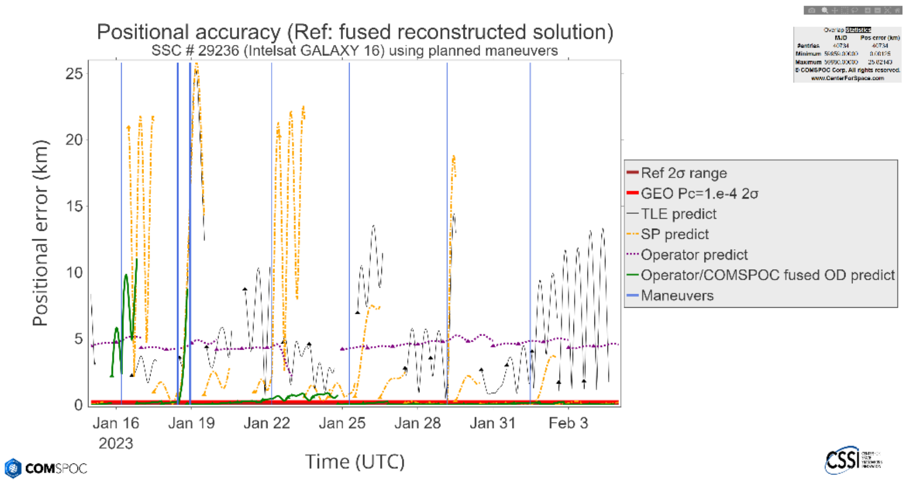

Figure 64: Median accuracy versus time for SSC #29236 (Intelsat Galaxy 16)

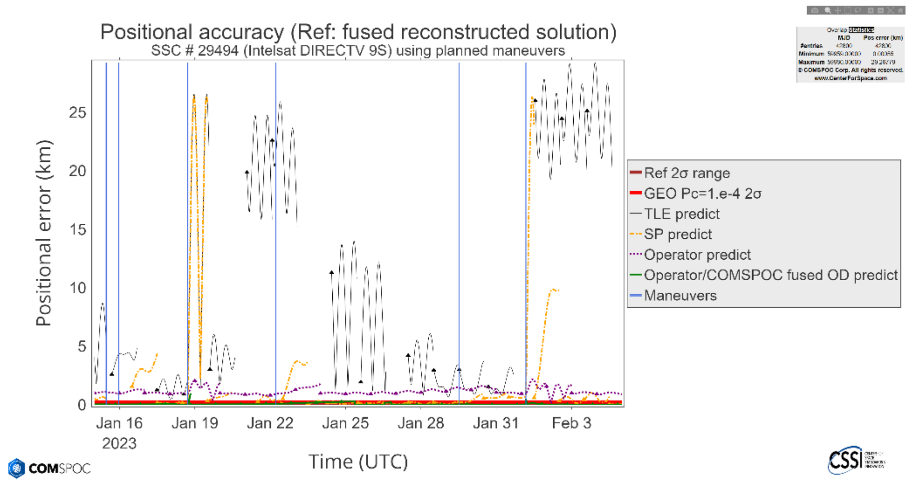

Figure 65: Median accuracy versus time for SSC #29494 (Intelsat DirecTV 9S)

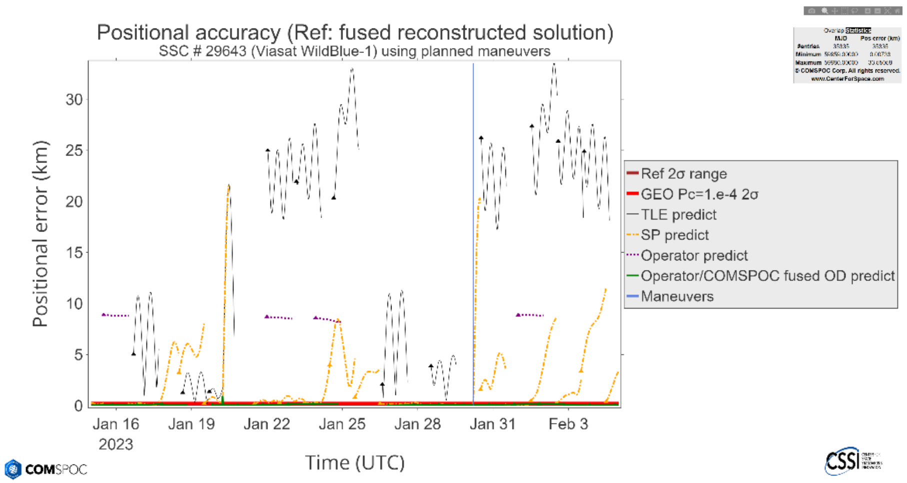

Figure 66: Median accuracy versus time for SSC #29643 (Viasat WildBlue-1)

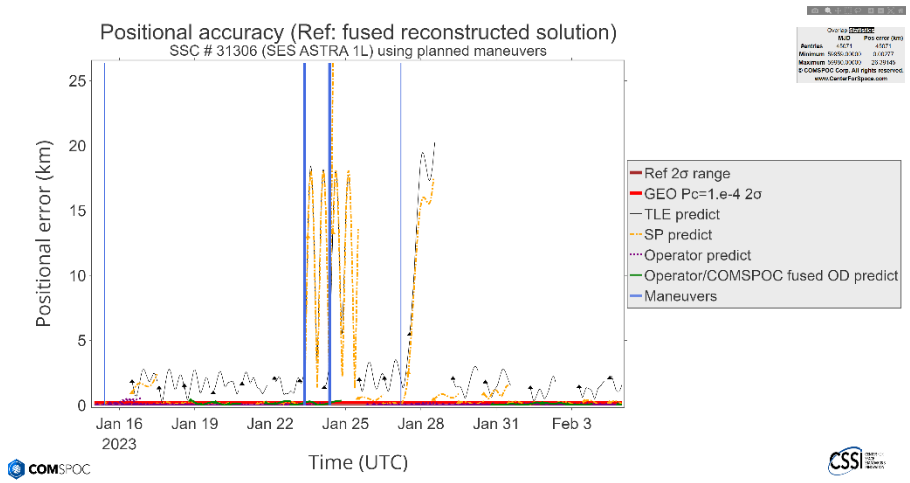

Figure 67: Median accuracy versus time for SSC #31306 (SES Astra 1L)

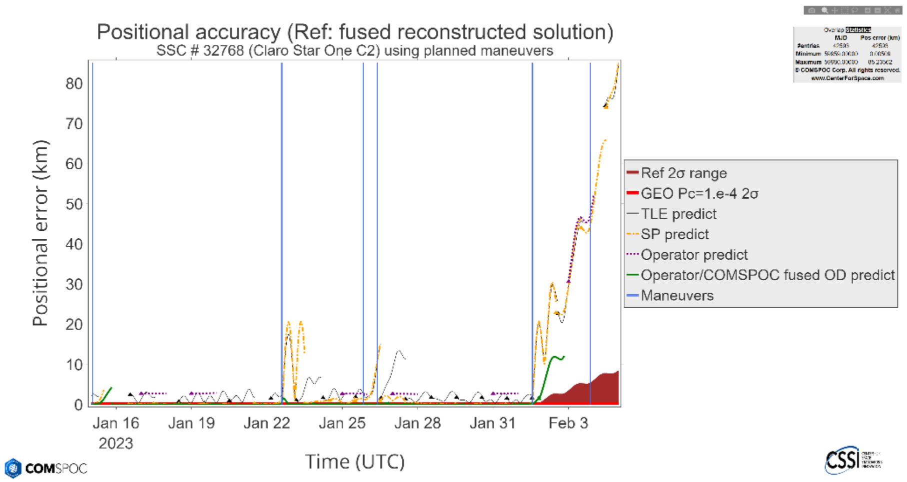

Figure 68: Median accuracy versus time for SSC #32768 (Claro Star One C2)

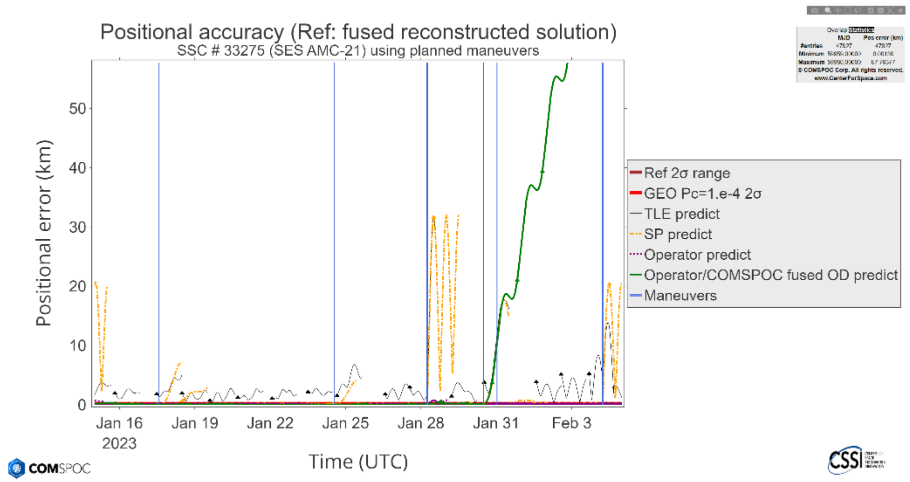

Figure 69: Median accuracy versus time for SSC #33275 (SES AMC-21)

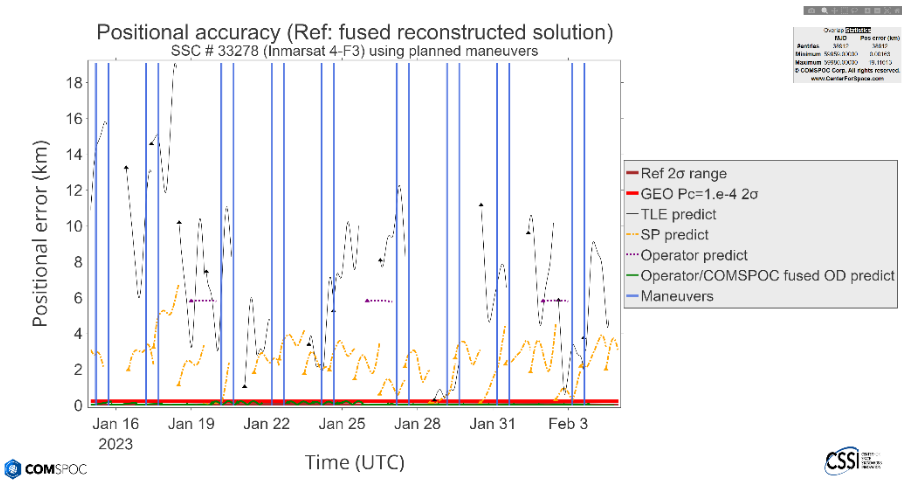

Figure 70: Median accuracy versus time for SSC #33278 (Inmarsat 4-F3)

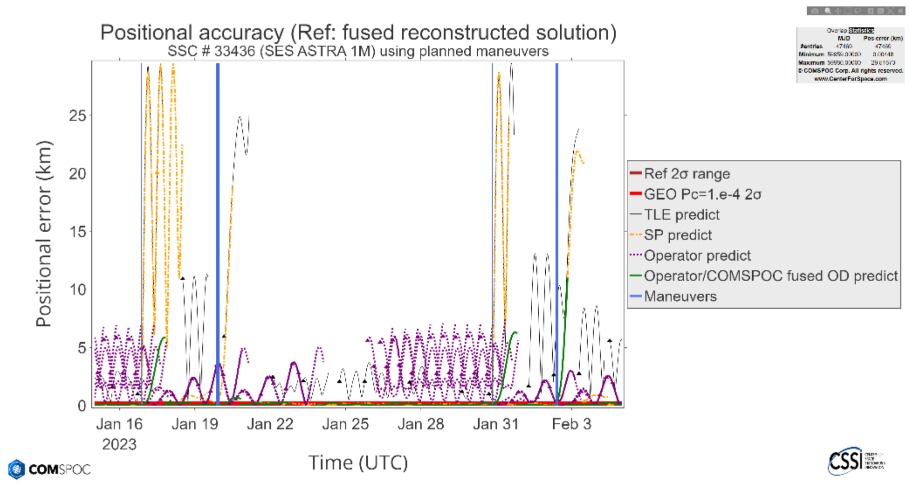

Figure 71: Median accuracy versus time for SSC #33436 (SES Astra 1M)

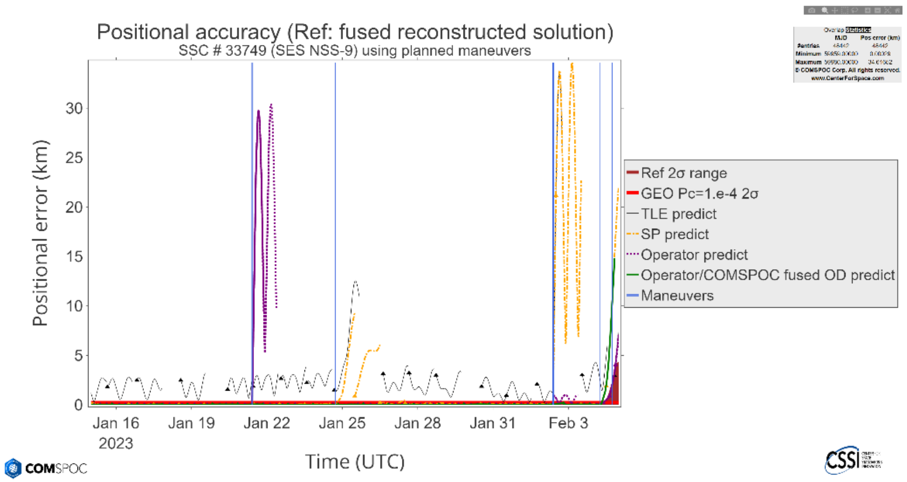

Figure 72: Median accuracy versus time for SSC #33749 (SES NSS-9)

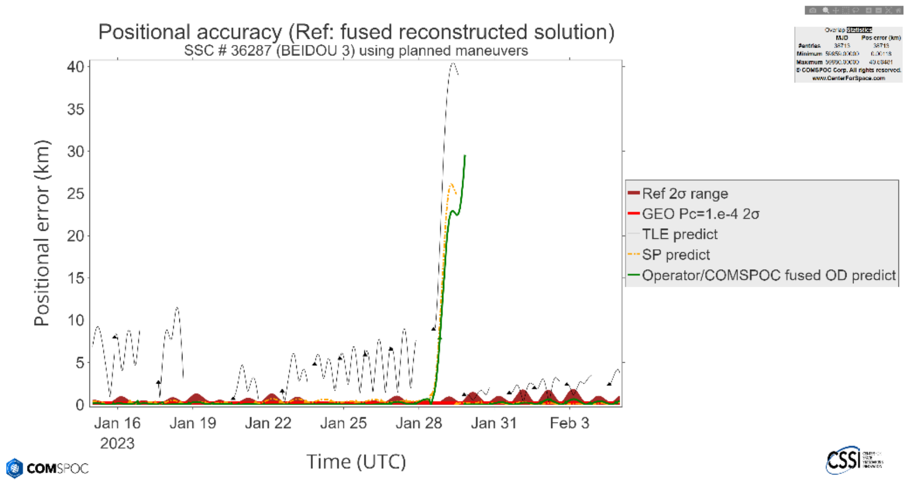

Figure 73: Median accuracy versus time for SSC #36287 (China Beidou 3)

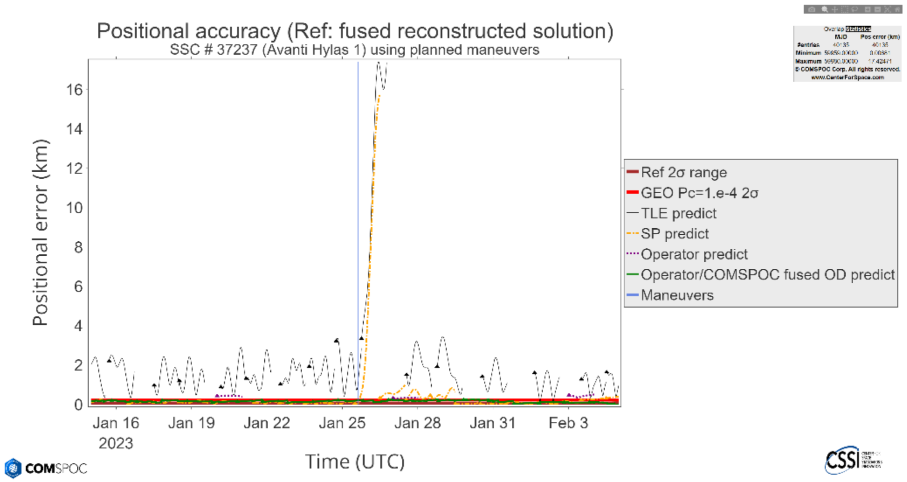

Figure 74: Median accuracy versus time for SSC #37237 (Avanti Hylas 1)

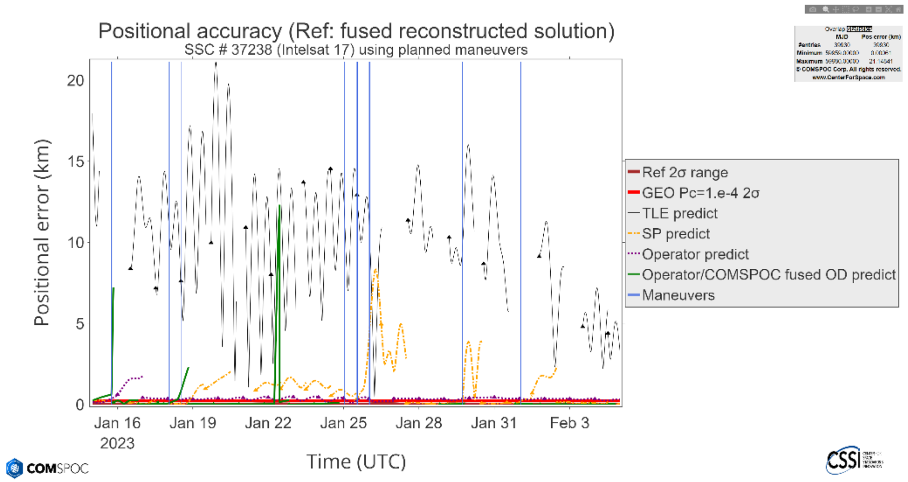

Figure 75: Median accuracy versus time for SSC #37238 (Intelsat 17)

