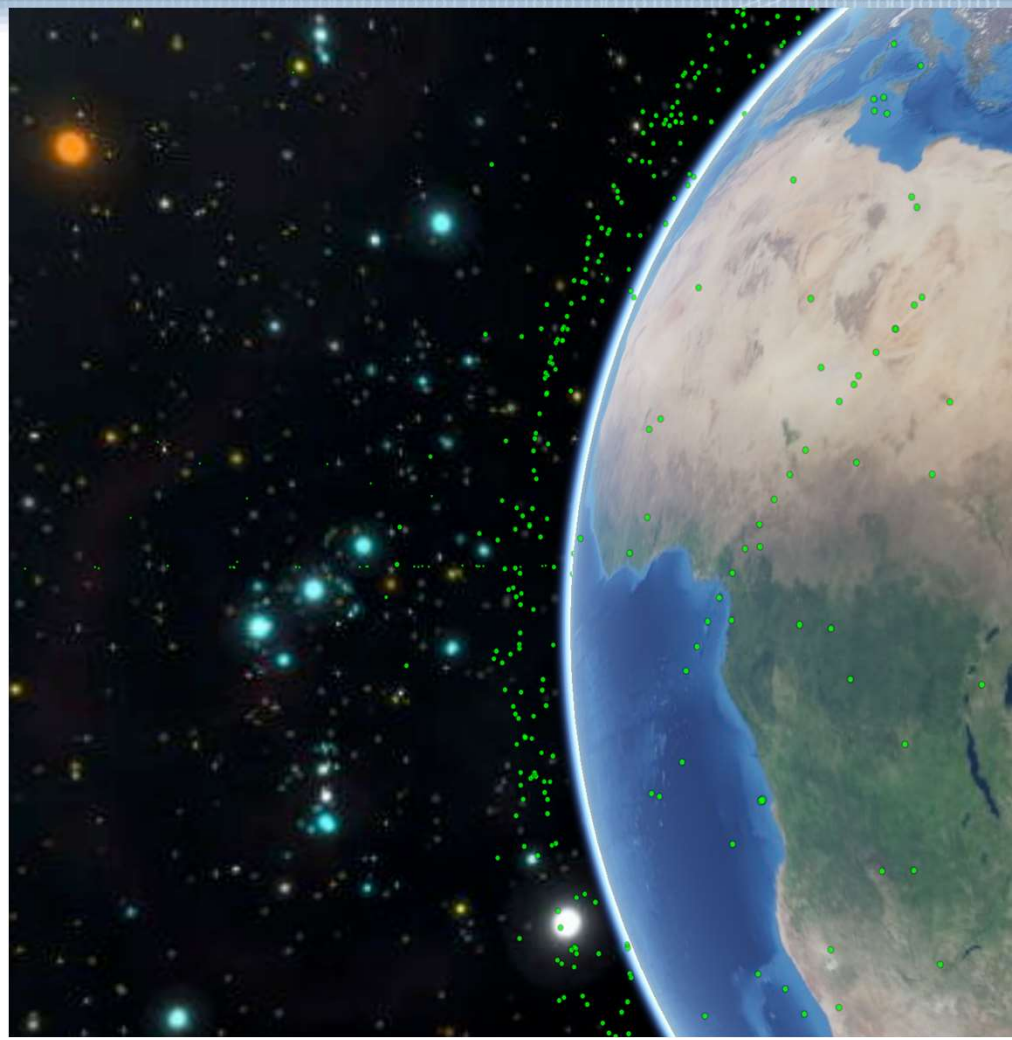
SPACE DATA ASSOCIATION

SDA Contributions to SSA and Space Flight Safety



26 June 2024

Dan Oltrogge

SDA Member Meeting

How is the SDC Unique?

- SDC has been operational for fourteen years with very high availability.
- SDC technical support for SDC users, conjunction threats or technical issues.
- SDC screens all latest Owner/Operator (O/O) ephemerides every six hours.
- SDA and SDC's "crowd-sourcing" model, addressing proprietary and IP issues via data pooling in secure computational and legal frameworks
- SDC can draw upon rich set of operator data typically not available
  - Points-of-contact by role (mgmt., FDS, IS, RFI)
  - Launch and Early Orbit Phase (LEOP) plans
  - Ephemerides incorporating planned maneuvers
  - Covariance
  - Maneuver plans (including low-thrust, finite burns, and acceleration profiles)
  - Spacecraft dimensions and attitude rules
  - RF characteristics

SDC = The pioneer of flight safety services

- SDC pioneered many traits now widely accepted as baseline STCM
  - Computationally and legally secure frameworks
    - Behind-the-firewall SSA and STC processing ensures operator data confidentiality
  - Data Lake (format-agnostic) ingest of crowd-sourced operator data
  - Machine-to-machine interfaces
  - Verified data normalization converters.
  - Operator phonebook that is sufficiently granular by area of responsibility, location and management level to allow operators to communicate
  - Extensive comparative SSA for quality control and to identify discrepancies
  - Data sharing (when authorized by the operators) makes SDC one of the largest contributors of space data from multiple operators to 18SPCS

But what progress has been made to achieve actionable SSA?

- CA largely a **massive bookkeeping exercise**, fully dependent upon its input data.
- In the "noise," one can easily miss the critical difference between (1) just having a safety process; and (2) having one that is **fit for purpose** and **effective**.
- The **SDA was formed to address known gaps** in SSA data, making it **unfit for purpose**.
- In the SDC's 14 years of full operations, realized that **no single source "does it all"**.
- Led us to explore deeply collaborative SSA… with very promising results!
- Let's examine **five key aspects of actionable SSA**:
  1. **What accuracy is required**?
  2. How crowd-sourcing, data fusion, and **collaboration yield dramatic improvements**;
  3. Operationalizing **Synthetic Covariance** as a viable estimate of SSA data errors
  4. How accurate are SSA alternatives, and **do they meet requirements**?

Covariances… What's at the root of SSA error?

- Positional knowledge approximate inaccuracies by source†:

Inaccuracy	Orbit regime(s)	Source
Up to **1500 km**	All	Unmodeled/mismodeled maneuvers (incl. low-thrust) Latencies of up to 1 week to recover OD solution
100 – 200 km	GEO	Cross-tagging & track mis-association
Up to **50 km**	All	Obs undersampling
Variable	All	Sensor priority/mission
1 – 100 km; 1-5 km typically	All	Lack of operator sensor calibration (biases)
Average of **12 km/day**	Low LEO (250 km)	Inaccurate space weather predictions
< **2 km**	All	Orbit theory limitations (TLEs)*
10 – 1000 km error	All	OD technology (Batch vs Sequential)

- Synthetic covariances can reflect discrepancies in predicted position as a proxy for error

† Oltrogge, D., et al, "Order-of-Magnitude Actionability Characterization for SSA," Improving Space Operations Workshop, 31 April 2013.

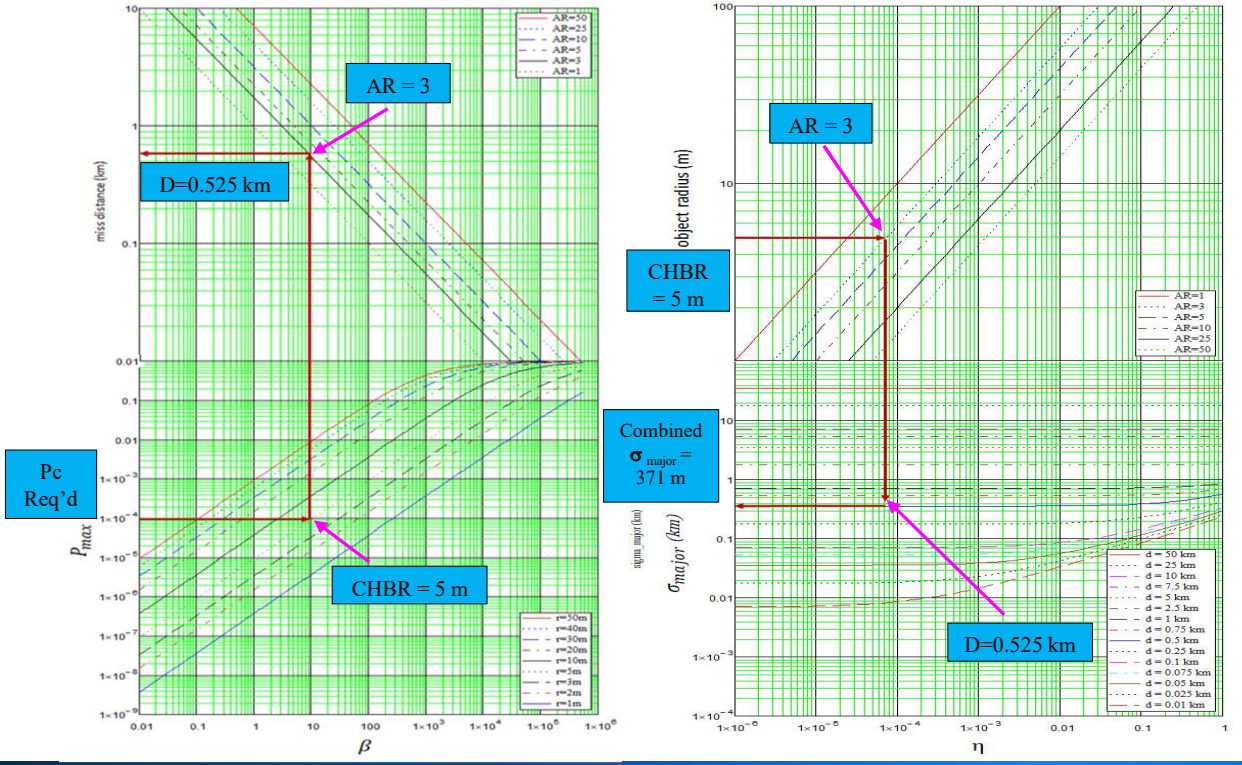
* Oltrogge & Ramrath, "Parametric Characterization of SGP4 Theory and TLE Positional Accuracy," AMOS 2014.