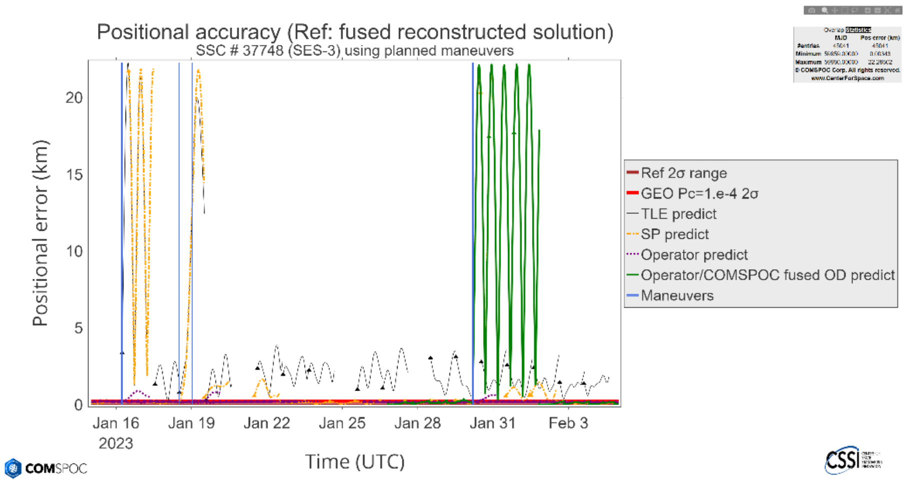

Figure 76: Median accuracy versus time for SSC #37748 (SES-3)

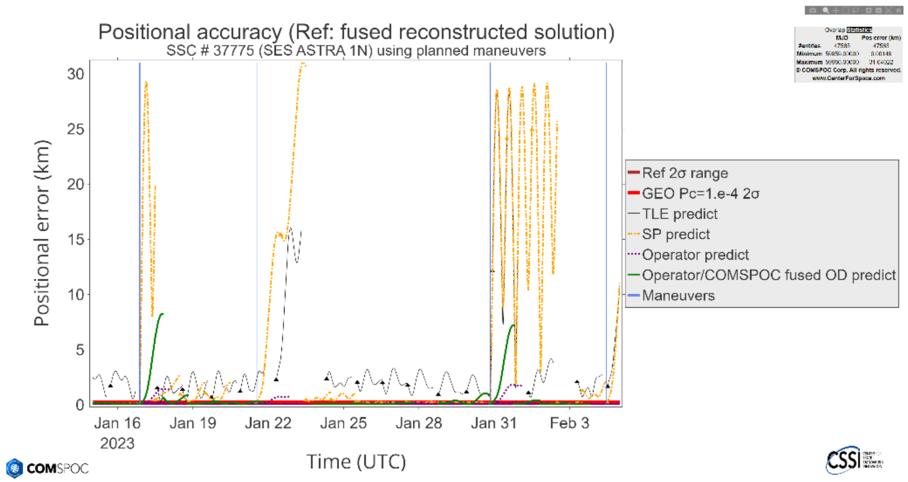

Figure 77: Median accuracy versus time for SSC #37775 (SES Astra 1N)

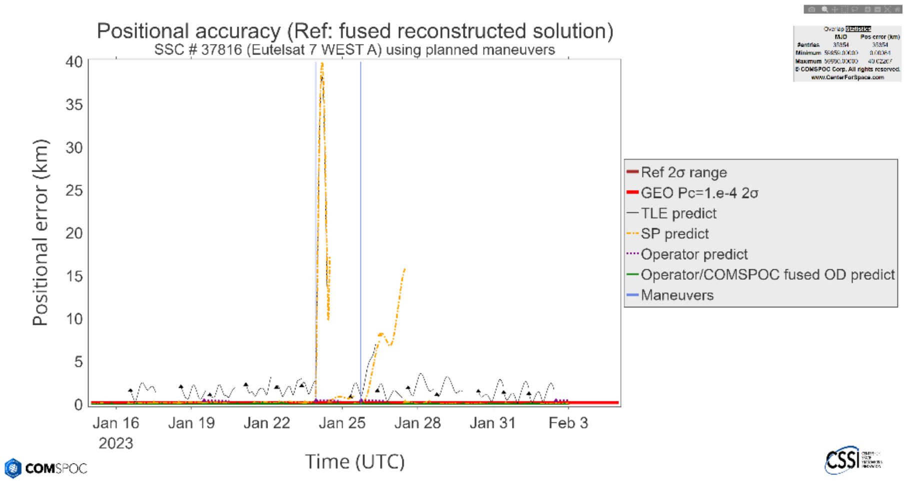

Figure 78: Median accuracy versus time for SSC #37816 (Eutelsat 7 West A)

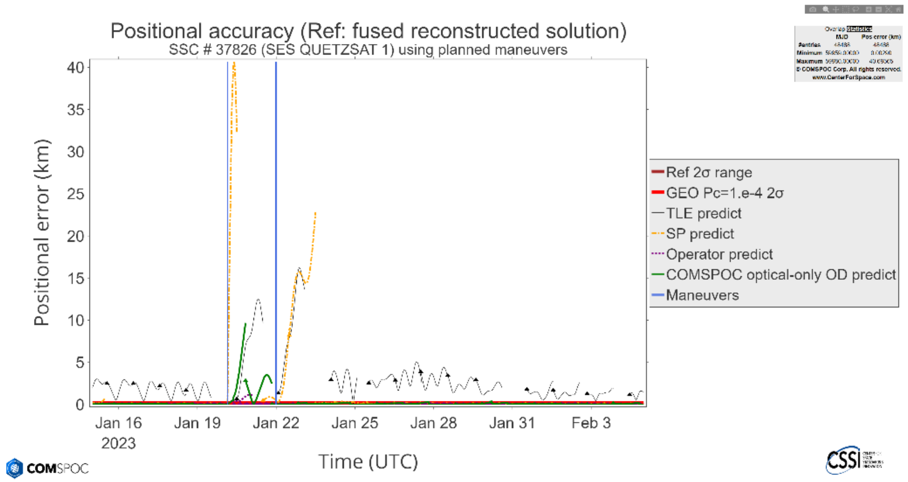

Figure 79: Median accuracy versus time for SSC #37826 (SES Quetzsat 1)

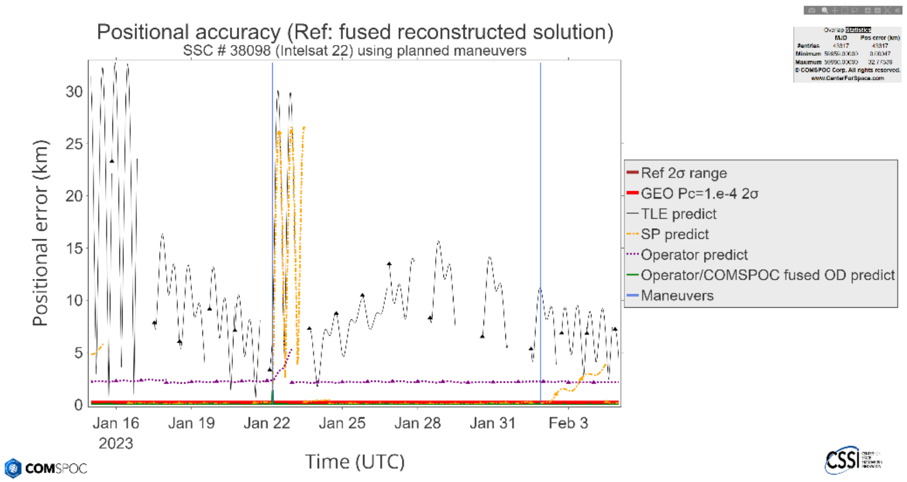

Figure 80: Median accuracy versus time for SSC #38098 (Intelsat 22)

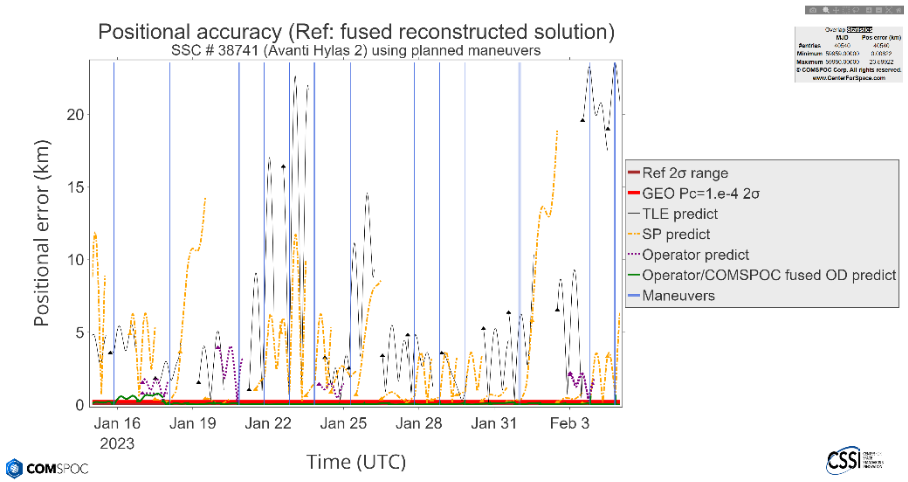

Figure 81: Median accuracy versus time for SSC #38741 (Avanti Hylas 2)

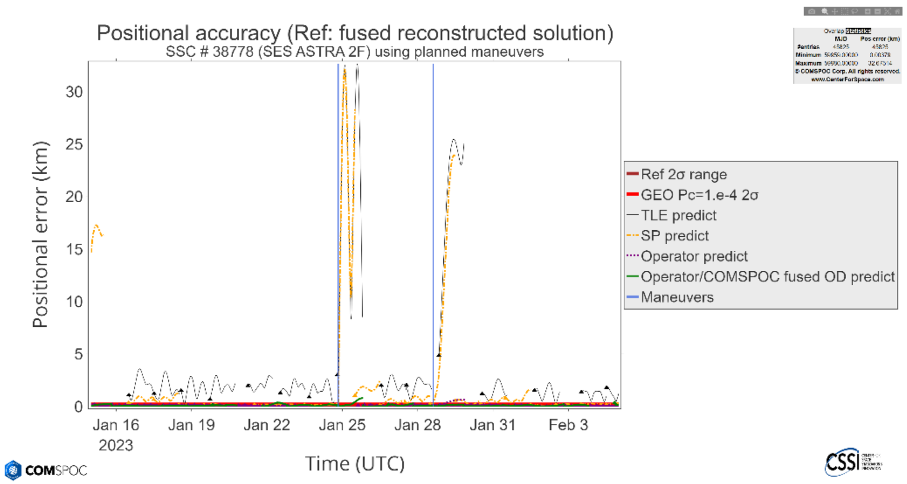

Figure 82: Median accuracy versus time for SSC #38778 (SES Astra 2F)

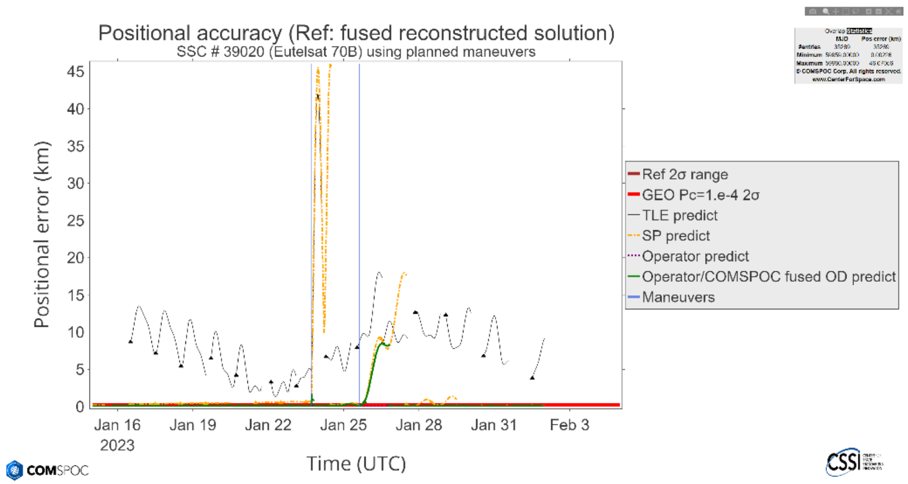

Figure 83: Median accuracy versus time for SSC #39020 (Eutelsat 70B)

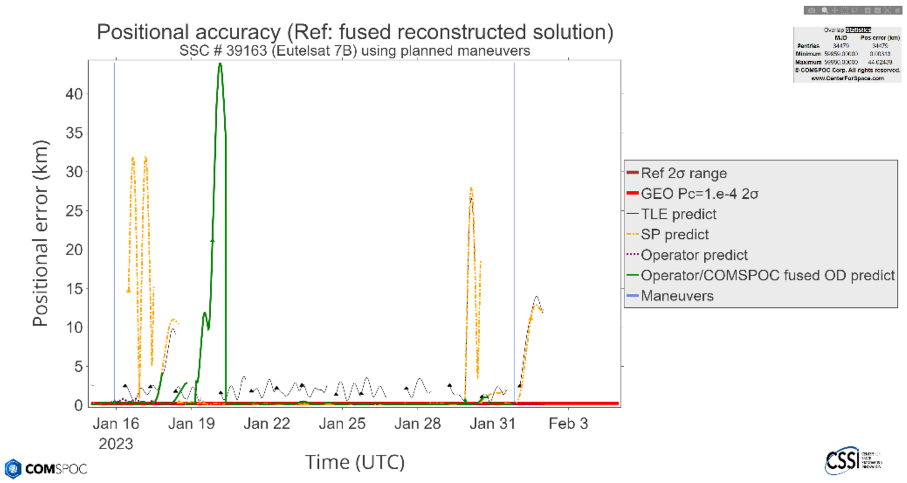

Figure 84: Median accuracy versus time for SSC #39163 (Eutelsat 7B)

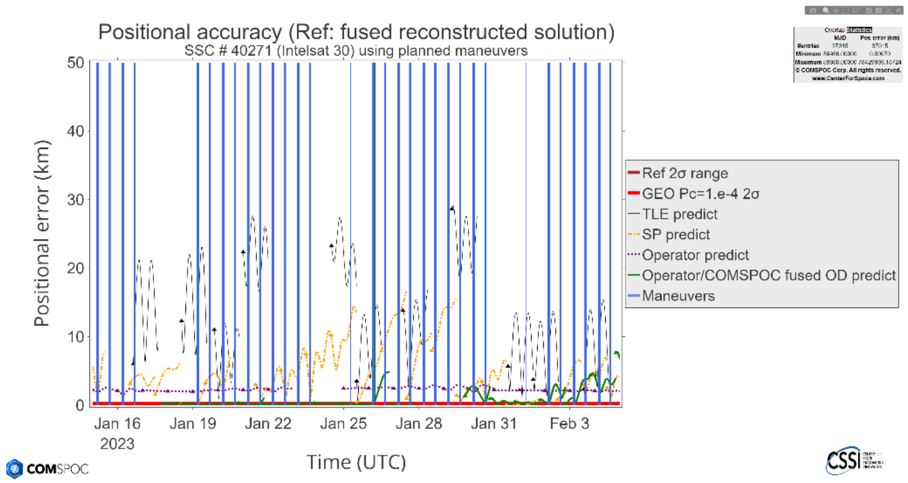

Figure 85: Median accuracy versus time for SSC #40271 (Intelsat 30)

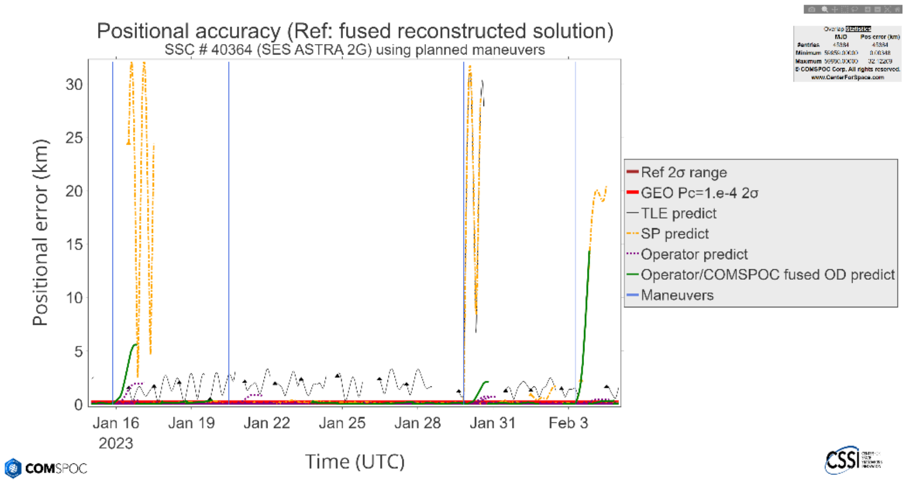

Figure 86: Median accuracy versus time for SSC #40364 (SES Astra 2G)

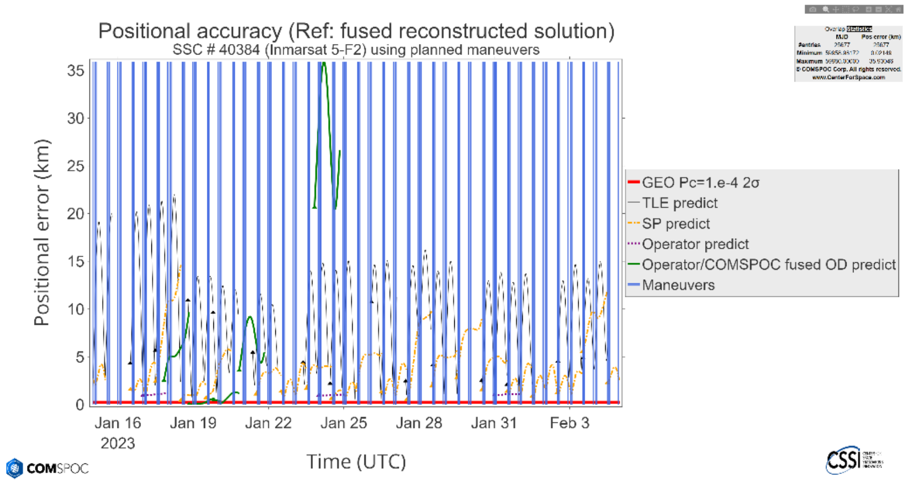

Figure 87: Median accuracy versus time for SSC #40384 (Inmarsat 5-F2)

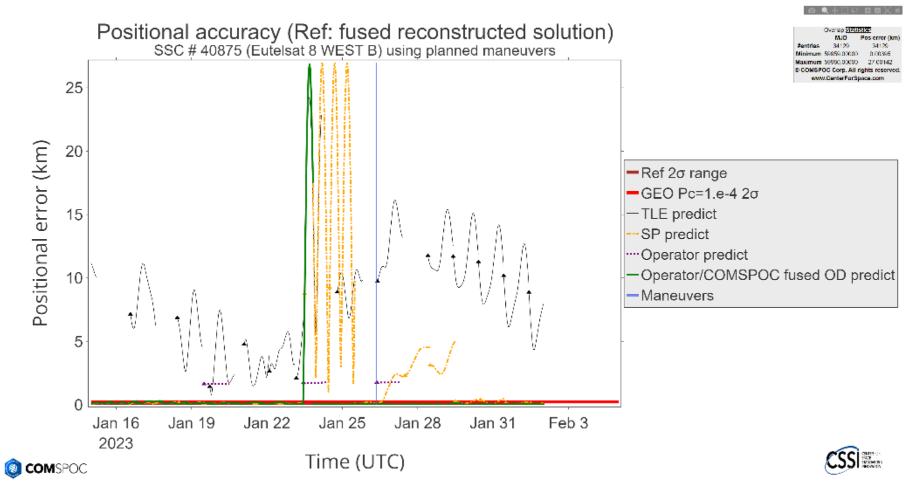

Figure 88: Median accuracy versus time for SSC #40875 (Eutelsat 8 West B)