What SSA positional accuracy is required?

- Required accuracy = f(mission, orbit, alert metrics, thresholds, staffing).
- Too much reliance upon making do with “best-effort” tools, staffing and analyses.
- Glaring issue in today’s SSA products: they largely do not meet accuracy requirements!
- For example, many operators employ a collision probability threshold (Pc) of 1/10,000.
  - Pc = f(miss distance, object sizes, covariance Aspect Ratio and size).
  - These “ingredients” are largely unavailable and often unrealistic.
- Despite the general unavailability and unrealism of Pc inputs, derived SSA accuracy requirements must be met for the use of Pc metrics to be considered “operational”.

What SSA accuracy is required?

- Can reverse engineer accuracy requirements using “Maximum Probability Nomograms” in order to ensure Pc thresholds are detectable.



Pmax	CHBR (m)	AR	distance (m)	combined one-sigma major (m)	individual one-sigma major (m)
1.E-04	0.5	3	53	37	26
1.E-04	1	3	105	74	53
1.E-04	1.5	3	158	111	79
1.E-04	5	3	525	371	263
1.E-04	10	3	1050	743	525
1.E-04	20	3	2101	1486	1051
1.E-04	50	3	5252	3714	2624
5.E-04	0.5	3	24	17	12
5.E-04	1	3	47	33	24
5.E-04	1.5	3	70	50	35
5.E-04	5	3	235	166	117
5.E-04	10	3	470	332	235
5.E-04	20	3	939	665	470
5.E-04	50	3	2348	1661	1174
1.E-03	0.5	3	17	12	8
1.E-03	1	3	33	24	17
1.E-03	1.5	3	50	35	25
1.E-03	5	3	166	117	83
1.E-03	10	3	332	235	166
1.E-03	20	3	664	470	332
1.E-03	50	3	1659	1174	830

SDA support to U.S. Department of Commerce (DOC) Pilot

- DOC initiative to provide Space Traffic Coordination and Management (STCM) services and other government initiatives like the European Union Space Surveillance and Tracking system (EU SST)
- SDA and COMSPOC supported DOC STM Pilot
  - Fusing operator observations and planned maneuvers with commercial SSA
    - 100 spacecraft of 13 MEO/GEO operators
- Purpose of the DOC Pilot: ***"To establish that commercial SSA sector can provide safety services at least on par with existing US DOD legacy STC services"***

Commerce Department Awards Contracts for Space Traffic Coordination Pilot Project

POSTED ON **DECEMBER 6, 2022** POSTED IN **COMMERCIAL SPACE SOLUTIONS FOR NOAA, DATA BUYS, SSA/STM**
TAGGED WITH , **CONTRACTSDOD**

NOAA

On December 5, 2022, the U.S. Department of Commerce's NOAA took a step forward in its plans to provide space traffic coordination services to commercial and civil satellite operators operating in the increasingly congested orbits around Earth.

As part of a new pilot project to provide spaceflight safety mission assurance to select spacecraft in the medium Earth orbit (MEO) and geostationary Earth orbit (GEO), NOAA's Office of Space Commerce (OSC) partnered with the Department of Defense to award seven contracts

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.

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	✓	✓	✓	✓		

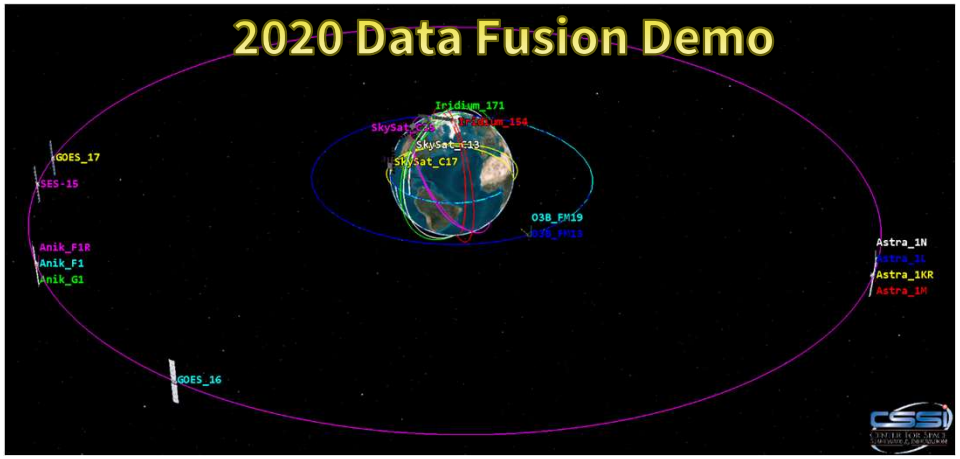
Comparison of SDA/COMSPOC 2020 and 2023 data fusion campaigns

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

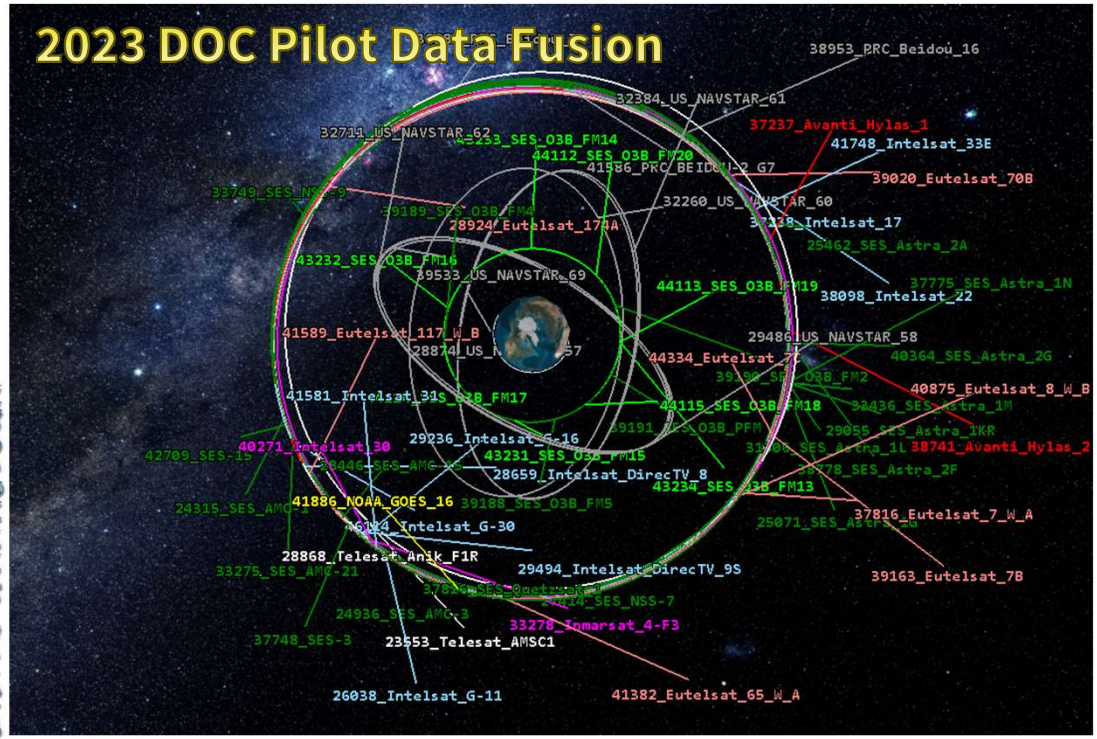
** Initially tried for 100, but not all data flows & calibrations were completed within Pilot timeframe

DOC GEO/MEO Pilot included 18 MEO and 82 GEO active spacecraft



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 D	•	
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	•	

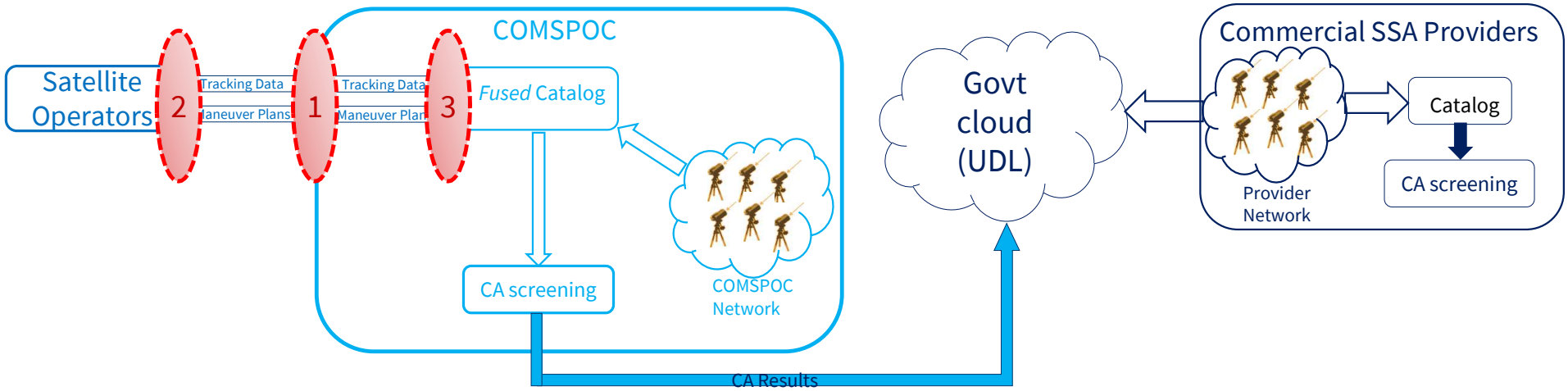
2023 DOC Pilot Data Fusion



SDA / COMSPOC Operator Collaboration for DOC Pilot

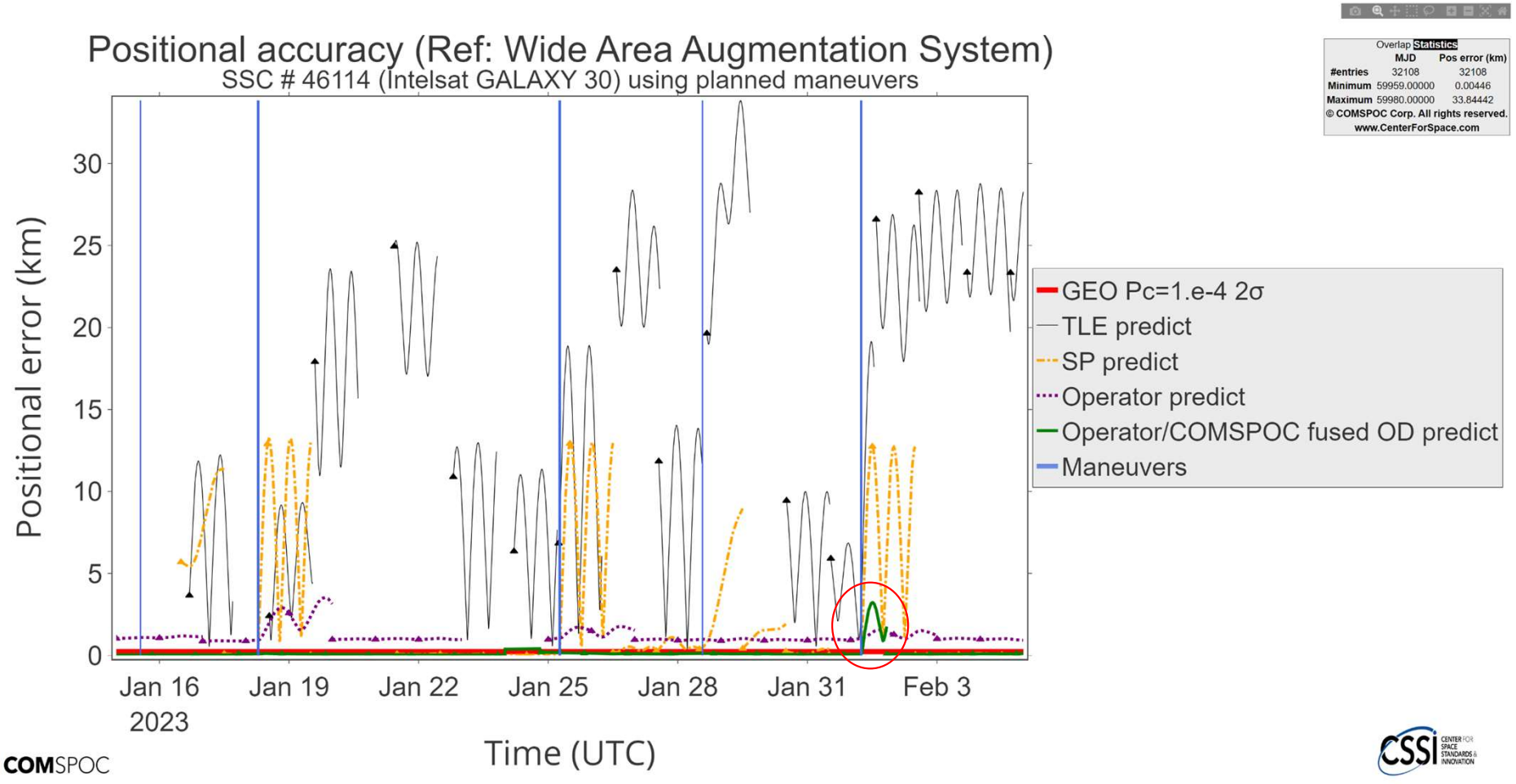
- COMSPOC SSA system already provides extensive data fusion ability
- SDA operators & COMSPOC worked to bring the data into the system

1. Establish Network connectivity via IT rules
2. Operator scripting to routinely push sensor data + maneuvers for selected sats – low latency req'd
3. COMSPOC: Operator-unique tracking and maneuver data readers + calibration of all operator sensors



The "intense" collaboration is largely non-recurring during the setup process

Fused non-cooperative maneuver processing recovers quickly



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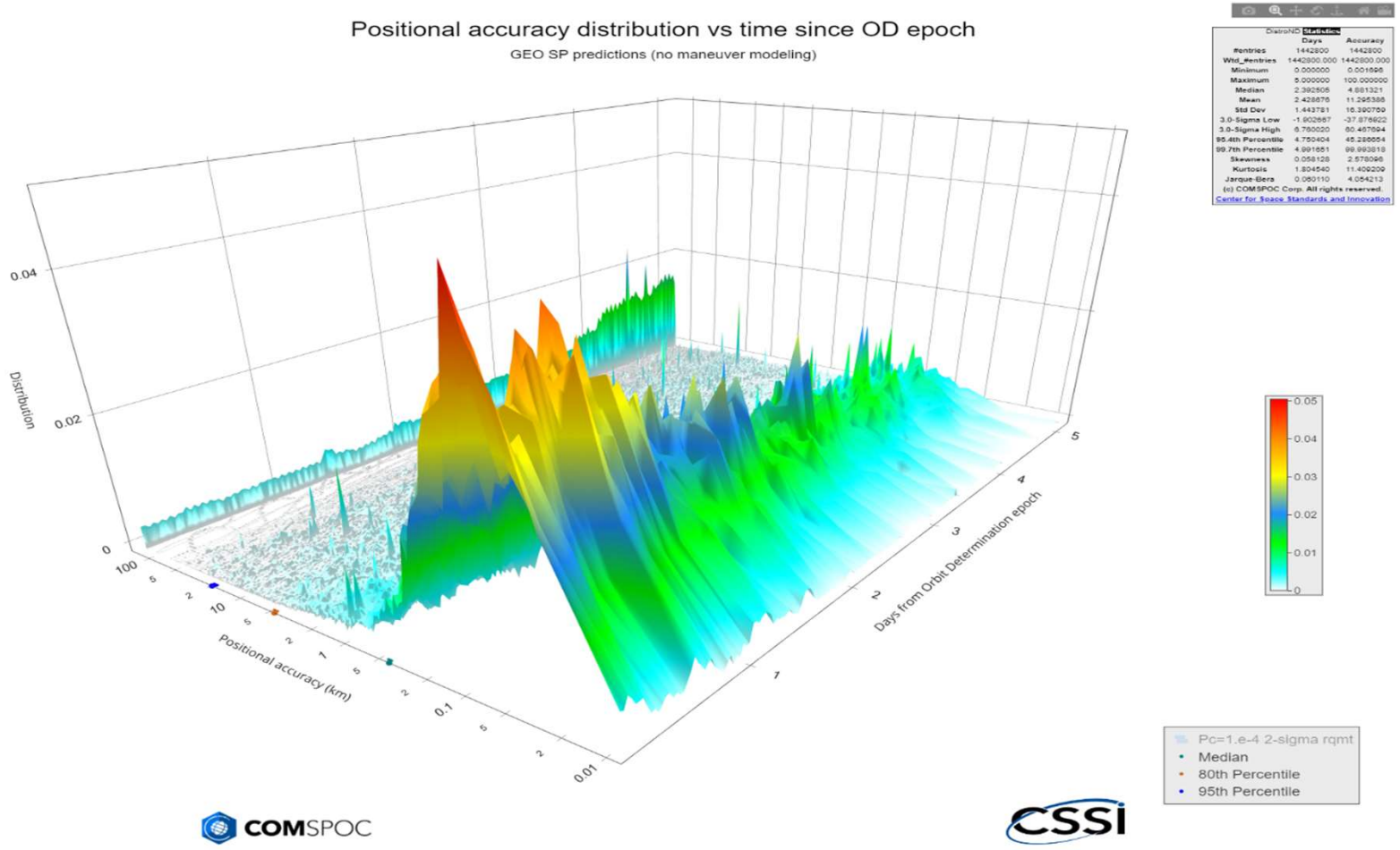
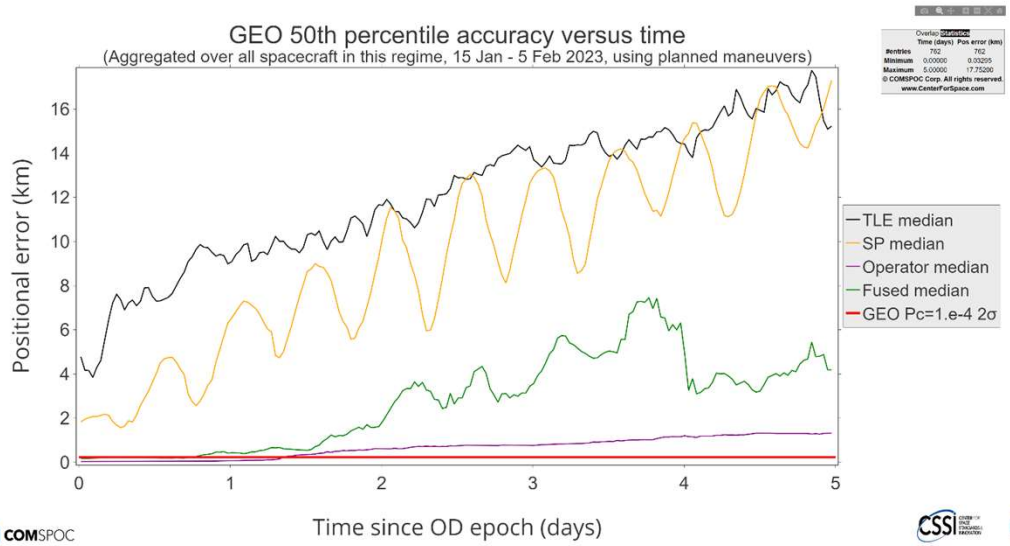
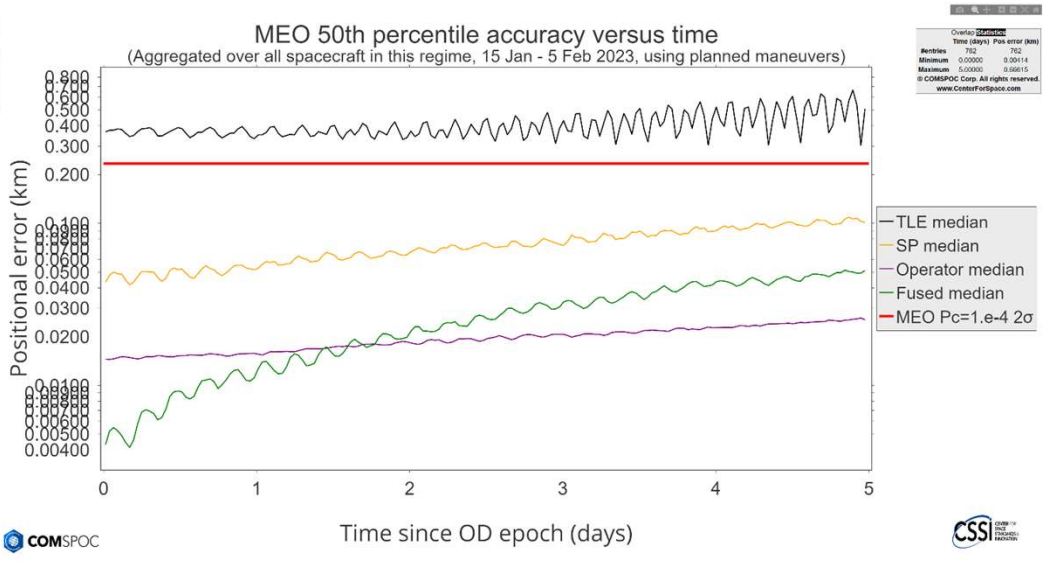
Accumulating accuracy statistics from the Probability Density Fn…