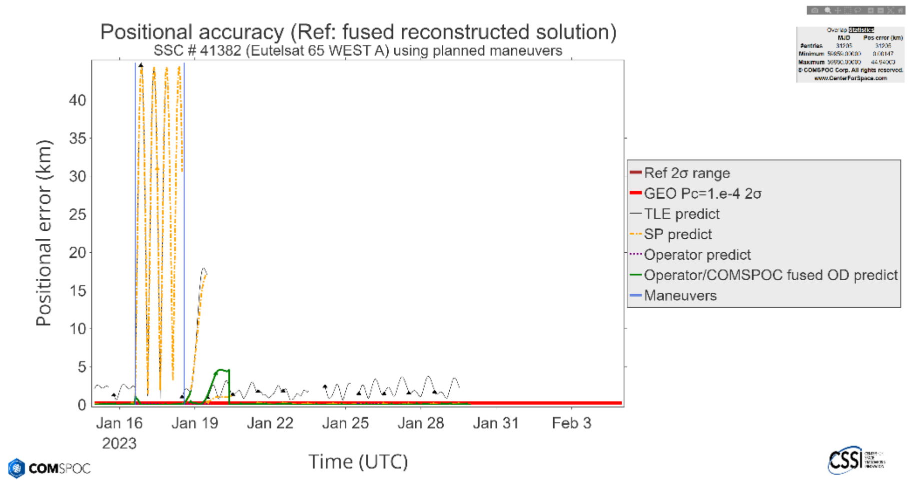

Figure 89: Median accuracy versus time for SSC #41382 (Eutelsat 65 West A)

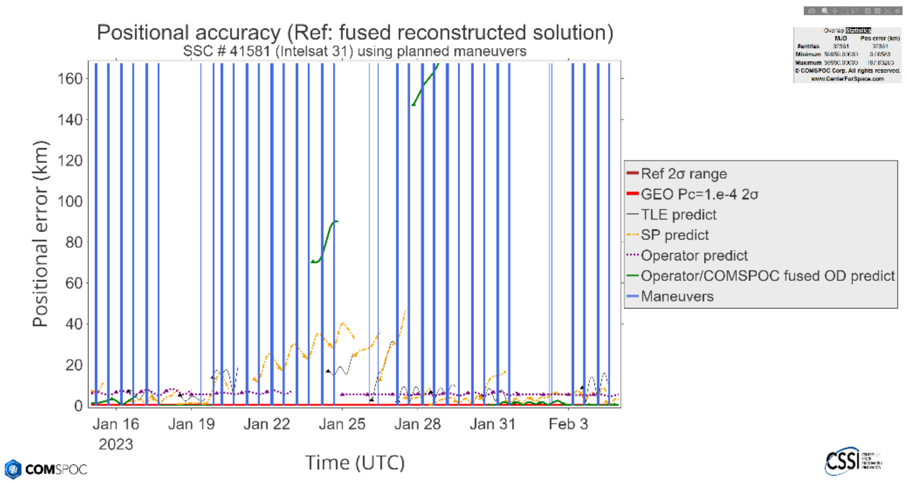

Figure 90: Median accuracy versus time for SSC #41581 (Intelsat 31)

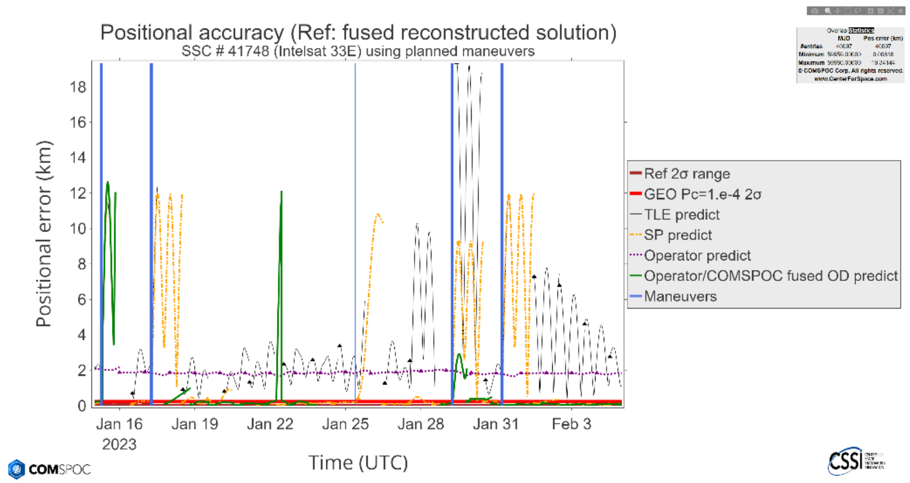

Figure 91: Median accuracy versus time for SSC #41748 (Intelsat 33E)

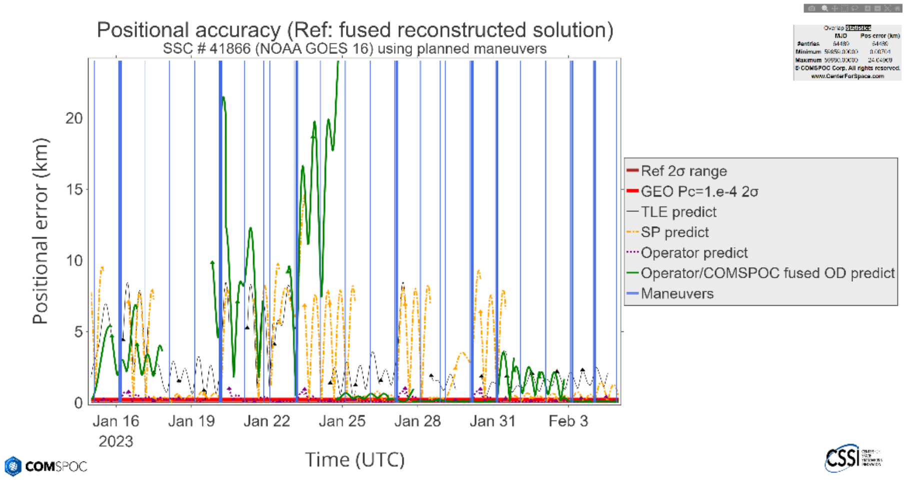

Figure 92: Median accuracy versus time for SSC #41866 (NOAA GOES 16)

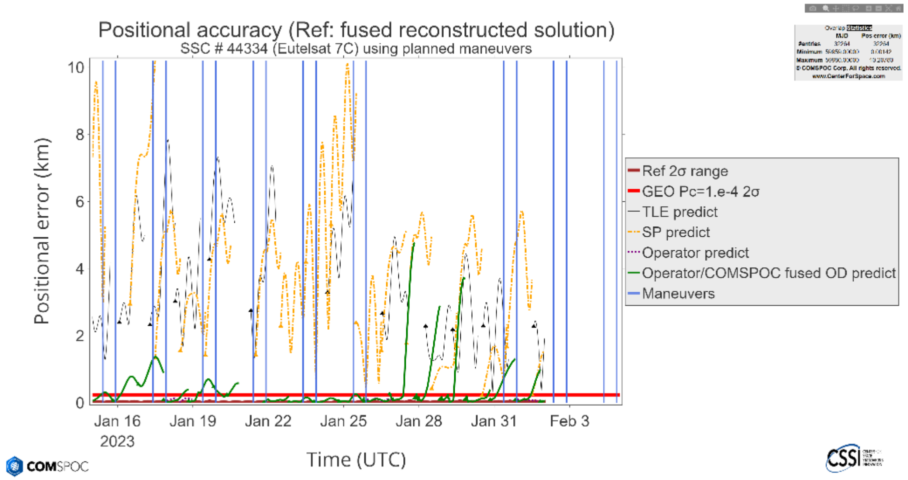

Figure 93: Median accuracy versus time for SSC #44334 (Eutelsat 7C)

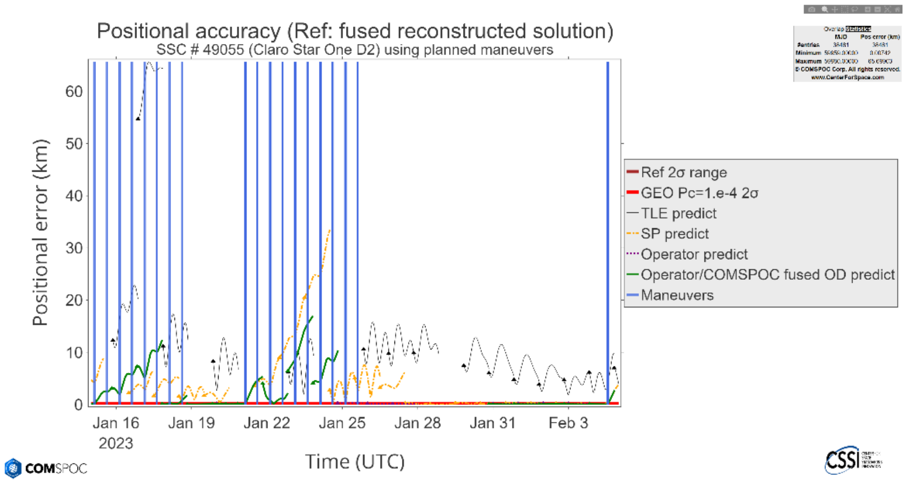

Figure 94: Median accuracy versus time for SSC #49055 (Claro Star One D2)

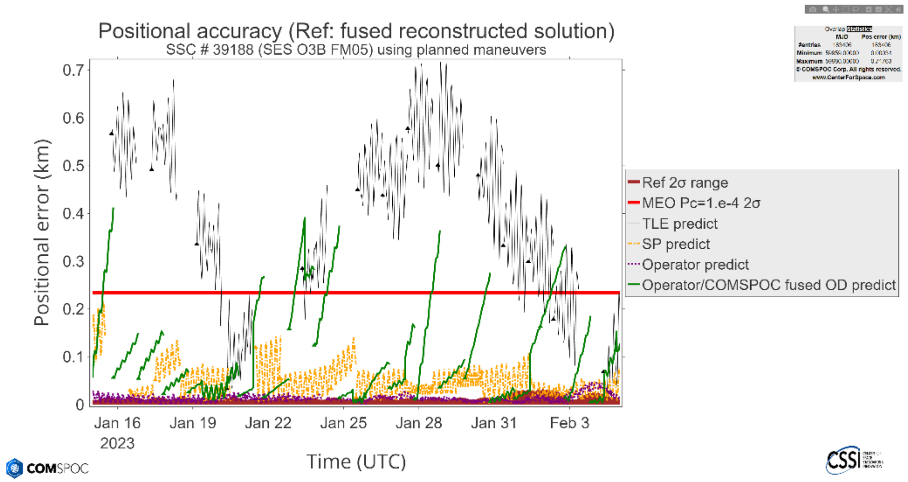

Figure 95: Median accuracy versus time for SSC #39188 (SES O3B FM05)

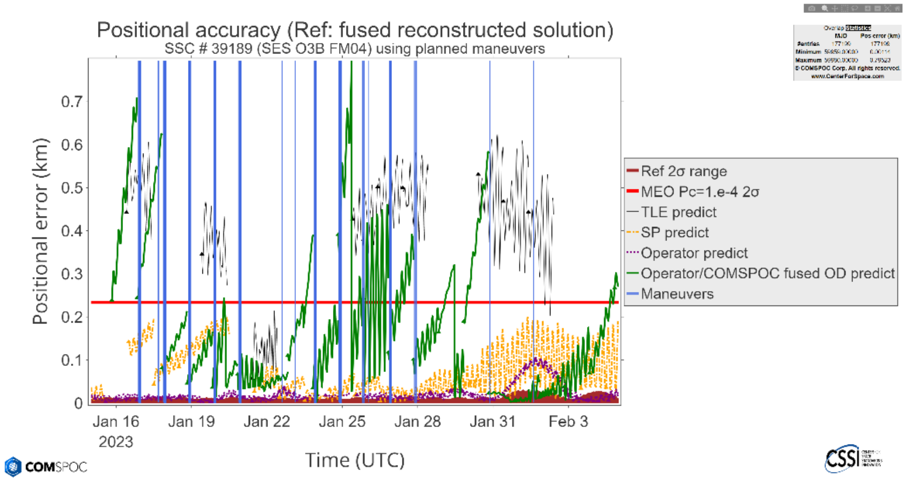

Figure 96: Median accuracy versus time for SSC #39189 (SES O3B FM04)

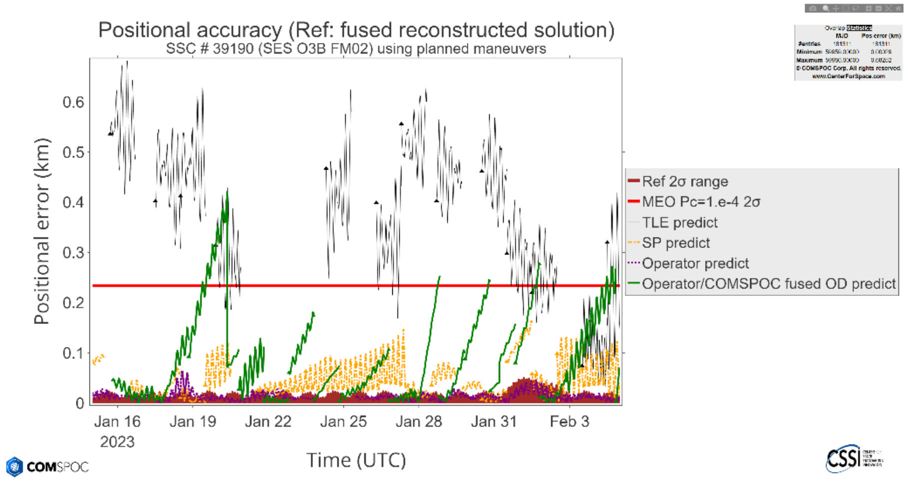

Figure 97: Median accuracy versus time for SSC #39190 (SES O3B FM02)

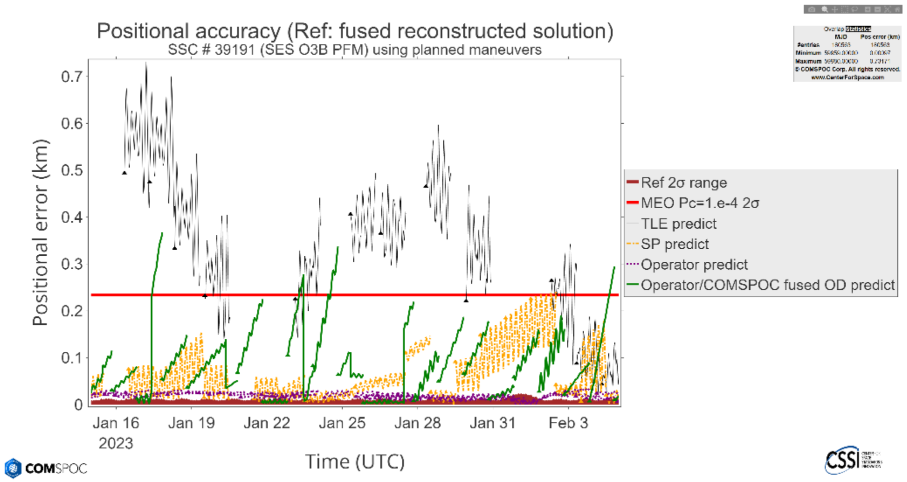

Figure 98: Median accuracy versus time for SSC #39191 (SES O3B PFM)

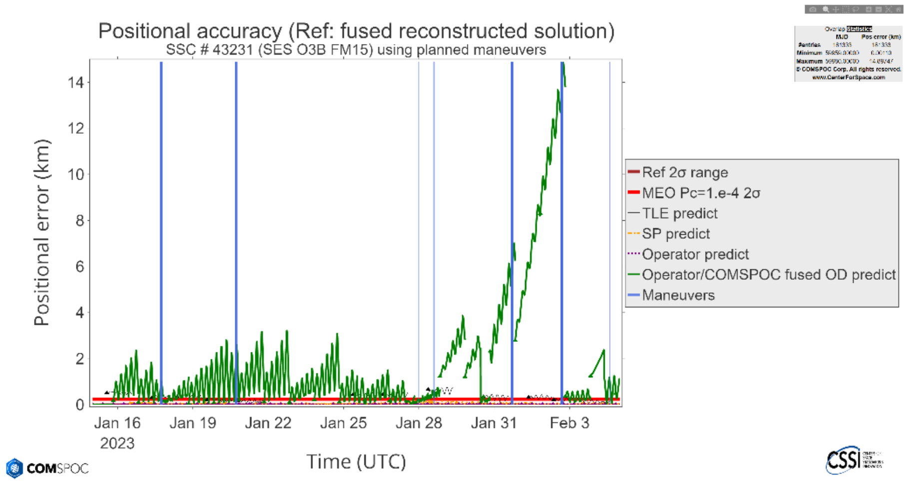

Figure 99: Median accuracy versus time for SSC #43231 (SES O3B FM15)

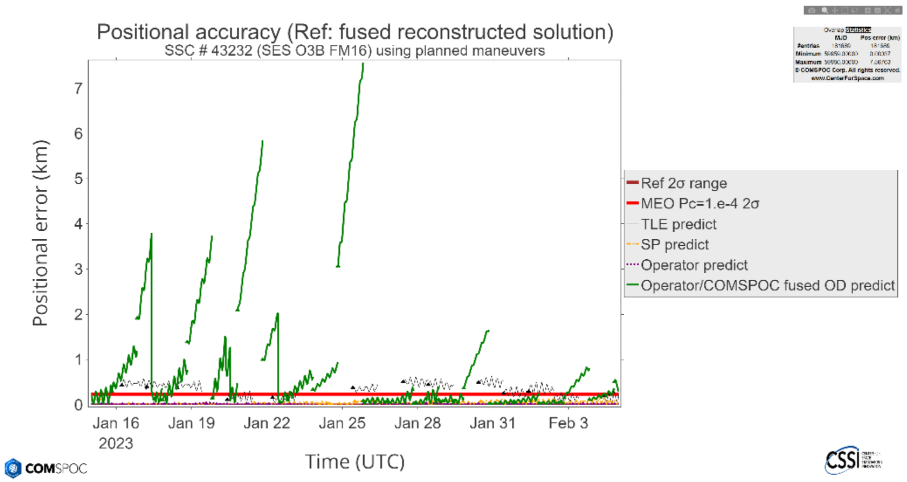

Figure 100: Median accuracy versus time for SSC #43232 (SES O3B FM16)

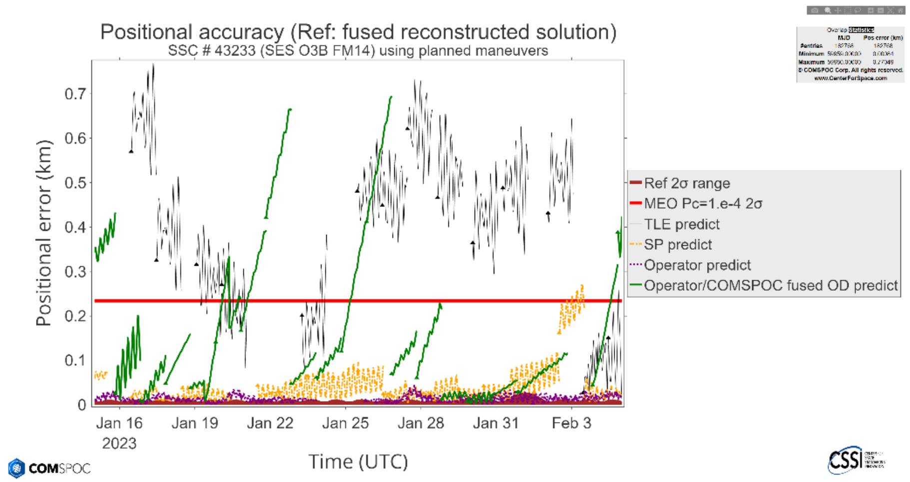

Figure 101: Median accuracy versus time for SSC #43233 (SES O3B FM14)

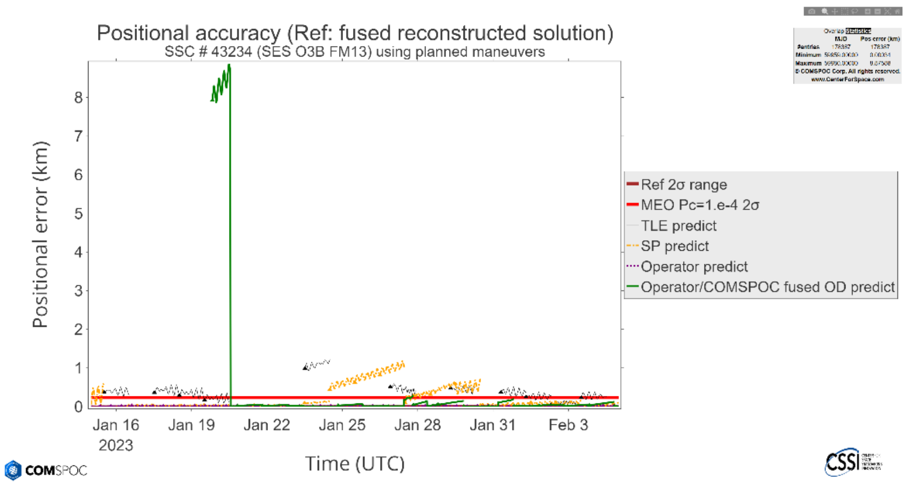

Figure 102: Median accuracy versus time for SSC #43234 (SES O3B FM13)

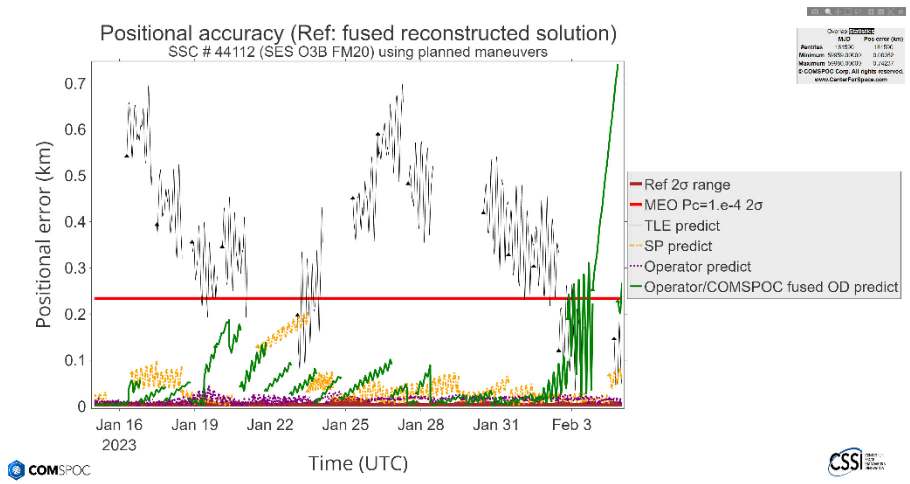

Figure 103: Median accuracy versus time for SSC #44112 (SES O3B FM20)

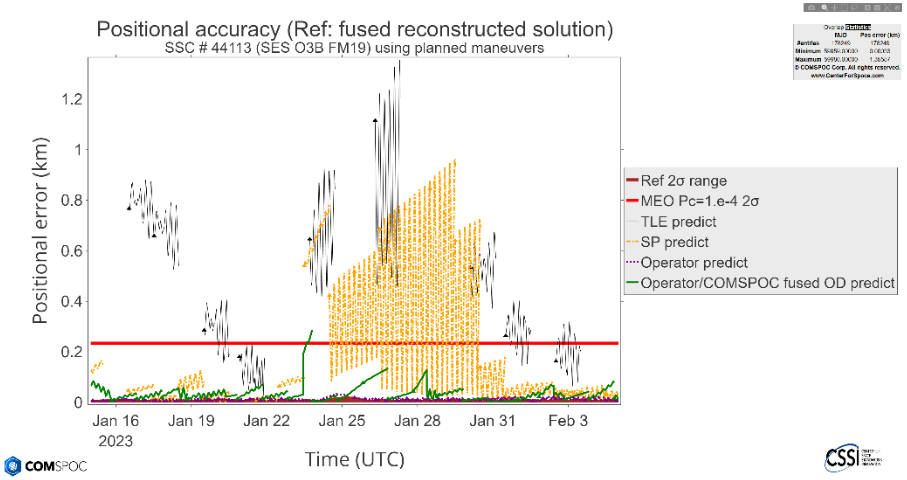

Figure 104: Median accuracy versus time for SSC #44113 (SES O3B FM19)

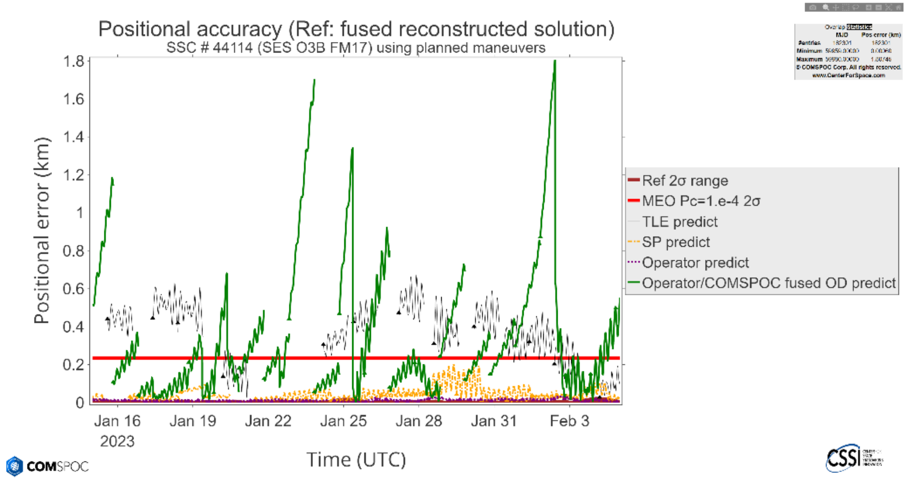

Figure 105: Median accuracy versus time for SSC #44114 (SES O3B FM17)

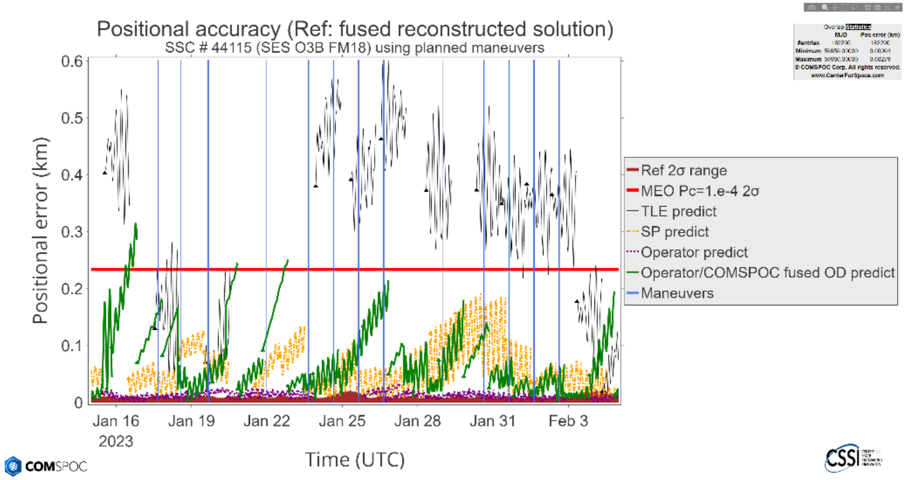

Figure 106: Median accuracy versus time for SSC #44115 (SES O3B FM18)

A2.2. Log-scale accuracy stats (referenced to COMSPOC smoothed ephemerides; sorted by GEO/MEO regime and then by SSC #)

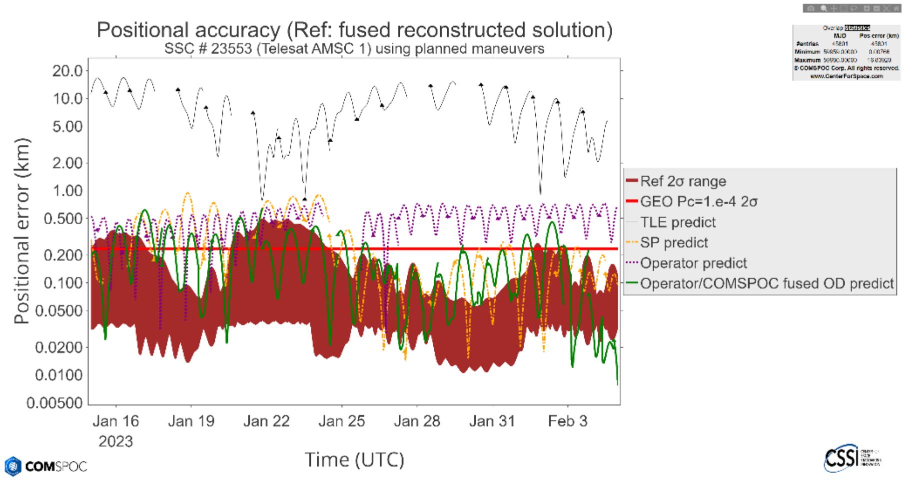

Figure 107: Log (median accuracy) versus time for SSC #23553 (Telesat AMSC-1)

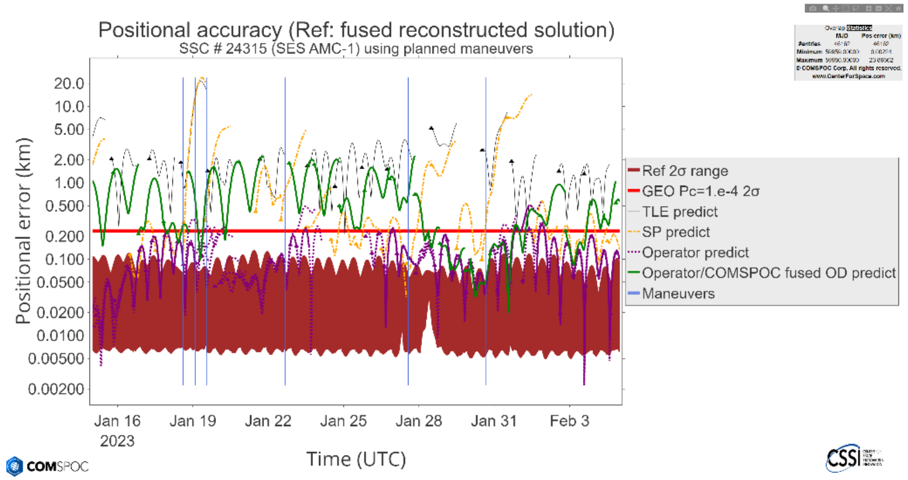

Figure 108: Log (median accuracy) versus time for SSC #24315 (SES AMC-1)

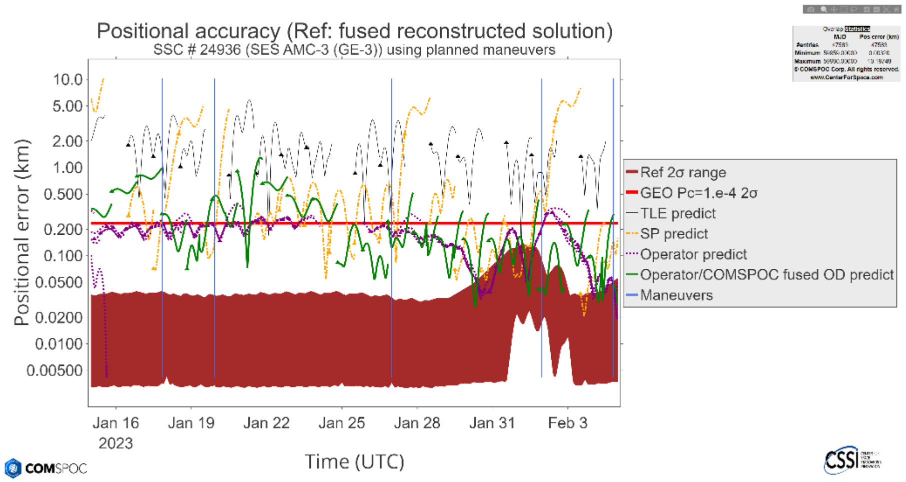

Figure 109: Log (median accuracy) versus time for SSC #24936 (SES AMC-3)

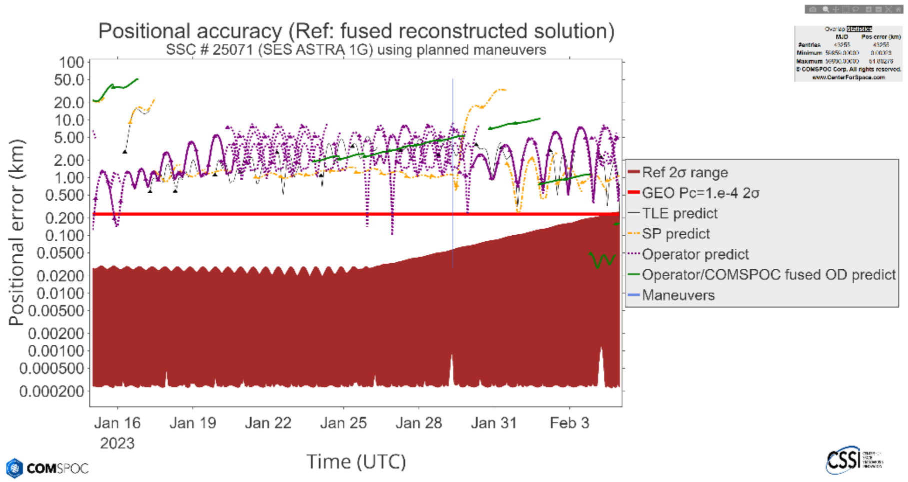

Figure 110: Log (median accuracy) versus time for SSC #25071 (SES Astra 1G)

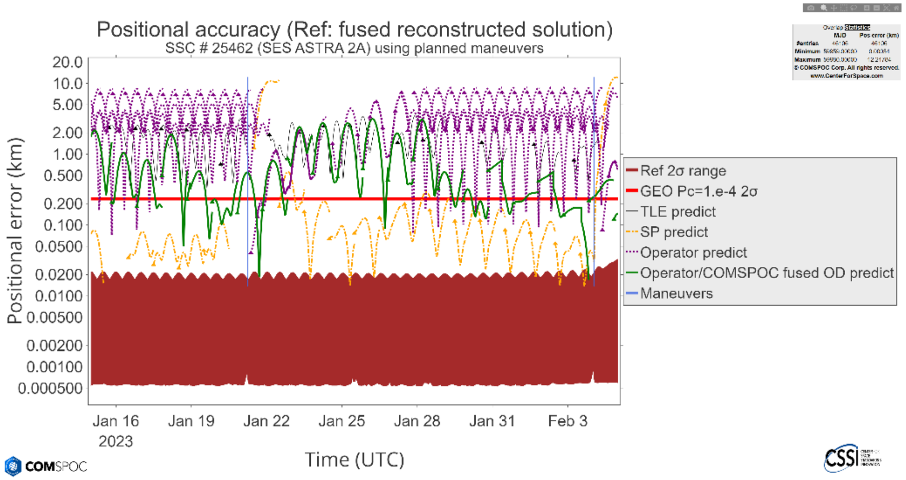

Figure 111: Log (median accuracy) versus time for SSC #25462 (SES Astra 2A)

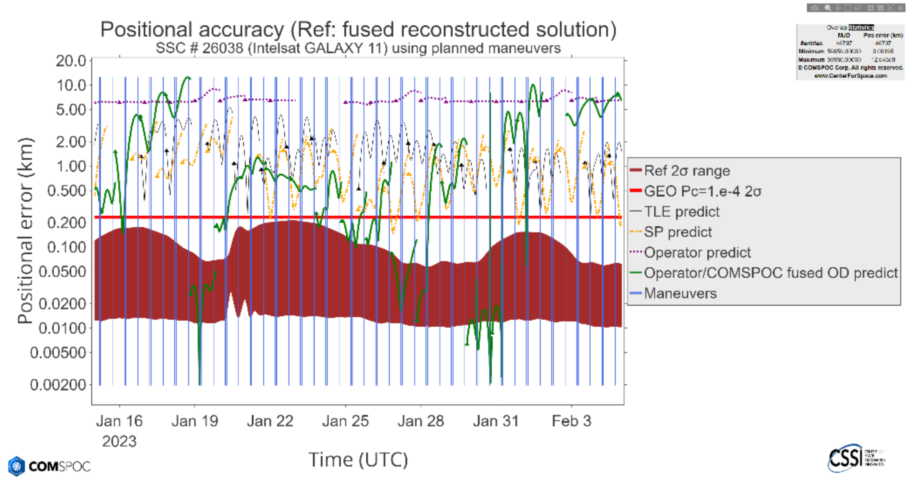

Figure 112: Log (median accuracy) versus time for SSC #26038 (Intelsat Galaxy 11)