Results: 6 GEO and 6 MEO for independent 3rd party reference S/C

- Assessed 50th percentile, or median (typical) performance for 6 GEO and 6 MEO spacecraft for which independent reference orbit ephemerides were available.
- Accuracy statistics revealed…
  - ☑ 7X GEO typical accuracy improvement for the fused solution
  - ☑ 3X GEO typical accuracy improvement for the fused solution





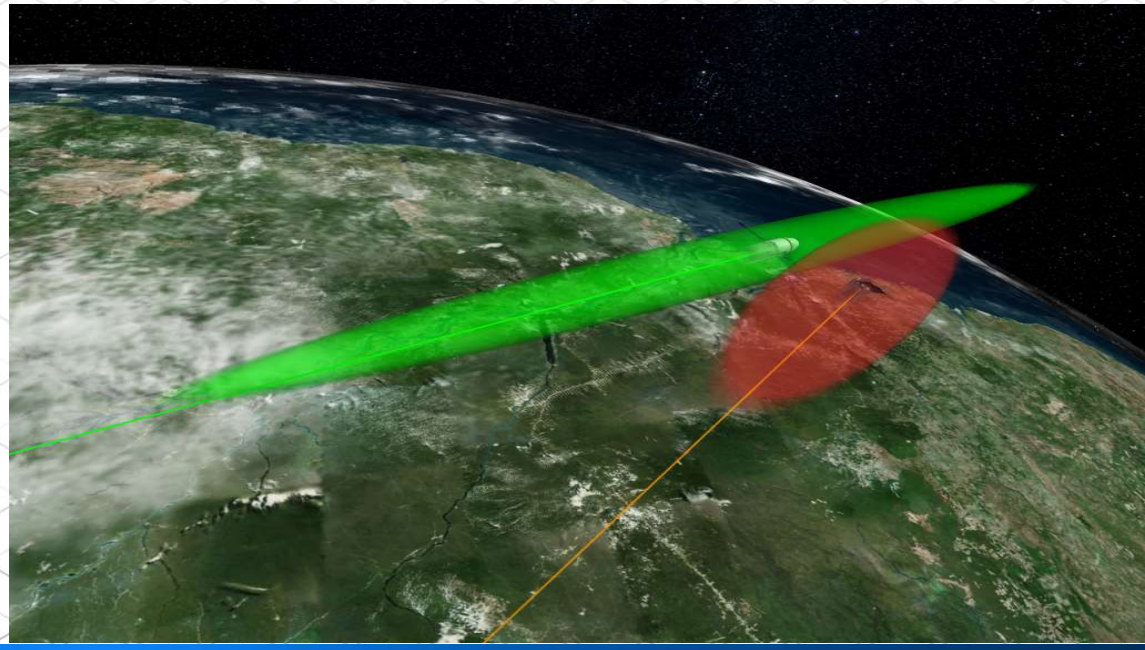
Conclusions

- **Improved accuracy of collaboratively-fused solutions reinforce earlier STCM study**
- **Every SSA provider has gaps** in capability in certain circumstances
  - 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.
  - More lead time necessary for optimal configuration and tuning of collaboratively-fused solution
- **Spacecraft operator ephemerides unsuited for CA system** w/o augmentation or data fusion, as they largely lack covariance information and have biases and latency issues
- Predictive positional products failing to incorporate planned maneuvers **substantially degraded**.
- Despite only COMSPOC optical + spacecraft operator observations, **fused solutions are at least equivalent and often superior to current legacy government SSA**.
- Imagine what could be done in an appropriately funded collaborative SSA framework (spacecraft operator + government (SSN obs) + commercial SSA data + data fusion system)
  - **Substantial accuracy, timeliness, comprehensiveness, and transparency improvements**

4TH International Conference on Space Situational Awareness (ICSSA)
Daytona Beach, FL, USA
IAA-ICSSA-24-16317

Synthetic covariance production using a new digital approach

Robert Gist
Dan Oltrogge
Salvatore Alfano



Why are error estimates (i.e., “covariances”) needed?

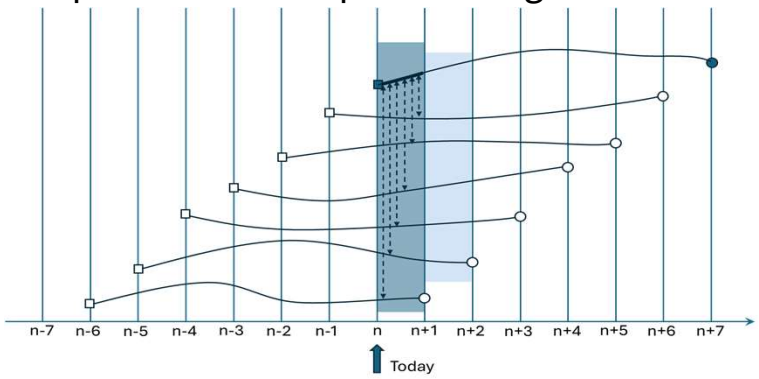
- Spacecraft operators have largely adopted collision probability (Pc) for Go/No-Go
  - Pc provides a mathematically rigorous way to estimate likelihood of collision
- Pc requires: (1) accurate nominal trajectories; (2) object dimensions; (3) covariances.
- SSA tracking network reacquisition typically needs nominals + covariances.
- … yet covariances are largely unavailable
  a) Semi-analytic orbit theory (SGP/TLEs) does not provide error estimates
  b) Covariance information largely unavailable for High Accuracy Catalog (HAC) Special Perturbations(SP), with no way to propagate it when it is available
  c) Owner/operators often unable to generate covariance time histories, because:
     - Orbit Determination (OD) software may be “black box” delivered along with spacecraft procurement
     - If OD black box does produce covariance, it’s usually a 3x3 with no capability to propagate.
  d) CDMs only contain covariance at that epoch, unable to be propagated, and are likely unrealistic.
     - “Mining” of CDMs to aggregate statistics likely to be undersampled and of narrow applicability.

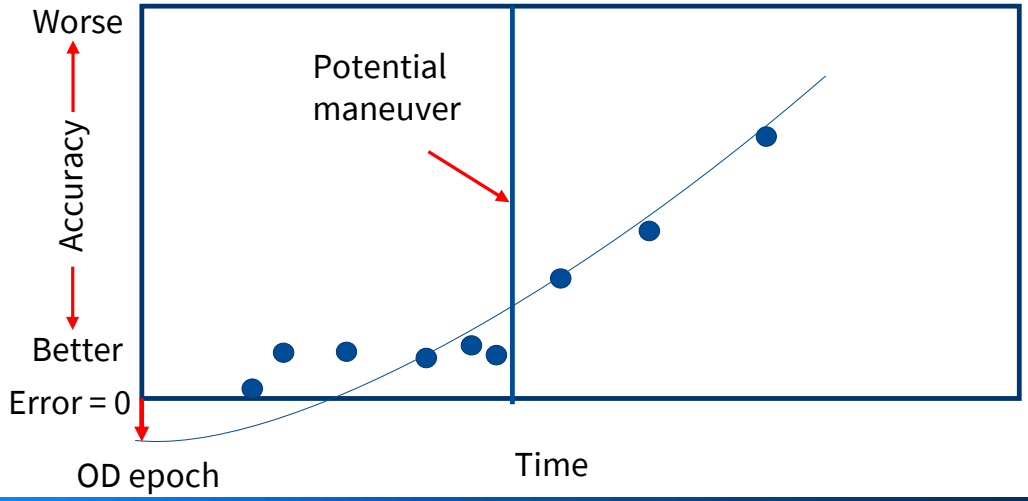
SynCoPate: A new digital approach to approximate covariance

- Can estimate accuracy from error function coefficients derived from precision (a.k.a., repeatability/veracity/consistency) of predicted trajectories as proxy for accuracy, since "accuracy cannot be better than precision".
  - Pitfalls:
    - Susceptible to "overlap gap" issues
    - Hard to accommodate variabilities in solar flux, Ap, and argument of latitude (viewing geometry) variations
    - Assumed error fit functions often unrealistic, i.e.,

"***All models are wrong. Some are useful.***" – D. McKnight

Ephemeris overlap statistics generation





Building a better mousetrap…

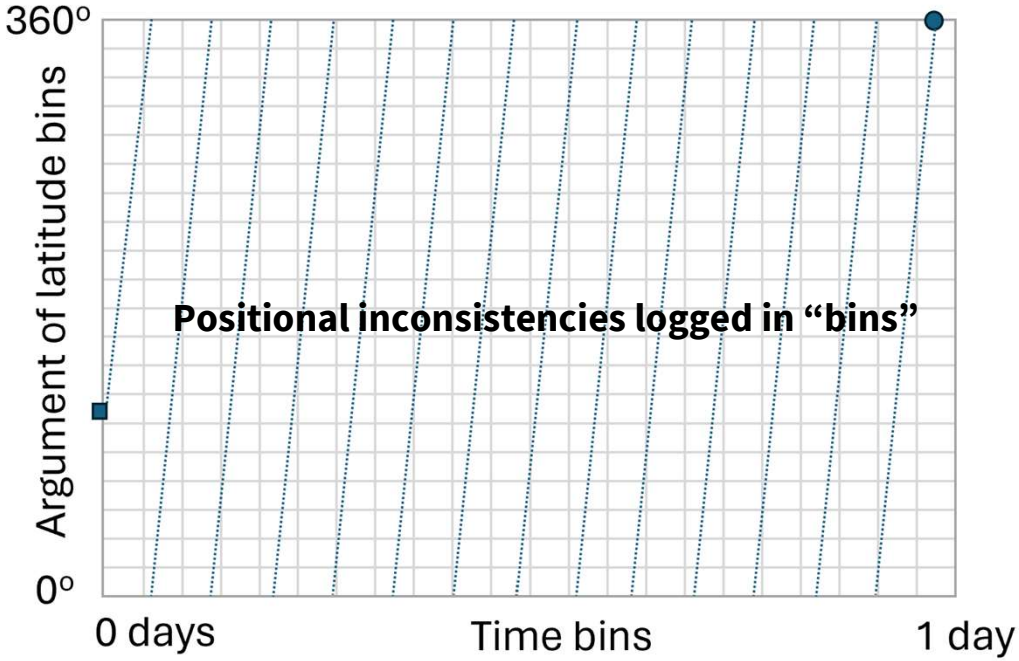
4) **Statistical aggregation of large amounts of overlap data into digitized "bins" or "cells" containing precision** (a.k.a., repeatability/veracity/consistency) of predicted trajectories as proxy for accuracy, since "***accuracy cannot be better than precision***".
   - Pitfalls:
     - Susceptible to "overlap gap" issues
     - Still hard to accommodate variabilities in solar flux and Ap

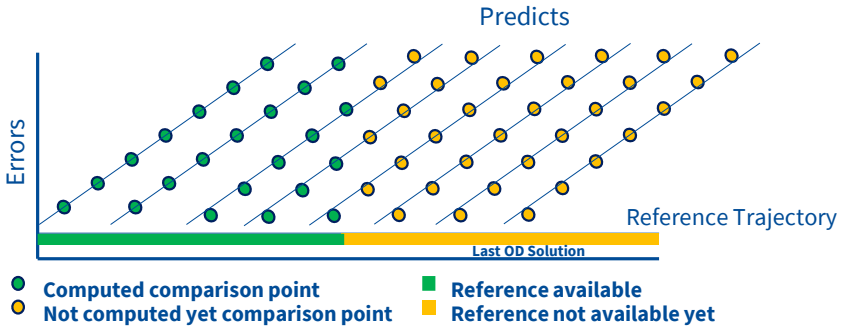
- Had 24 years to improve upon that approach; a mature approach needs to:
  - Not assume a "shape" to error growth
  - Work on all ephemeris time histories, for all classes of objects, orbit regimes, and maneuver capabilities
  - Produce 6x6 covariances
  - Account not just for **prediction time**, but also **argument of latitude** variations

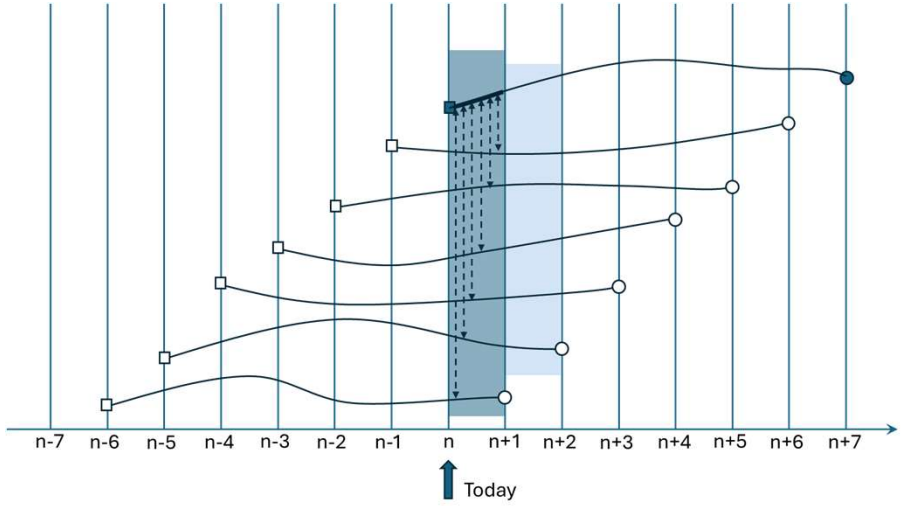
*Peterson, G.E., Gist, R.G., Oltrogge, D.L., "Covariance Generation for Space Objects using Public Data," AAS/AIAA Space Flt Mech Mtg, AAS 01-113

Basic principles of overlap statistics

- By differencing ephemeris predictions from a series of OD solutions, we can assess the repeatability (precision) of the ephemeris and its suitability for Pc