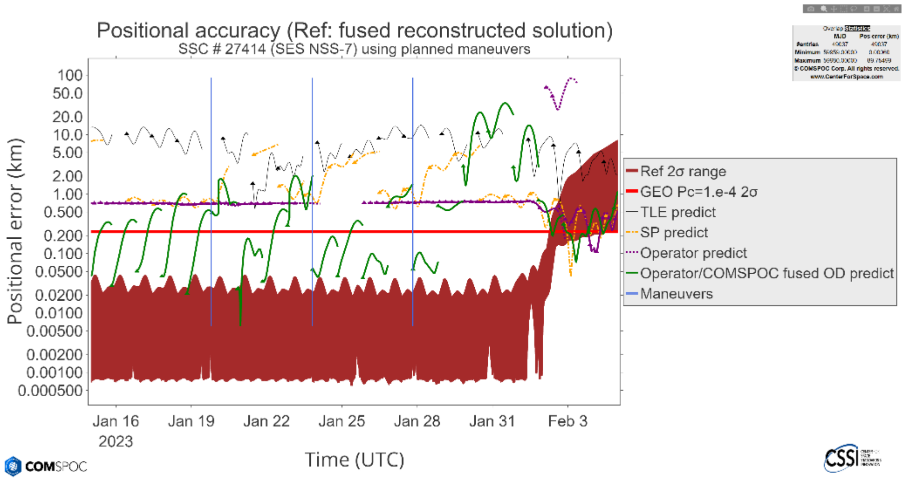

Figure 113: Log (median accuracy) versus time for SSC #27414 (SES NSS-7)

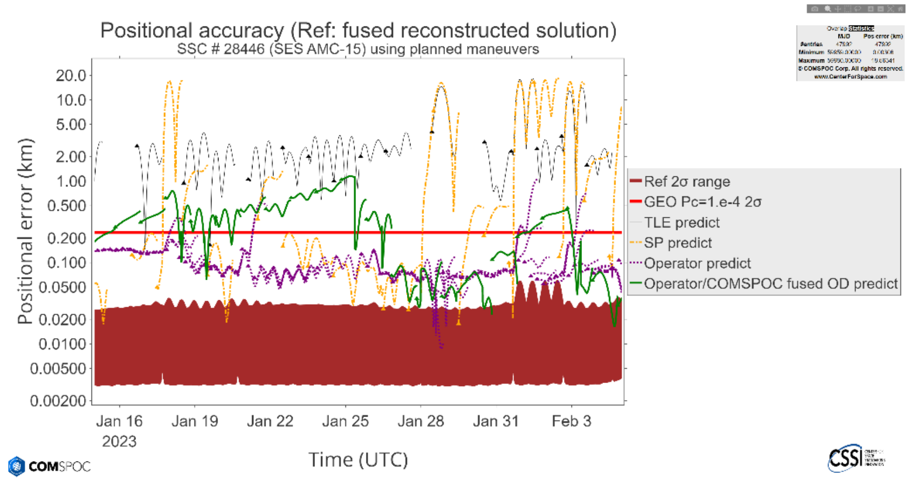

Figure 114: Log (median accuracy) versus time for SSC #28446 (SES AMC-15)

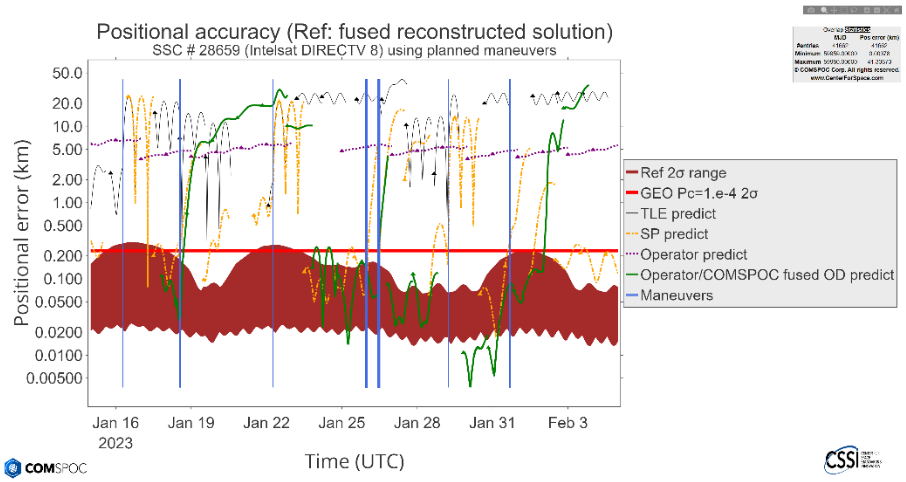

Figure 115: Log (median accuracy) versus time for SSC #28659 (Intelsat DirecTV 8)

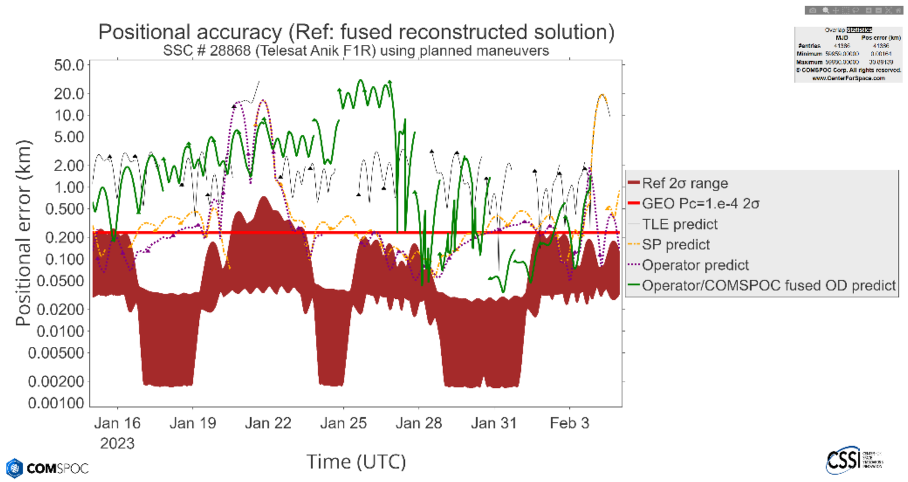

Figure 116: Log (median accuracy) versus time for SSC #28868 (Telesat Anik F1R)

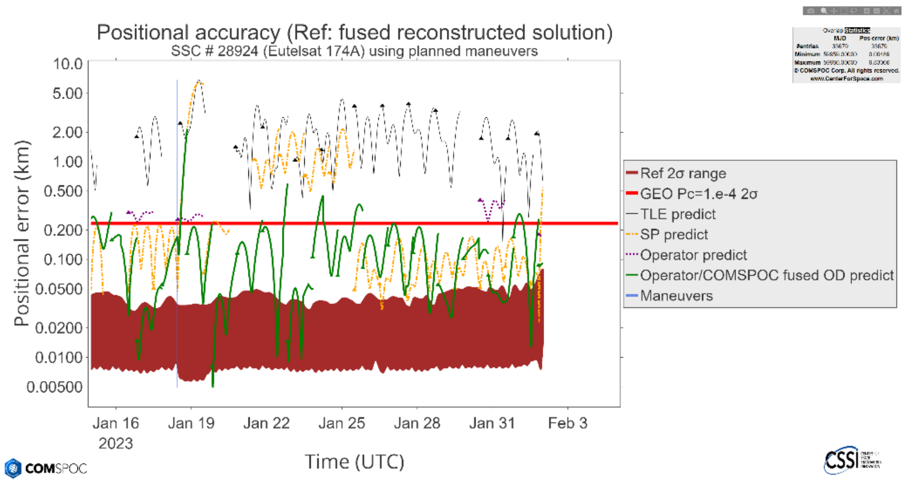

Figure 117: Log (median accuracy) versus time for SSC #28924 (Eutelsat 174A)

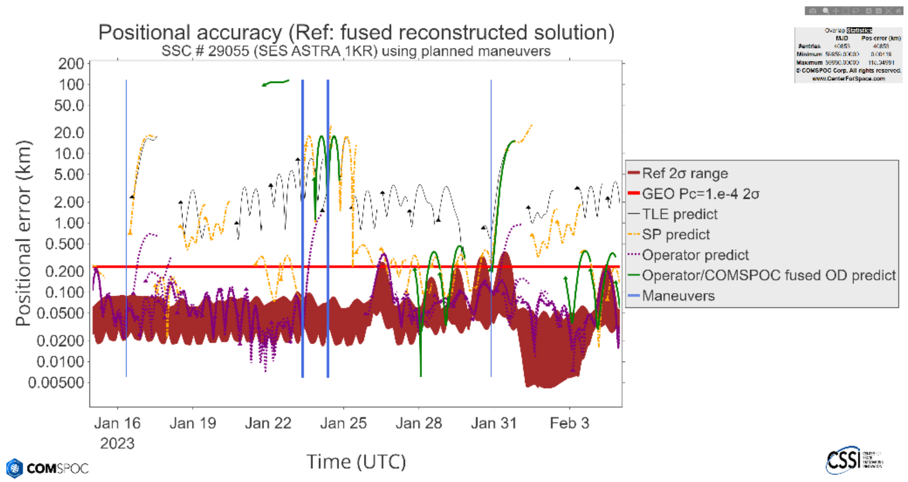

Figure 118: Log (median accuracy) versus time for SSC #29055 (SES Astra 1KR)

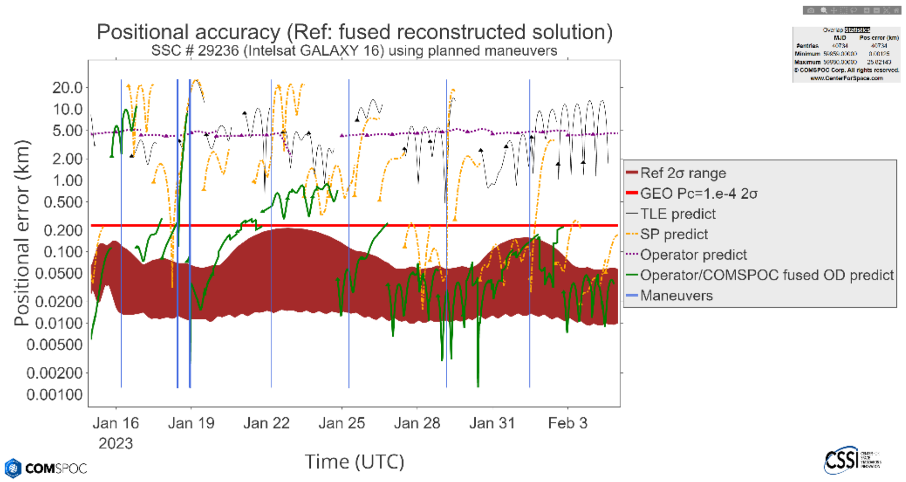

Figure 119: Log (median accuracy) versus time for SSC #29236 (Intelsat Galaxy 16)

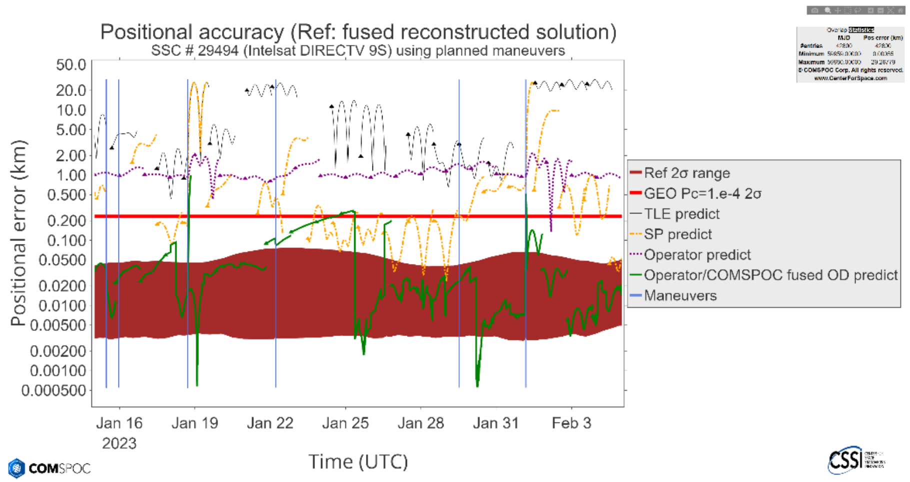

Figure 120: Log (median accuracy) versus time for SSC #29494 (Intelsat DirecTV 9S)

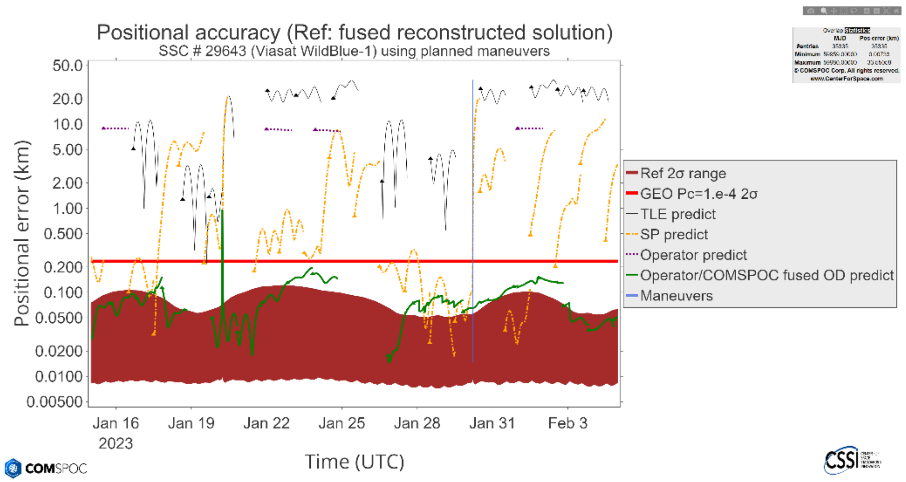

Figure 121: Log (median accuracy) versus time for SSC #29643 (Viasat WildBlue-1)

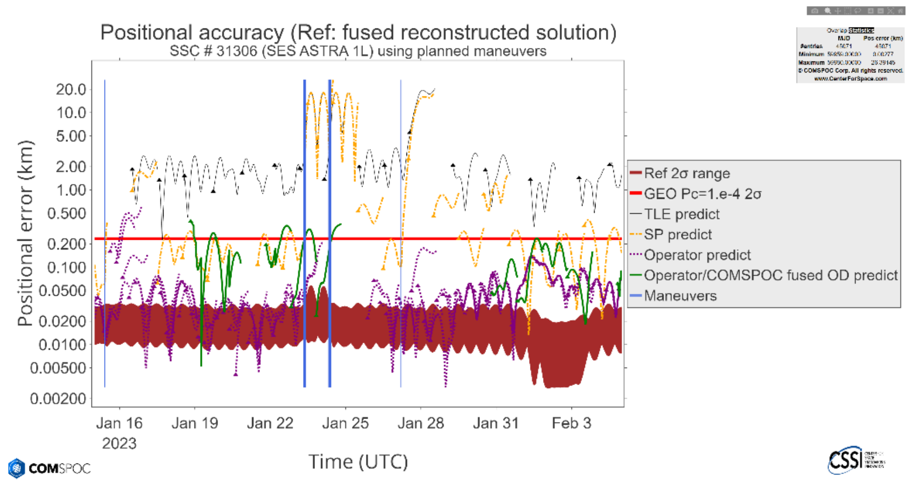

Figure 122: Log (median accuracy) versus time for SSC #31306 (SES Astra 1L)

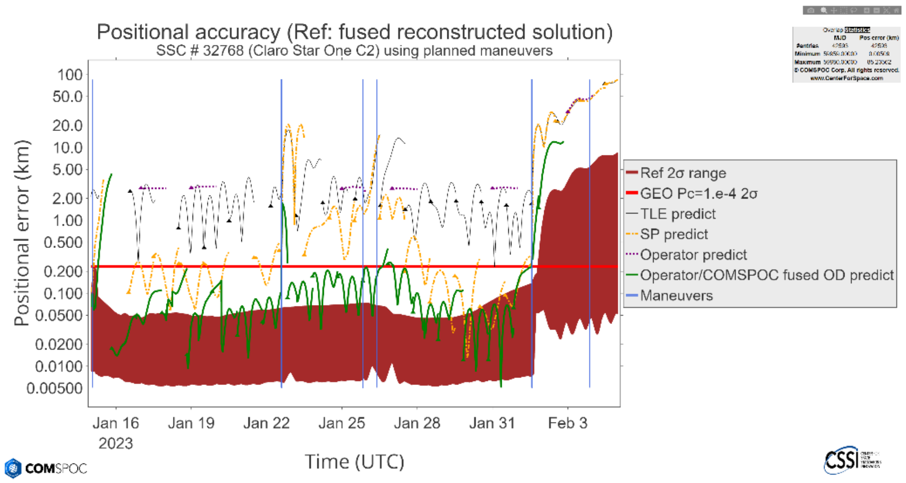

Figure 123: Log (median accuracy) versus time for SSC #32788 (Claro Star One C2)

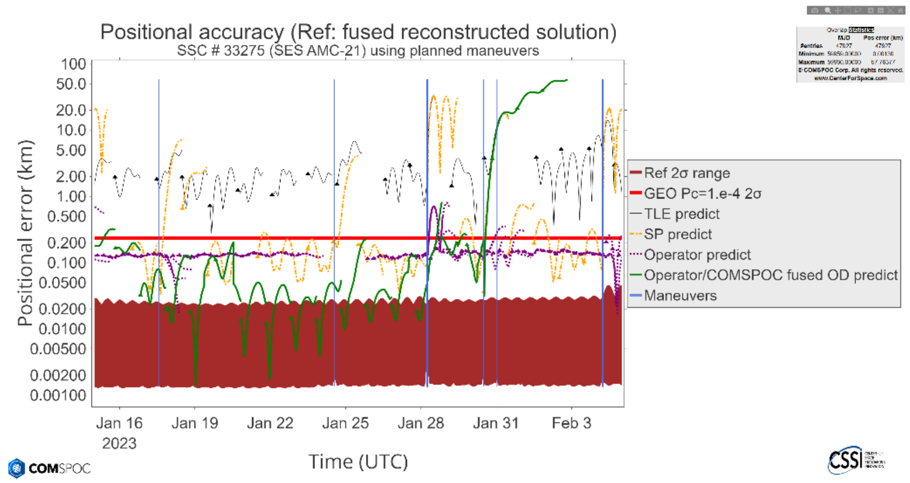

Figure 124: Log (median accuracy) versus time for SSC #33275 (SES AMC-21)