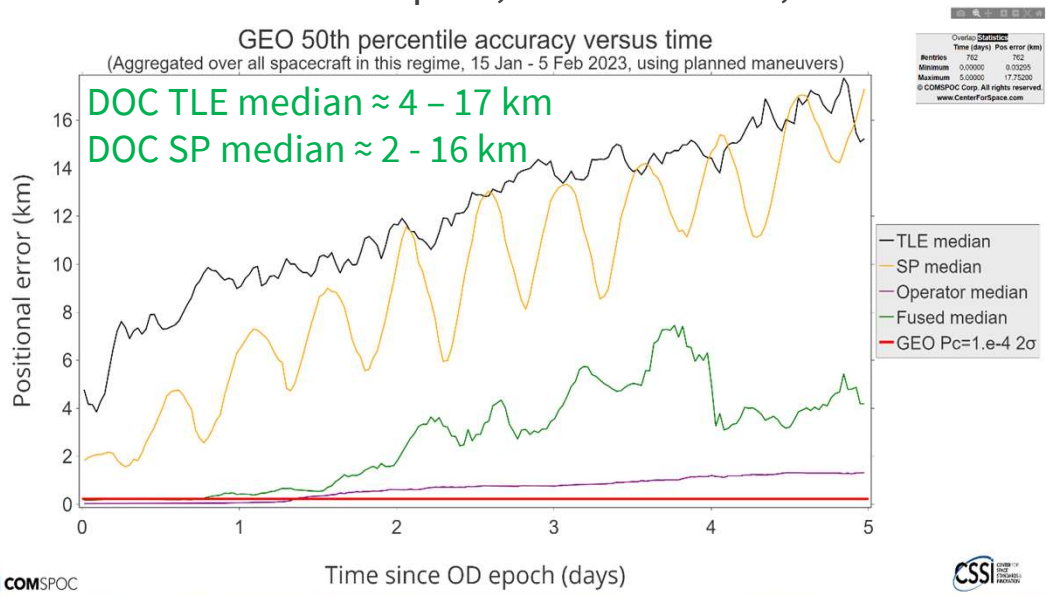


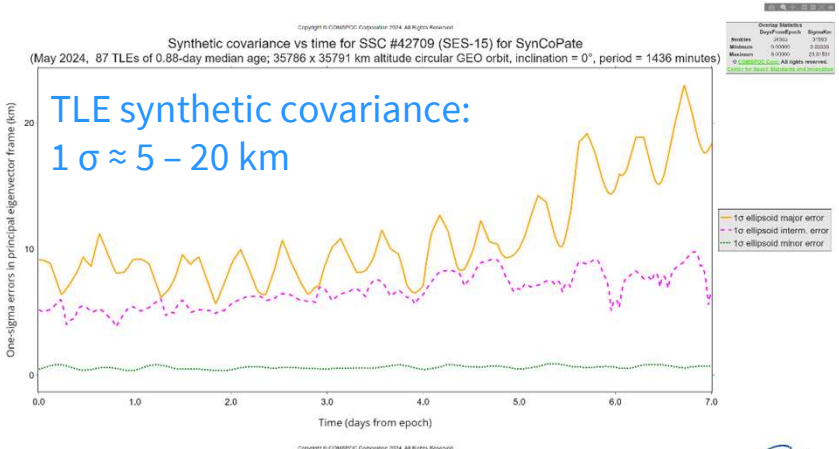


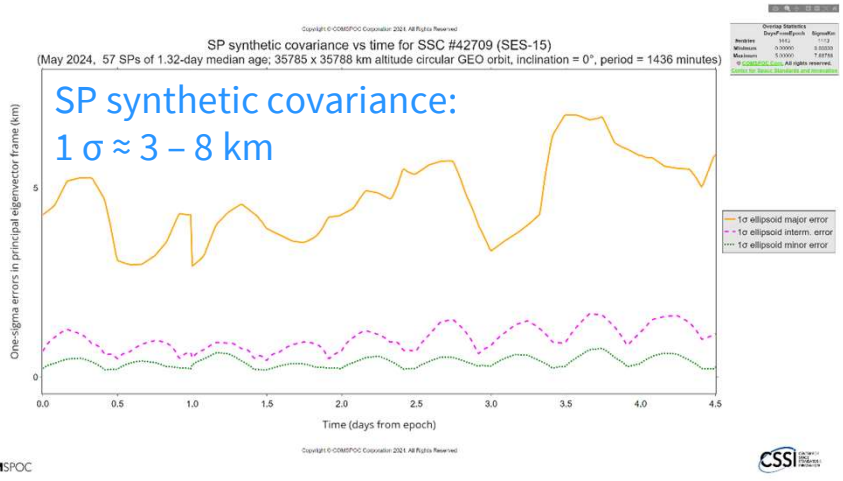


Comparison with DoC's GEO/MEO Pilot performance results

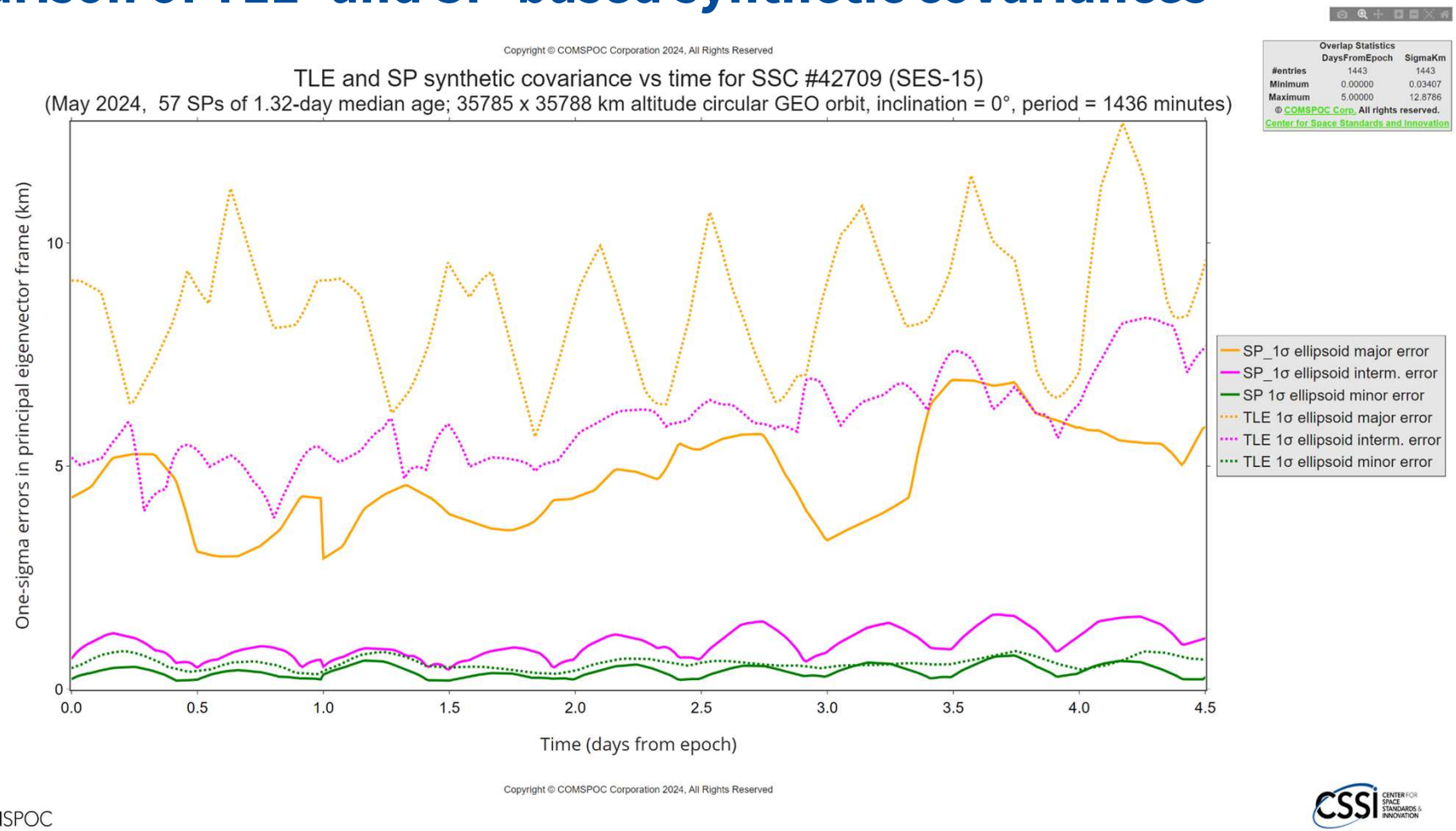
- Assessed 50th percentile, or median (typical) performance for 6 GEO and 6 MEO spacecraft for which independent reference orbit ephemerides were available.
  - Not direct compare; median 50th %; 1 σ ≈ 68.3th %







Comparison of TLE- and SP-based synthetic covariances



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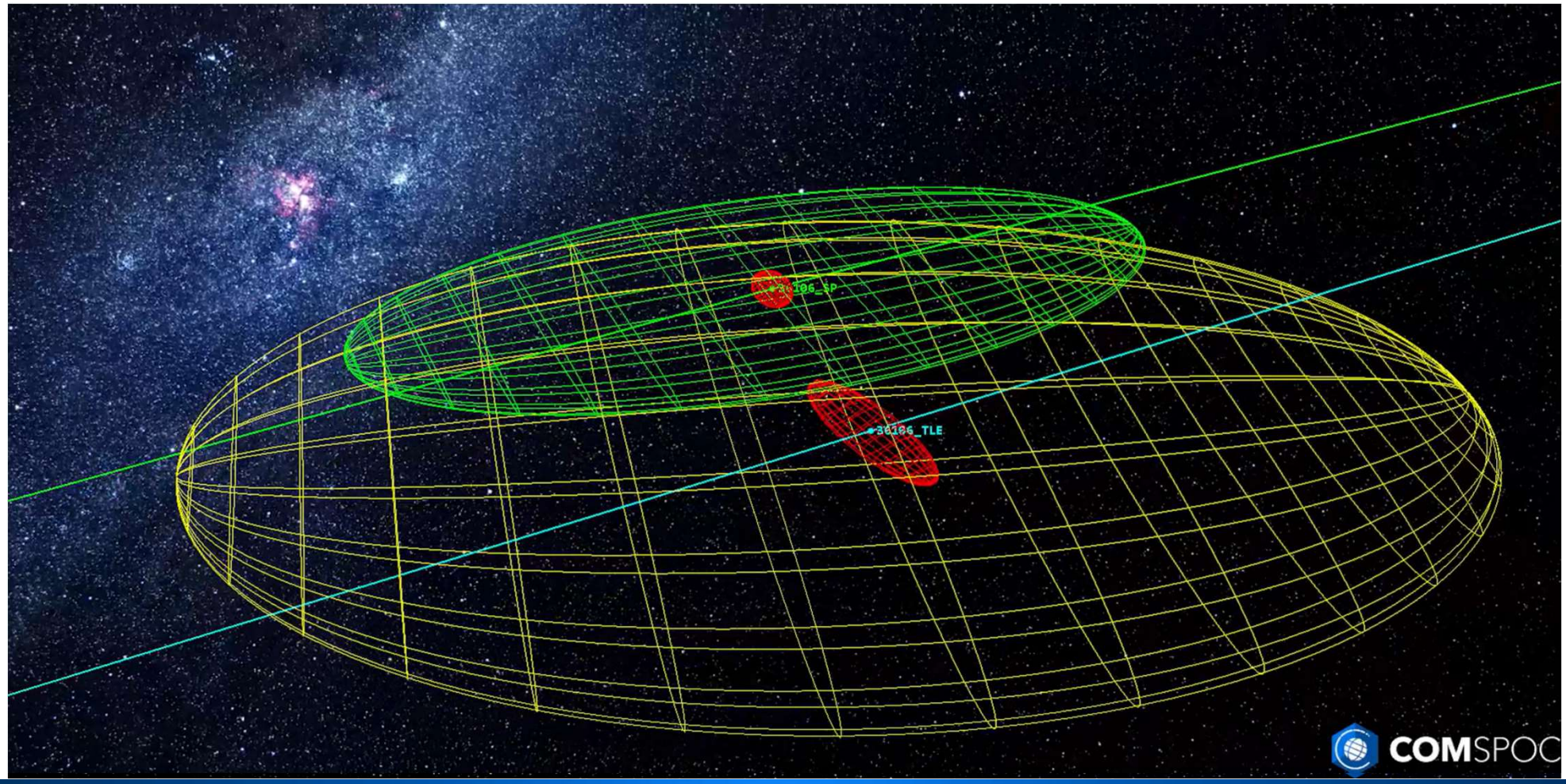
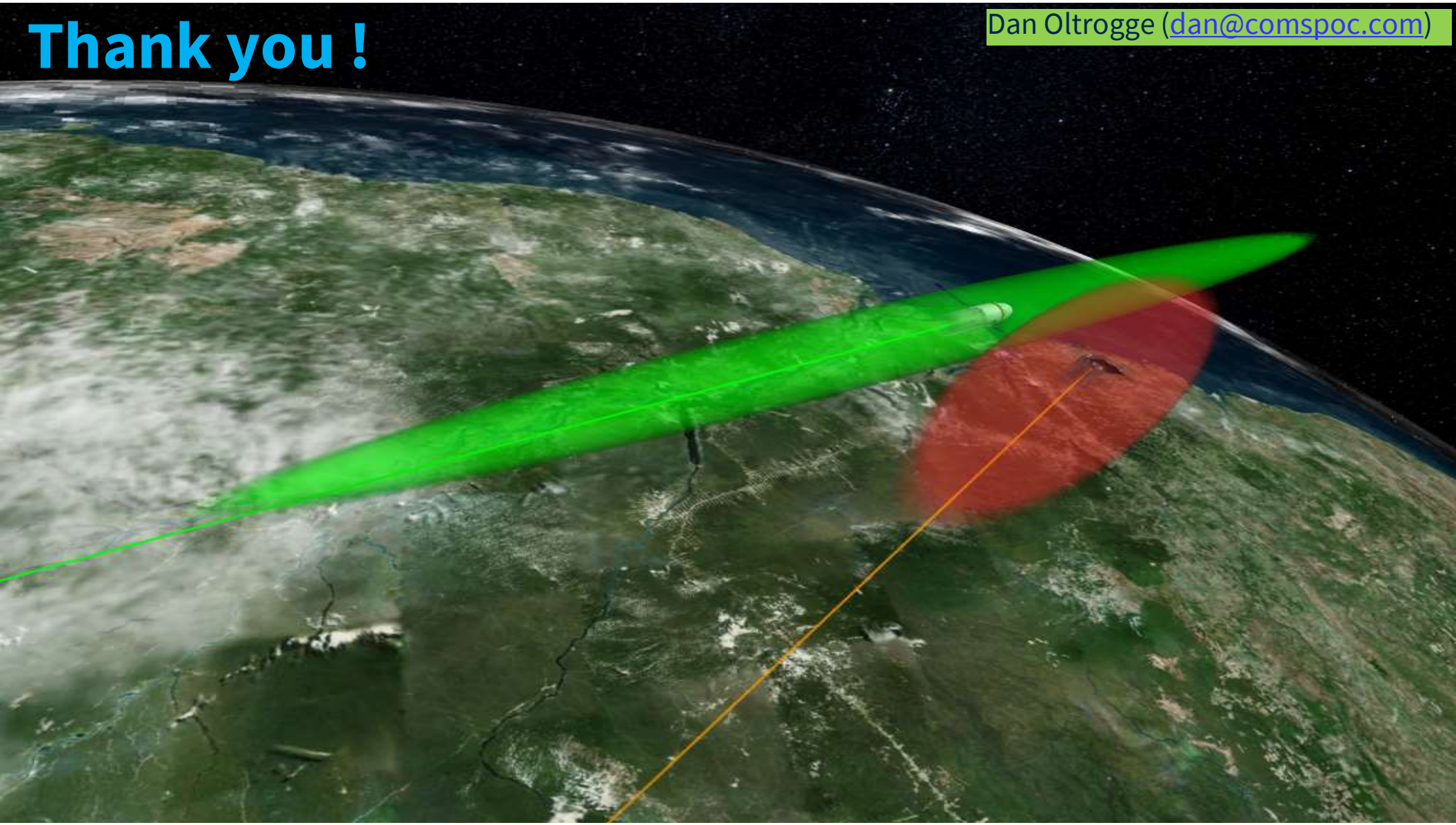
Can visually compare SP vs TLE synthetic covariances (Intelsat 15)