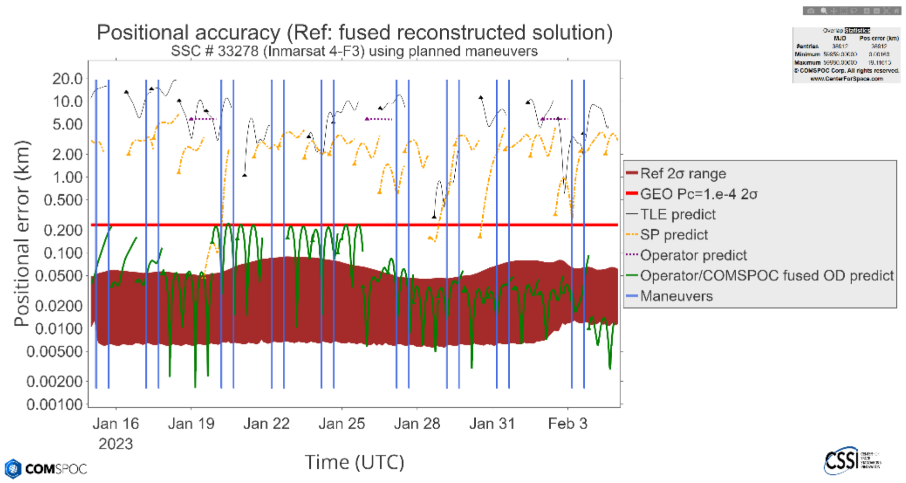

Figure 125: Log (median accuracy) versus time for SSC #33278 (Inmarsat 4-F3)

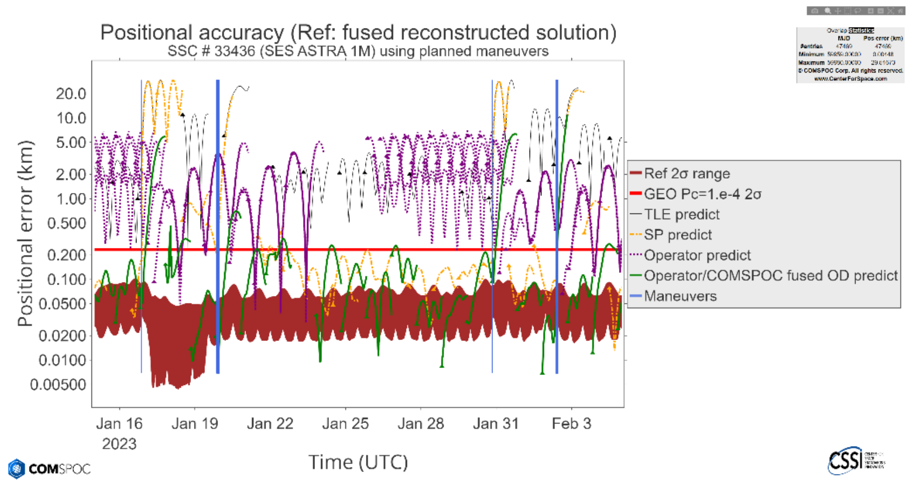

Figure 126: Log (median accuracy) versus time for SSC #33436 (SES Astra 1M)

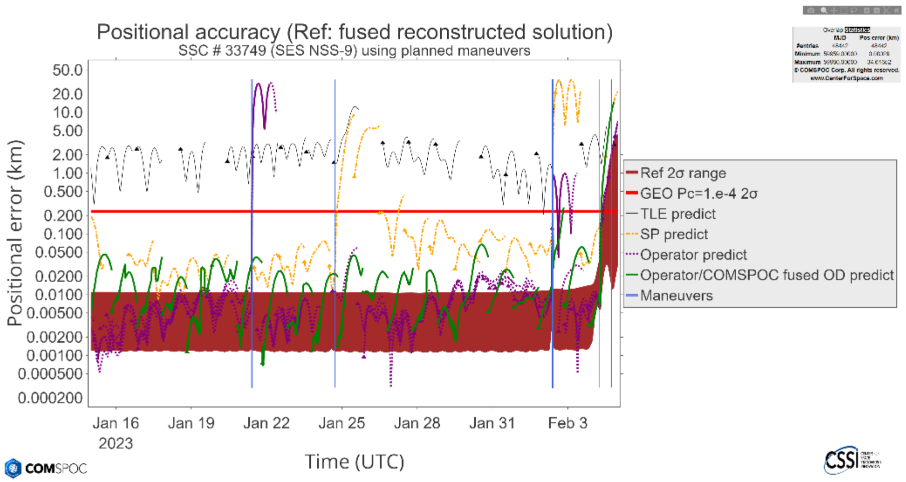

Figure 127: Log (median accuracy) versus time for SSC #33749 (SES NSS-9)

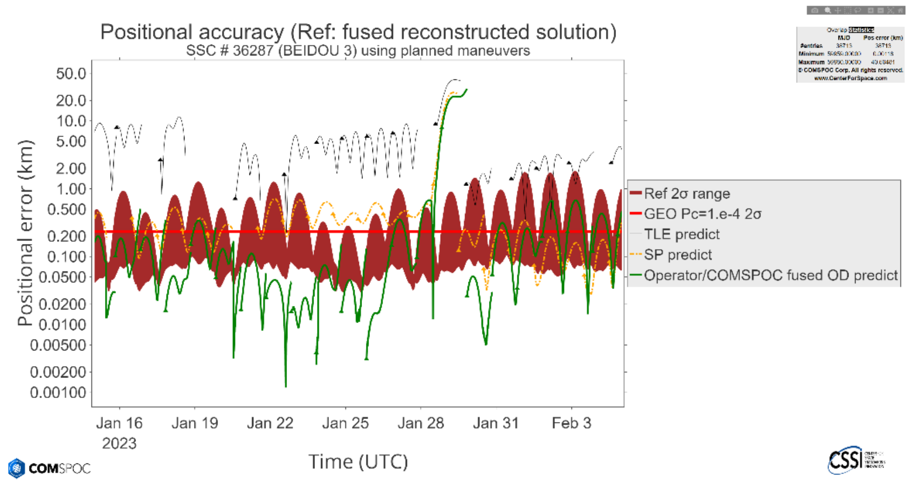

Figure 128: Log (median accuracy) versus time for SSC #36287 (China Beidou 3)

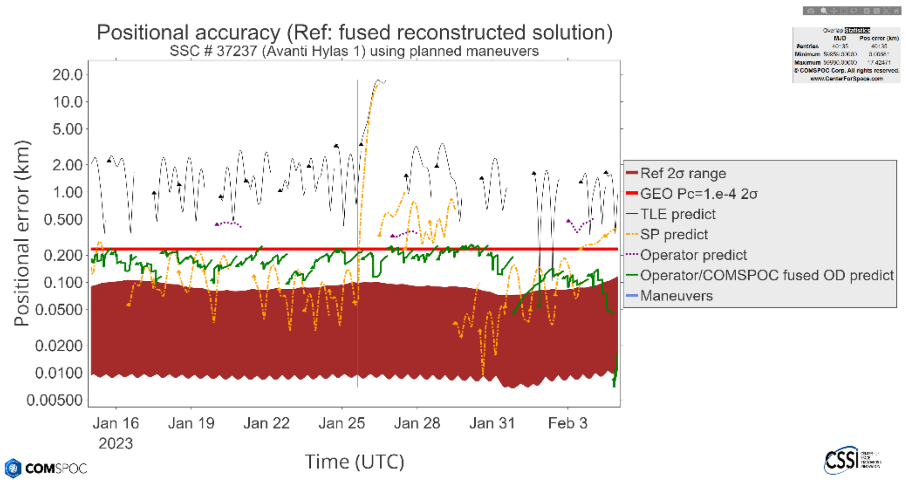

Figure 129: Log (median accuracy) versus time for SSC #37237 (Avanti Hylas 1)

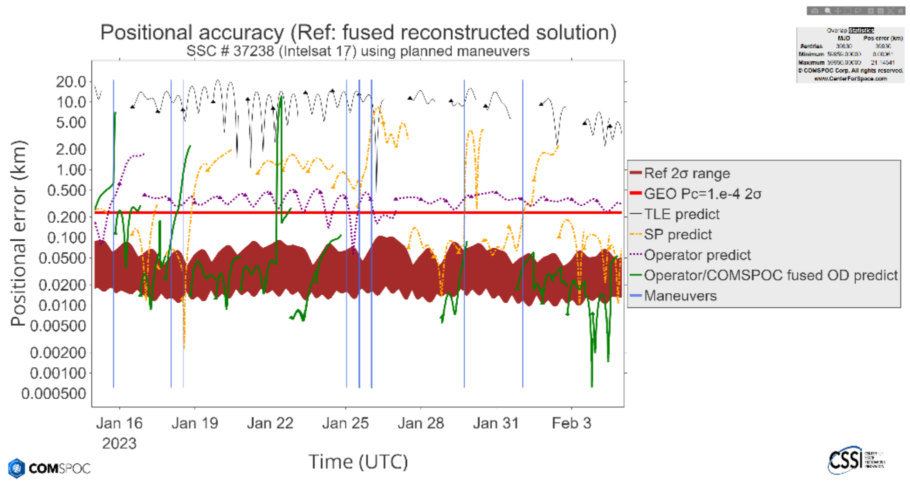

Figure 130: Log (median accuracy) versus time for SSC #37238 (Intelsat 17)

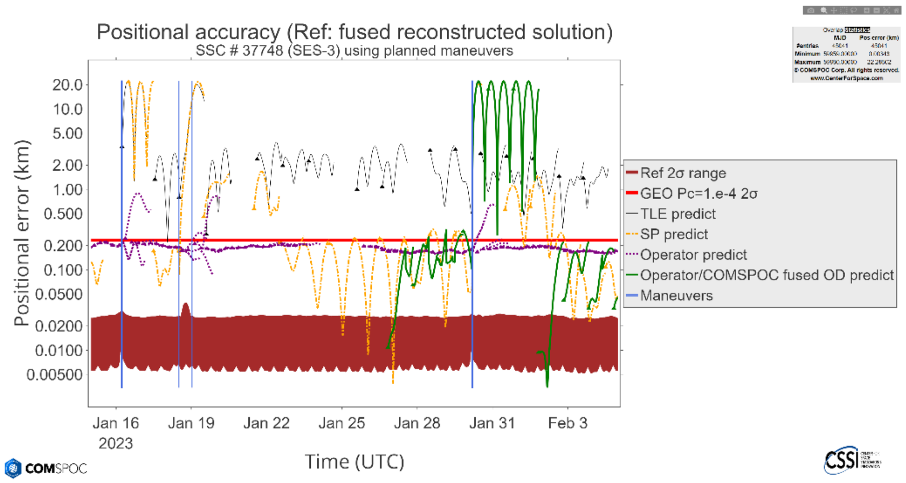

Figure 131: Log (median accuracy) versus time for SSC #37748 (SES-3)

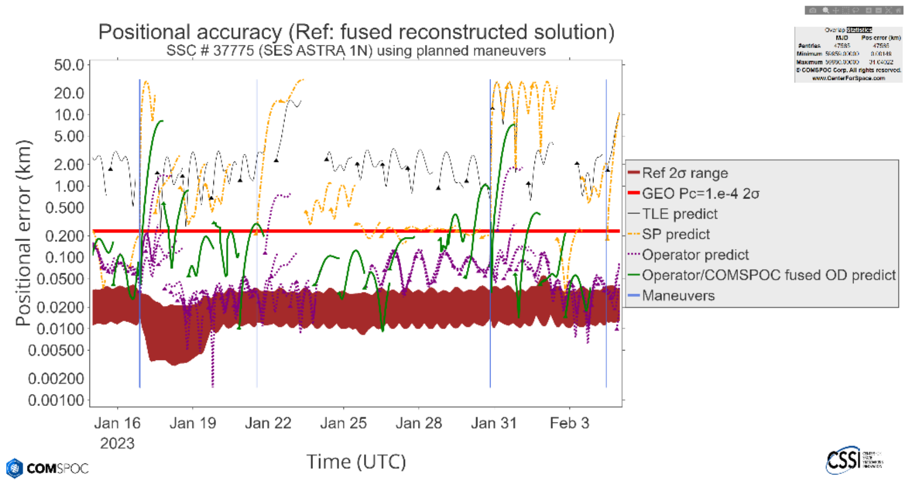

Figure 132: Log (median accuracy) versus time for SSC #37775 (SES Astra 1N)

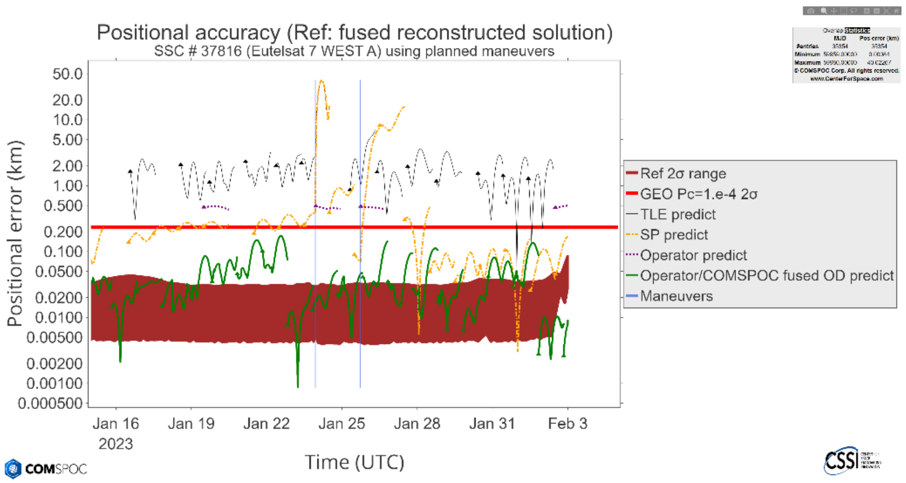

Figure 133: Log (median accuracy) versus time for SSC #37816 (Eutelsat 7 West A)

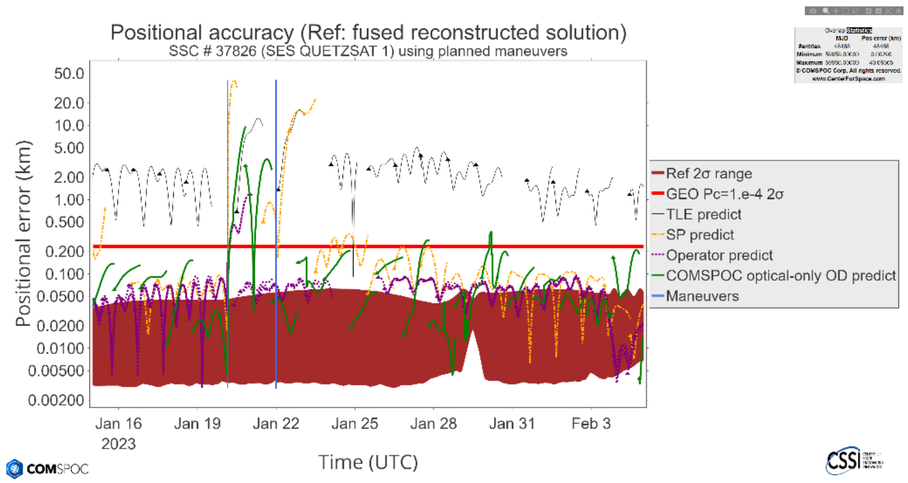

Figure 134: Log (median accuracy) versus time for SSC #37826 (SES Quetzsat 1)

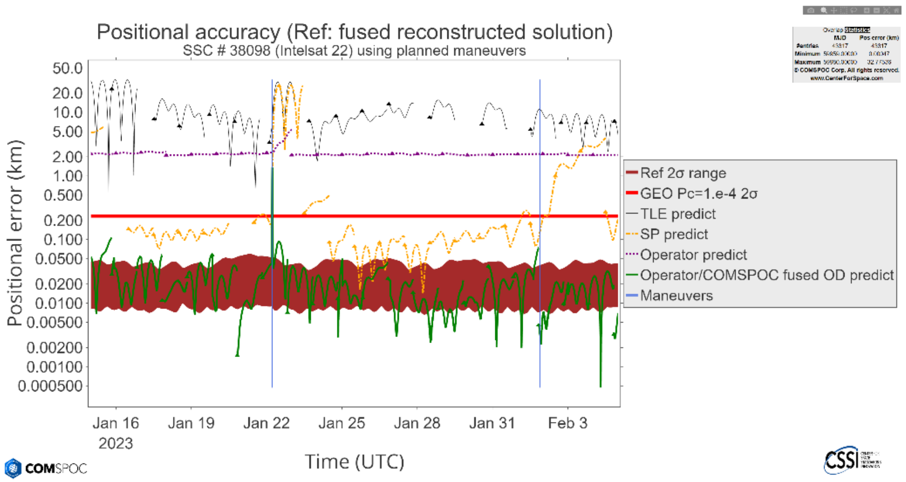

Figure 135: Log (median accuracy) versus time for SSC #38098 (Intelsat 22)

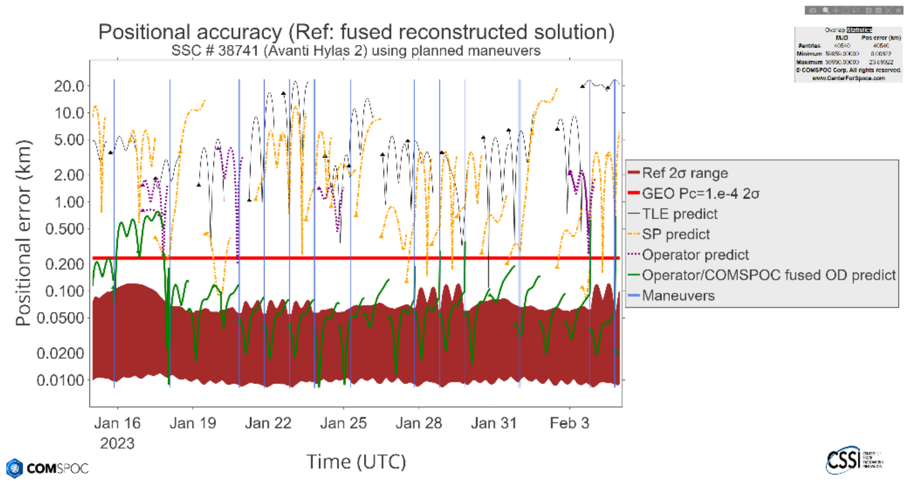

Figure 136: Log (median accuracy) versus time for SSC #38741 (Avanti Hylas 2)

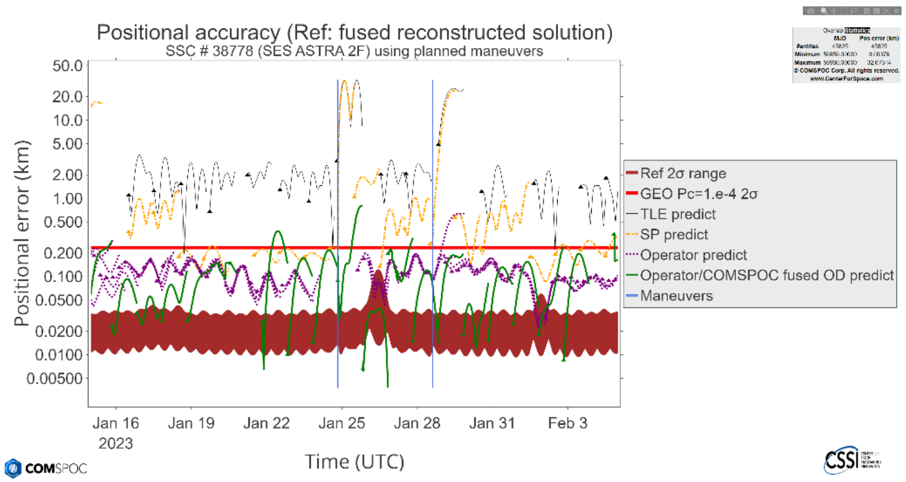

Figure 137: Log (median accuracy) versus time for SSC #38778 (SES Astra 2F)