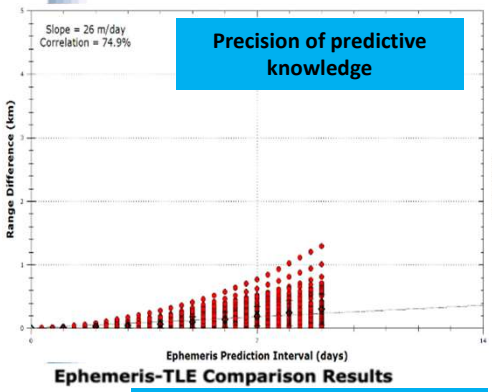
Thank you !

Dan Oltrogge (dan@comspoc.com)

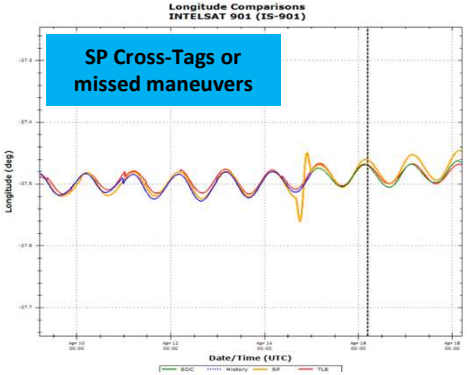


SDC conducts ongoing comparative SSA

- SDC scrutinizes ALL operator and 18 SPCS data, CDMs and SP ephemerides, to find and report irregularities.
  - Assesses veracity, accuracy, timeliness, and completeness of all SSA products.
  - SDC's scope and content appear to be <u>unique</u> in the space flight safety arena.



Precision of predictive knowledge



SP Cross-Tags or missed maneuvers

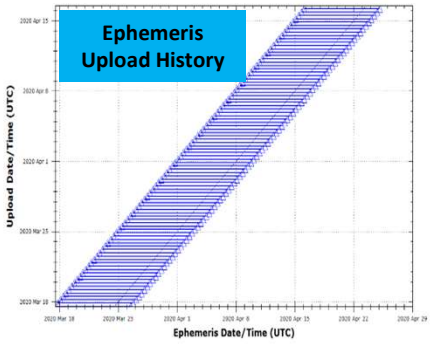
`Neighborhood watch

SSA data upload monitoring

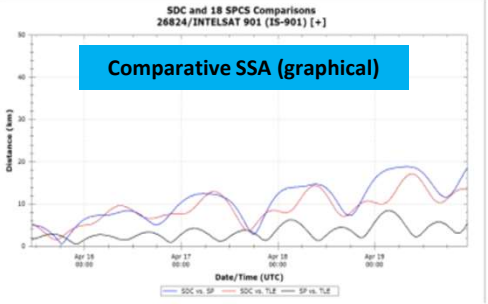
The following are the ephemeris-TLE comparison results for INMARSAT as of 2020 Apr 09 05:00:00 UTC. Results are provided in Table 2 for each of the satellites in Table 1 for which we have current ephemeris data.

Table 1. Satellites to be Validated

Official Name	NORAD Catalog Number	Ephemeris Upload (UTC)	Ephemeris Start (UTC)	Ephemeris Stop (UTC)	Ops Status
INMARSAT 3-F1	23839	2020 Apr 03 12:03:52	2020 Apr 03 00:00:00.000	2020 Apr 25 00:00:00.000	+
INMARSAT 3-F2	24307	2020 Apr 03 12:03:48	2020 Apr 03 00:00:00.000	2020 Apr 25 00:00:00.000	+
INMARSAT 3-F3	24674	2020 Apr 03 12:03:50	2020 Apr 03 00:00:00.000	2020 Apr 25 00:00:00.000	+
INMARSAT 3-F5	25153	2020 Apr 03 12:03:56	2020 Apr 03 00:00:00.000	2020 Apr 25 00:00:00.000	+
INMARSAT 4-F1	28628	2020 Apr 08 10:14:09	2020 Apr 08 00:00:00.000	2020 Apr 18 00:00:00.000	+
INMARSAT 4-F2	28899	2020 Apr 08 10:14:14	2020 Apr 08 00:00:00.000	2020 Apr 18 00:00:00.000	+
INMARSAT 4-F3	33278	2020 Apr 02 09:45:16	2020 Apr 02 00:00:00.000	2020 Apr 12 00:00:00.000	+
ALPHASAT	39215	2020 Apr 02	2020 Apr 02	2020 Apr 12	+



Ephemeris Upload History



Comparative SSA (graphical)

Comparative SSA (textual)

CDM min range at TCA (2020-04-18 08:53:21.842 UTC; 2.63 days out) = 0.921 km

Ephemeris vs. CDM/TLE Comparison		
Primary	SP Range at TCA: 11.079 km	TLE Range at TCA: 11.345 km

Primary ephemeris epoch: 2020-04-15 10:00:02.000 UTC (0.33 days old)

CDM vs. TLE Comparisons	
Primary Range at TCA: 0.298 km	Secondary Range at TCA: 3.994 km

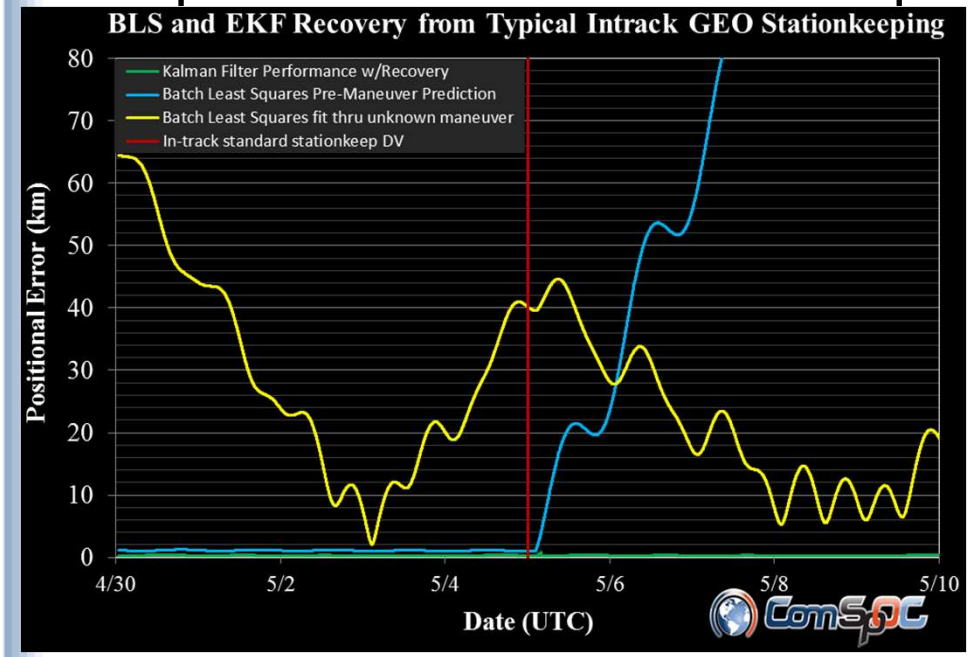
CDM Conjunction Comparisons	
SP vs. SP	TCA: 2020-04-18 08:53:21.842 UTC, 0.921 km
Ephemeris vs. SP	**TCA: 2020-04-18 08:53:21.114 UTC, 7.779 km**
Ephemeris vs. TLE	TCA: 2020-04-18 08:53:20.850 UTC, 4.673 km
Ephemeris vs. Ephemeris	N/A
Complete AGI Viewer Scenario	