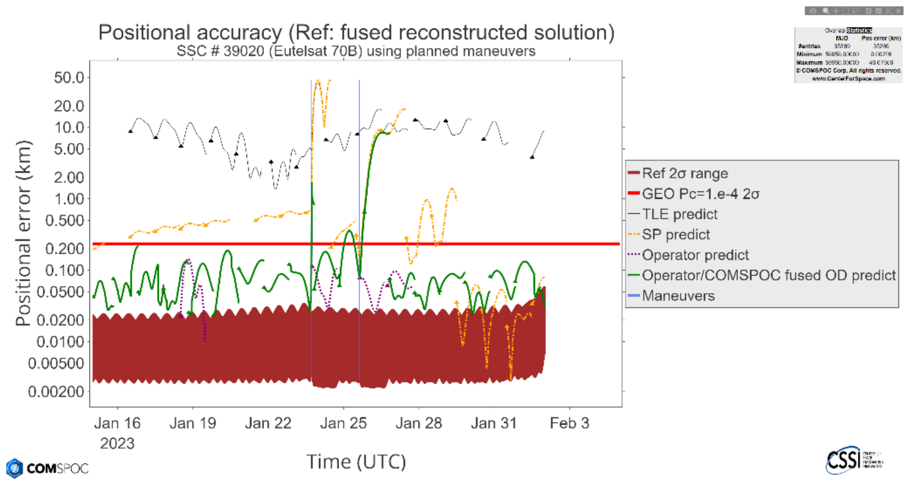

Figure 138: Log (median accuracy) versus time for SSC #39020 (Eutelsat 70B)

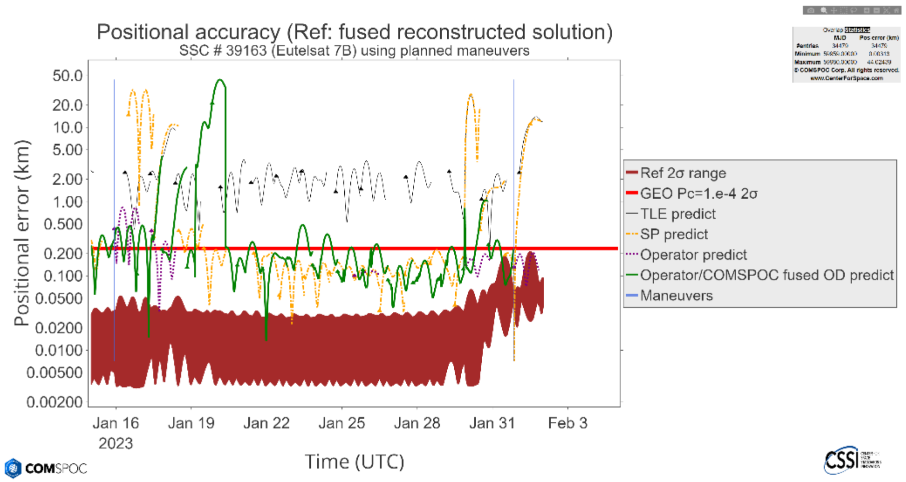

Figure 139: Log (median accuracy) versus time for SSC #39163 (Eutelsat 7B)

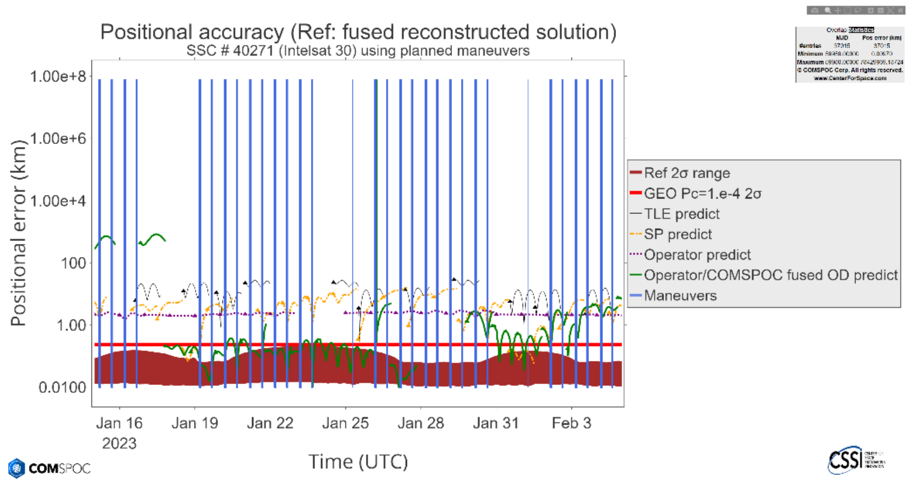

Figure 140: Log (median accuracy) versus time for SSC #40271 (Intelsat 30)

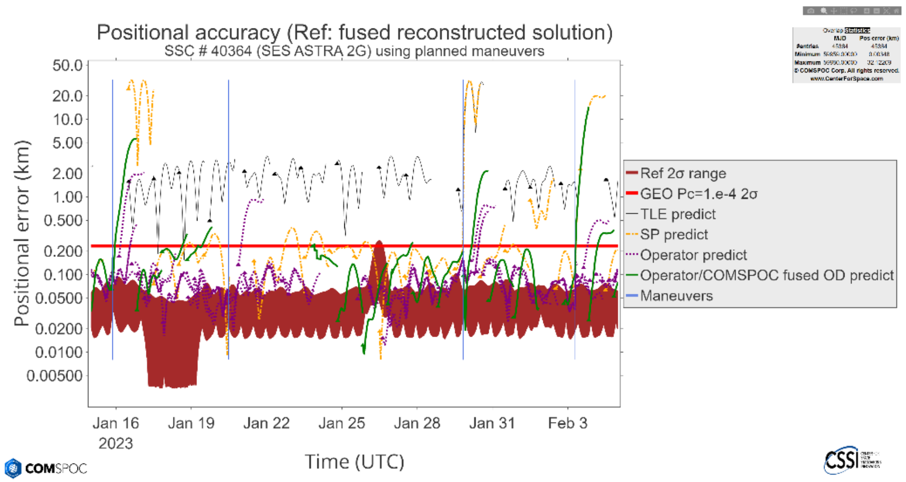

Figure 141: Log (median accuracy) versus time for SSC #40364 (SES Astra 2G)

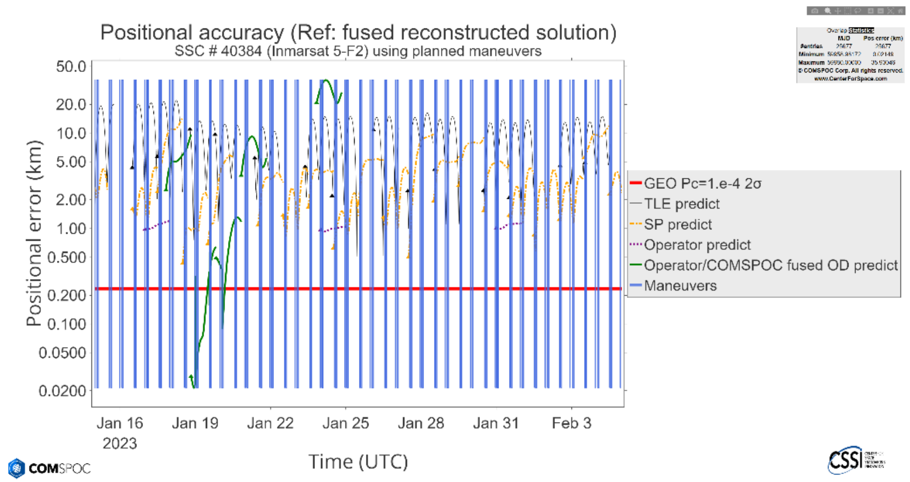

Figure 142: Log (median accuracy) versus time for SSC #40384 (Inmarsat 5-F2)

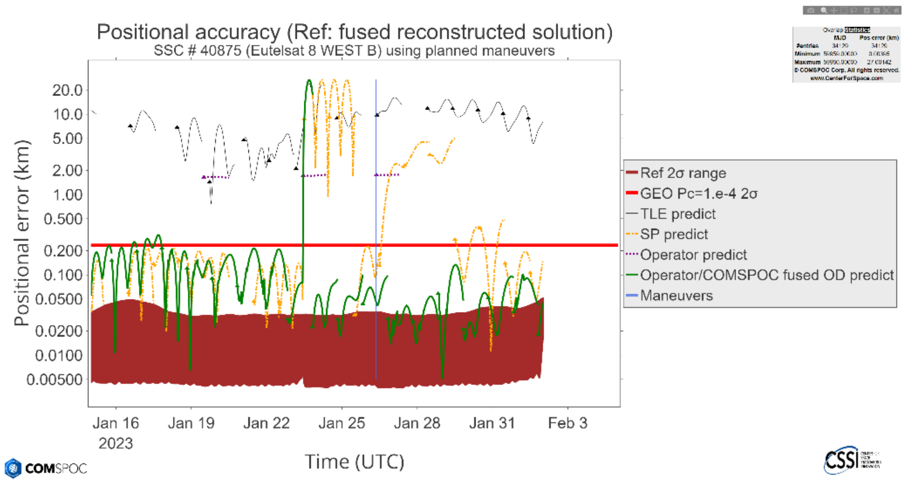

Figure 143: Log (median accuracy) versus time for SSC #40875 (Eutelsat 8 West B)

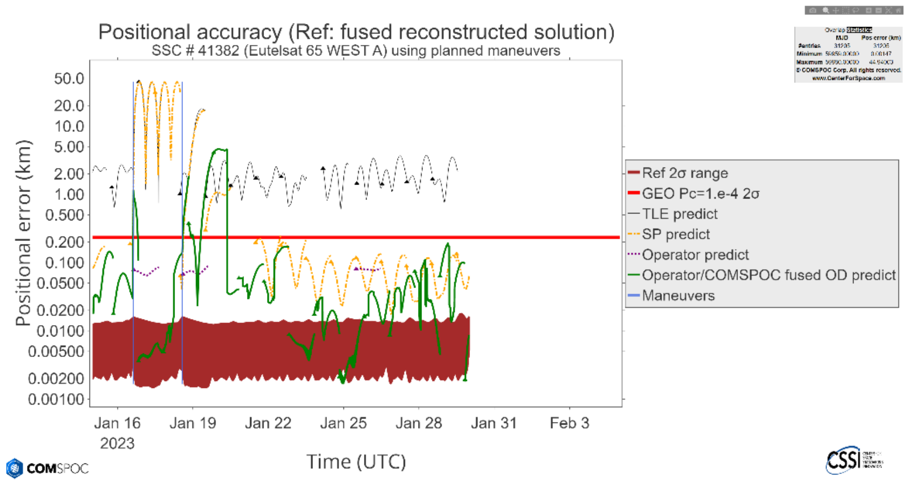

Figure 144: Log (median accuracy) versus time for SSC #41382 (Eutelsat 65 West A)

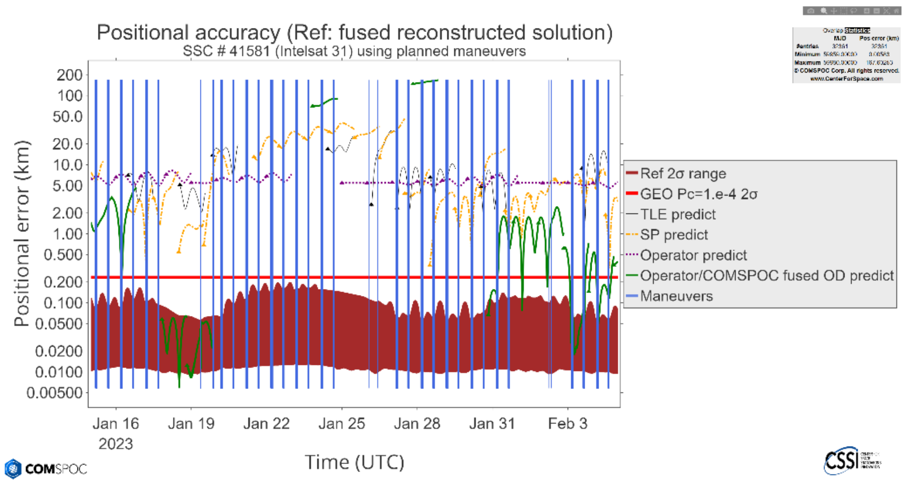

Figure 145: Log (median accuracy) versus time for SSC #41581 (Intelsat 31)

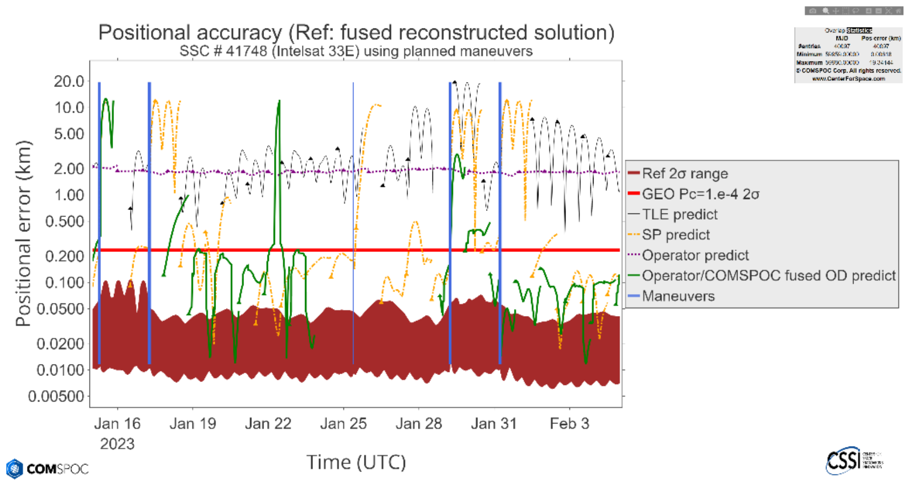

Figure 146: Log (median accuracy) versus time for SSC #41748 (Intelsat 33E)

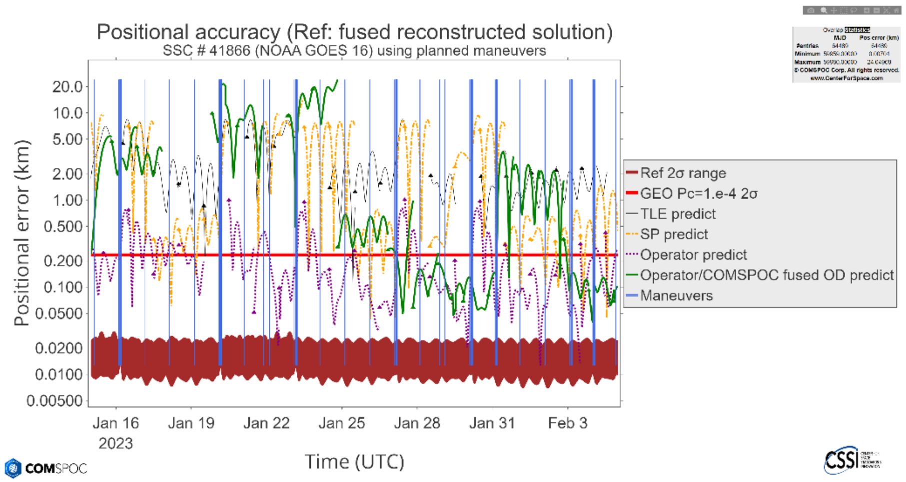

Figure 147: Log (median accuracy) versus time for SSC #41866 (NOAA GOES 16)

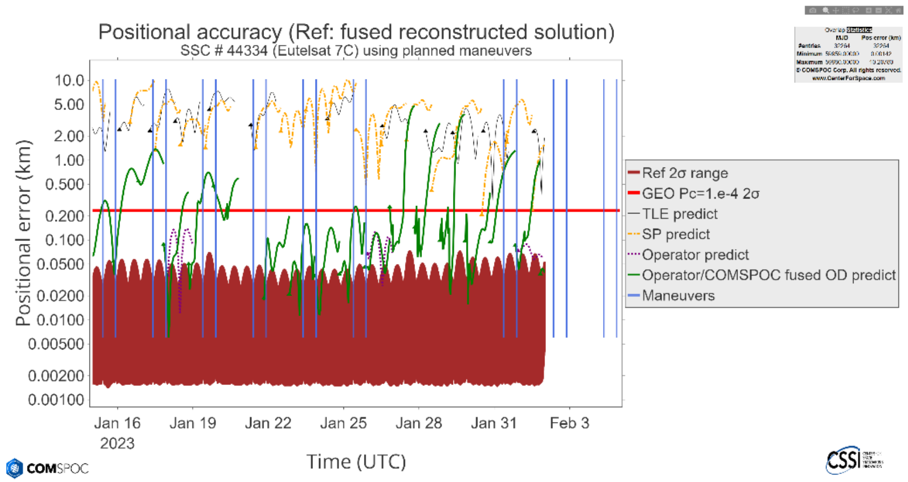

Figure 148: Log (median accuracy) versus time for SSC #44334 (Eutelsat 7C)

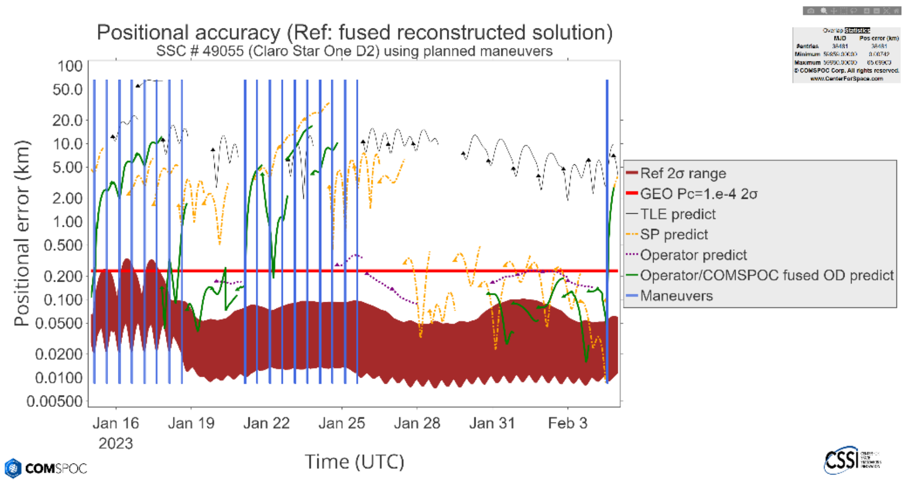

Figure 149: Log (median accuracy) versus time for SSC #49055 (Claro Star One D2)

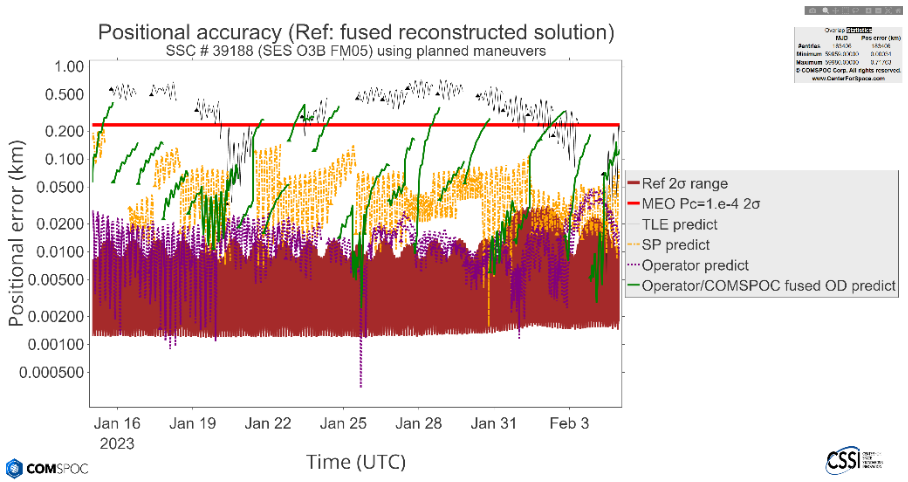

Figure 150: Log (median accuracy) versus time for SSC #39188 (SES O3B FM05)

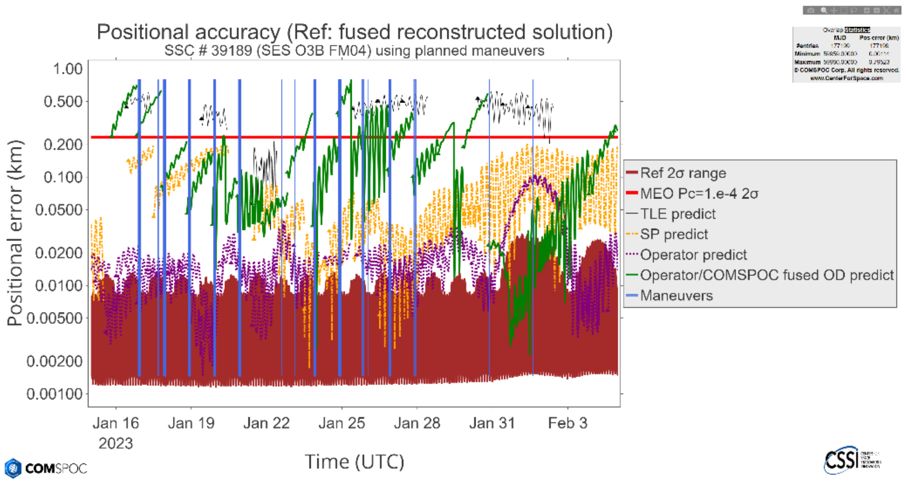

Figure 151: Log (median accuracy) versus time for SSC #39189 (SES O3B FM04)

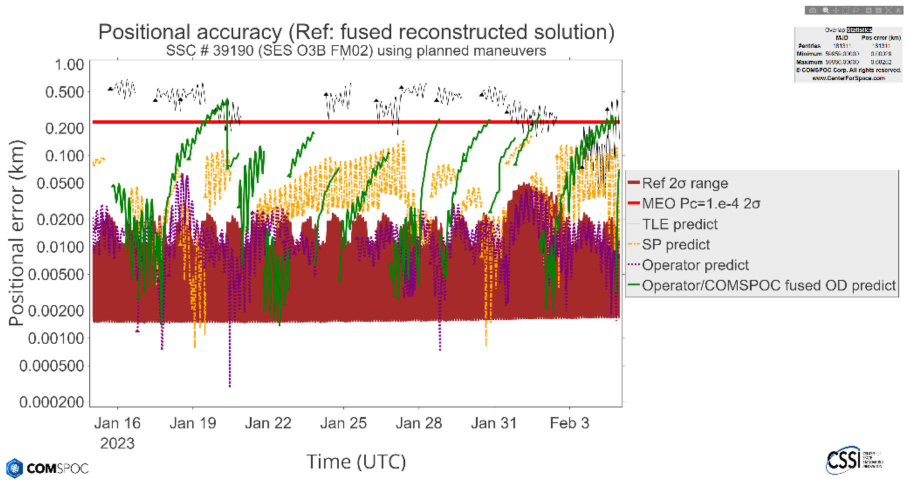

Figure 152: Log (median accuracy) versus time for SSC #39190 (SES O3B FM02)

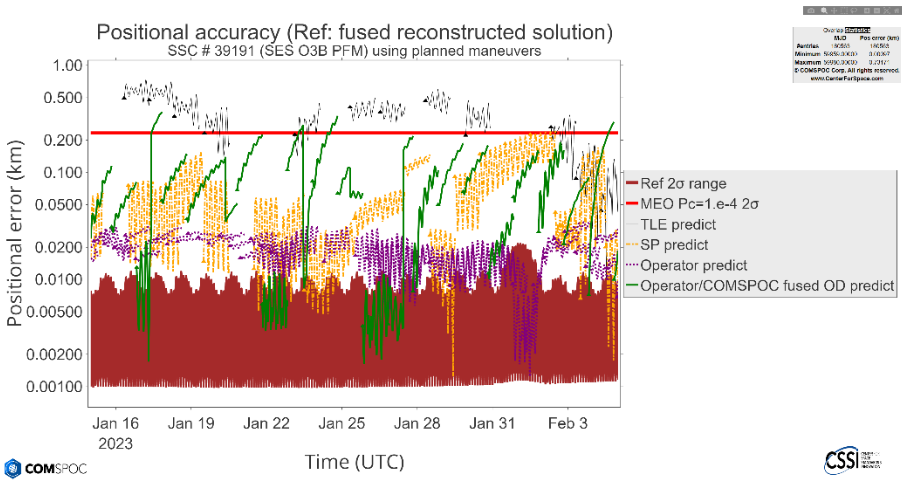

Figure 153: Log (median accuracy) versus time for SSC #39191 (SES O3B PFM)

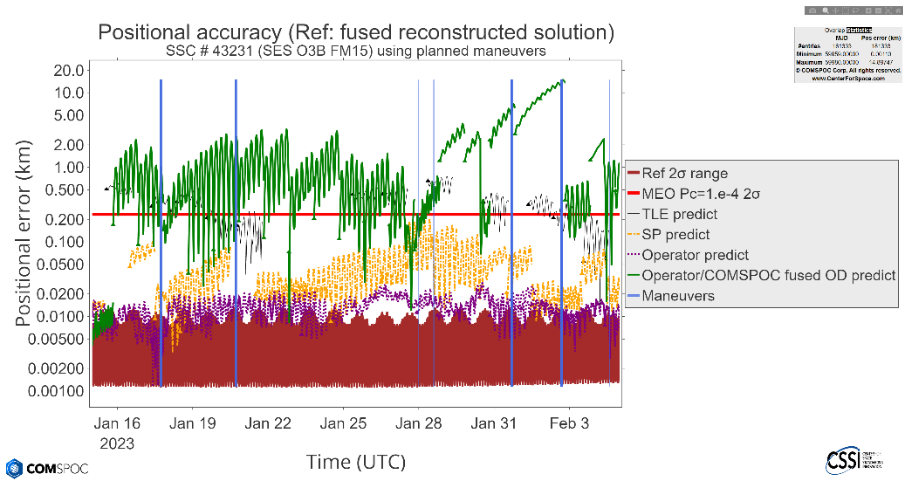

Figure 154: Log (median accuracy) versus time for SSC #43231 (SES O3B FM15)

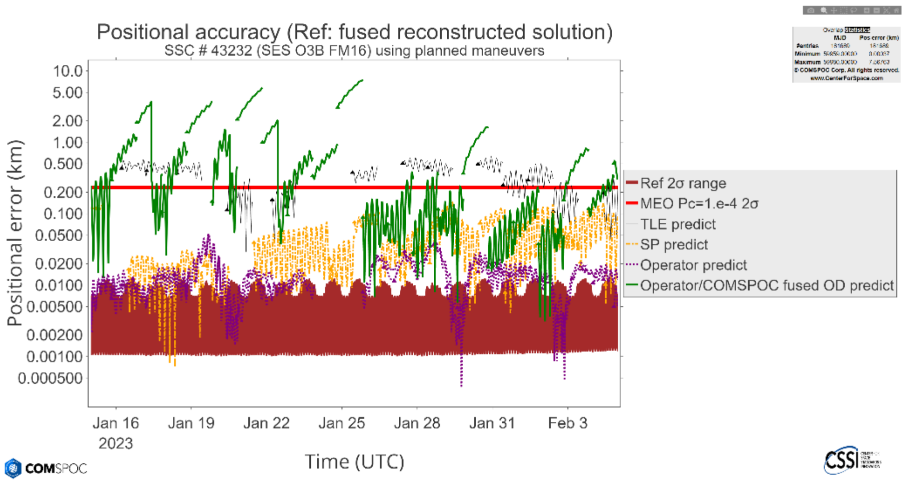

Figure 155: Log (median accuracy) versus time for SSC #43232 (SES O3B FM16)

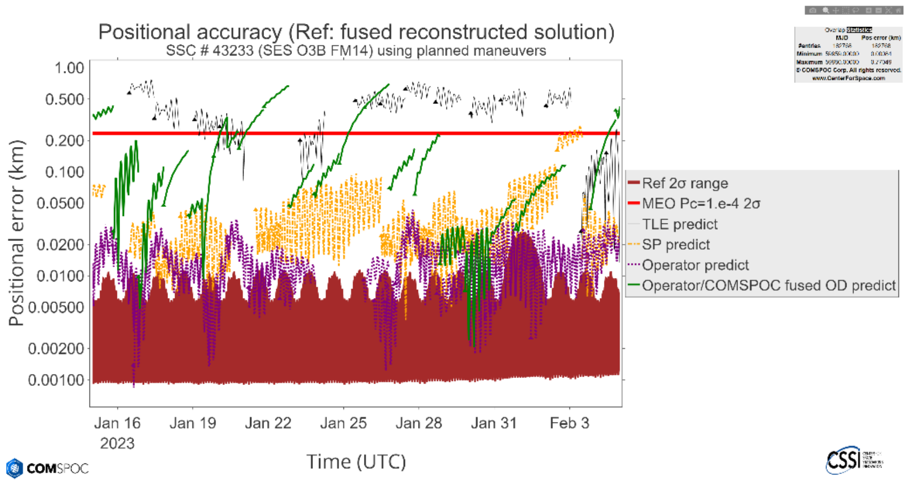

Figure 156: Log (median accuracy) versus time for SSC #43233 (SES O3B FM14)

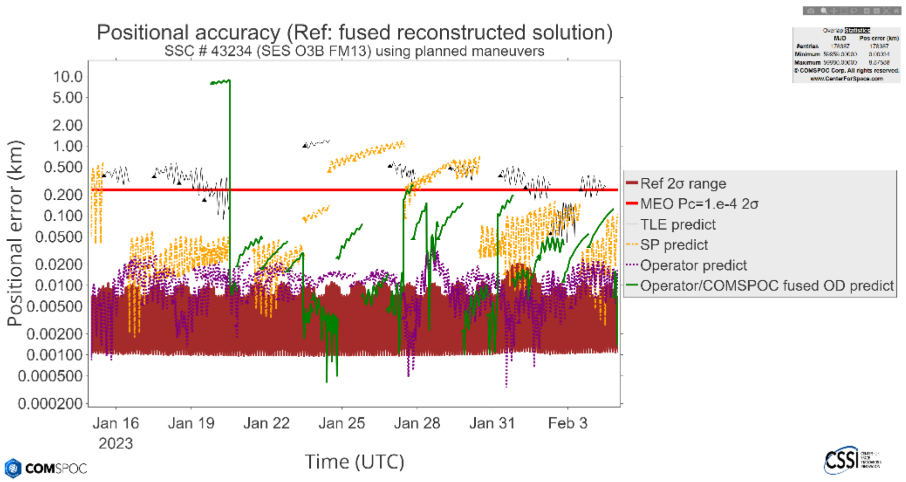

Figure 157: Log (median accuracy) versus time for SSC #43234 (SES O3B FM13)

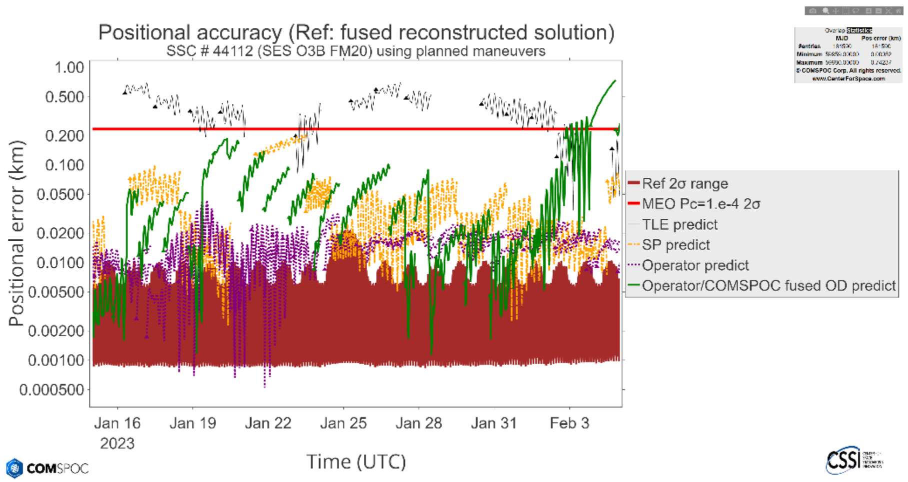

Figure 158: Log (median accuracy) versus time for SSC #44112 (SES O3B FM20)

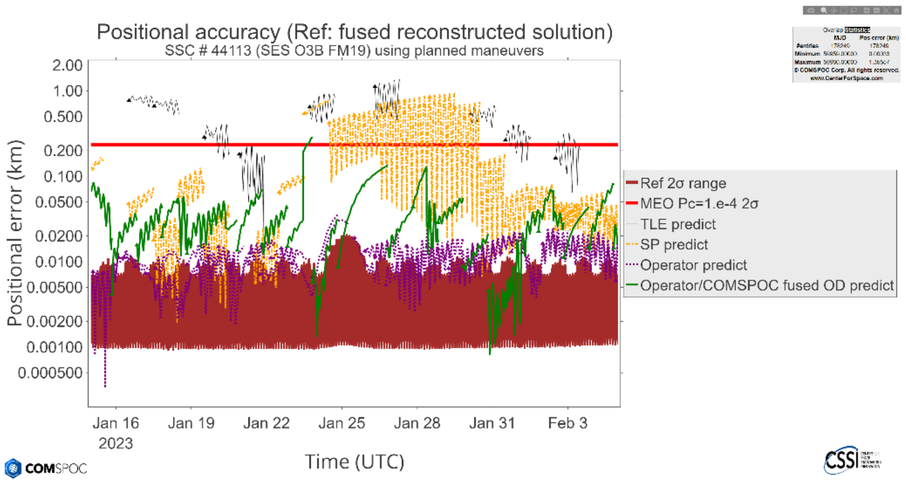

Figure 159: Log (median accuracy) versus time for SSC #44113 (SES O3B FM19)

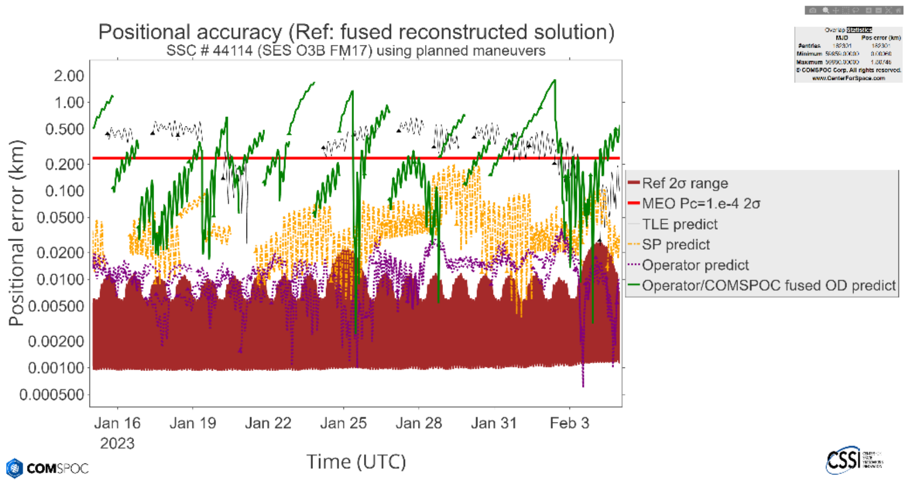

Figure 160: Log (median accuracy) versus time for SSC #44114 (SES O3B FM17)

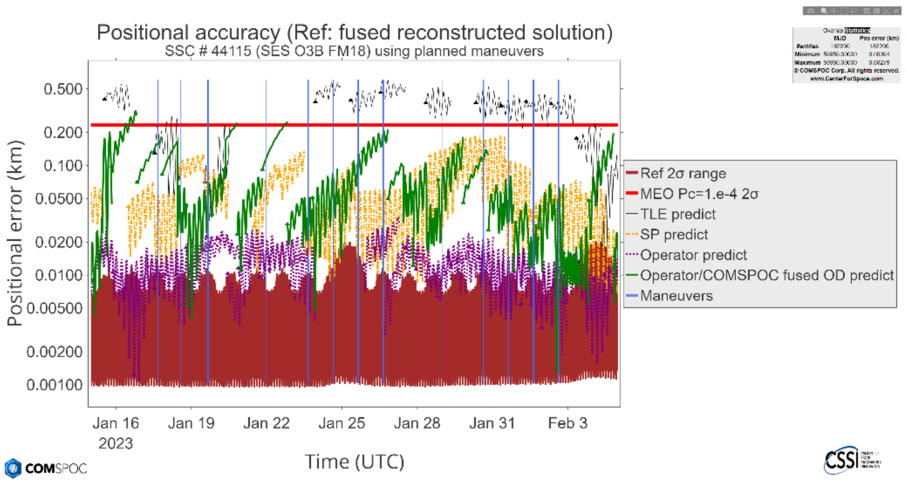

Figure 161: Log (median accuracy) versus time for SSC #44115 (SES O3B FM18)