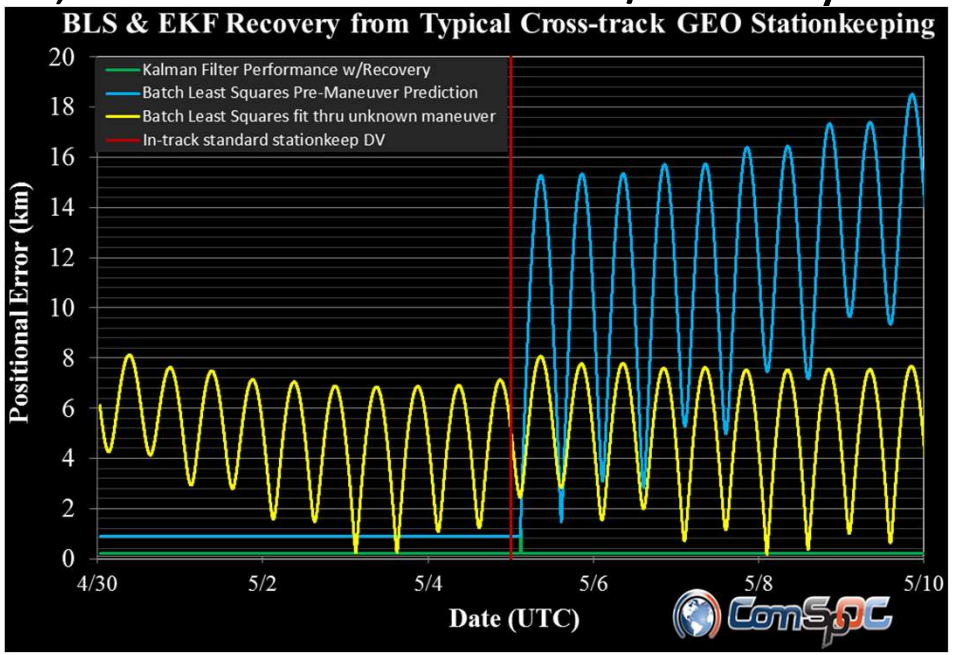
Notes:

- *Valid SDC ephemeris for primary*
- *No SDC ephemeris available for secondary*

Example: Batch OD fit through maneuver

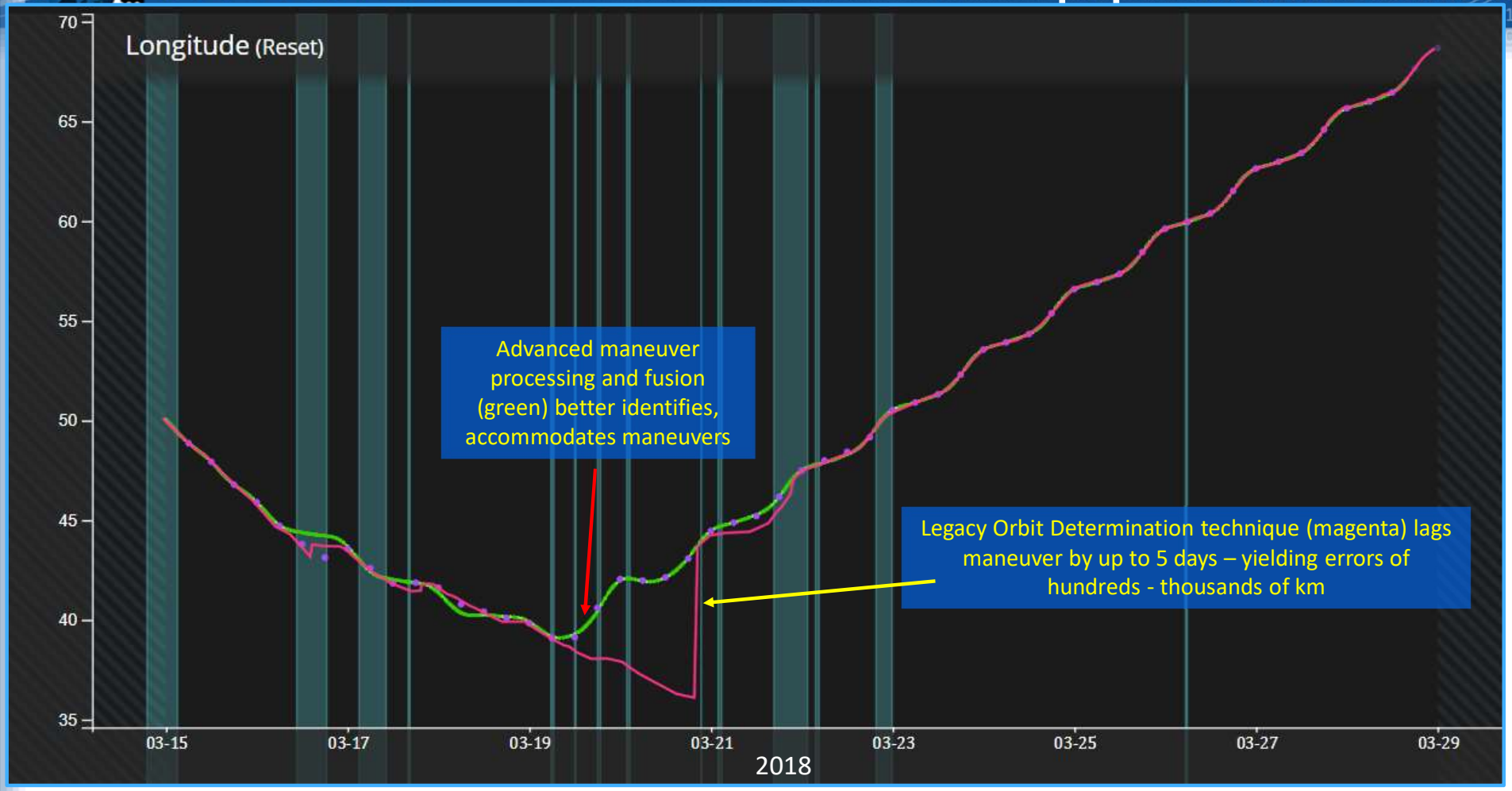
- "Batch Least Squares" (BLS) OD thru unknown or mismodeled maneuvers problematic
  - e.g., consider 9-day fit through typical in- & cross-track maneuvers
- Sequential filter OD less susceptible, and for shorter time/latency





SPACE DATA ASSOCIATION

Public space catalog maneuver ...

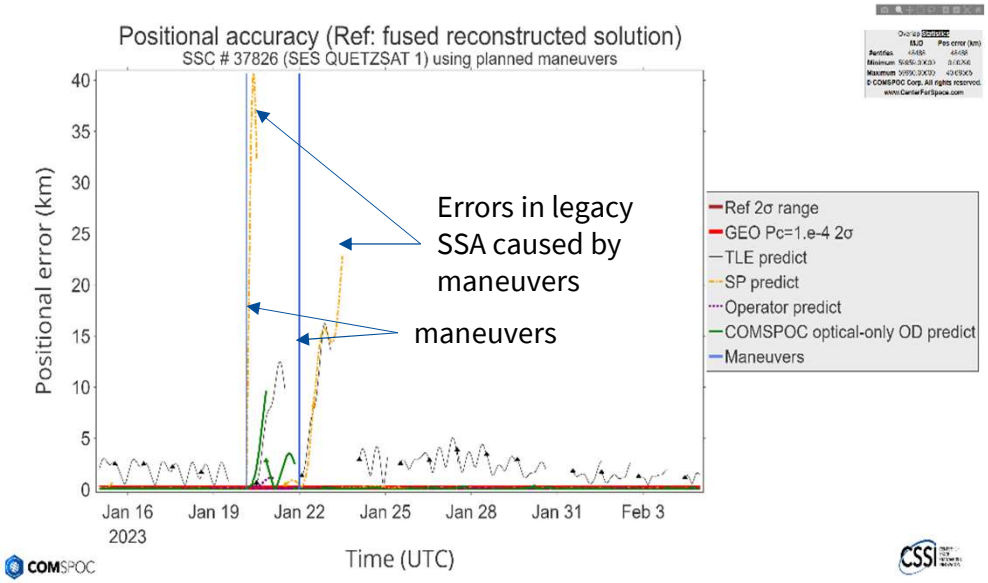


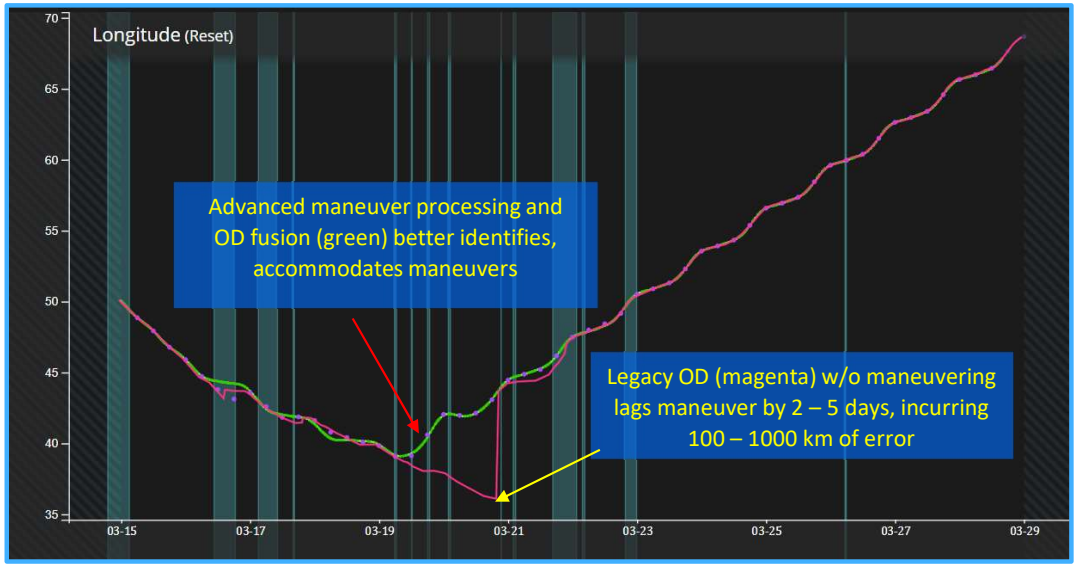
SSA strengths and weaknesses

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.

Current gaps: Unmodeled/mismodeled maneuvers

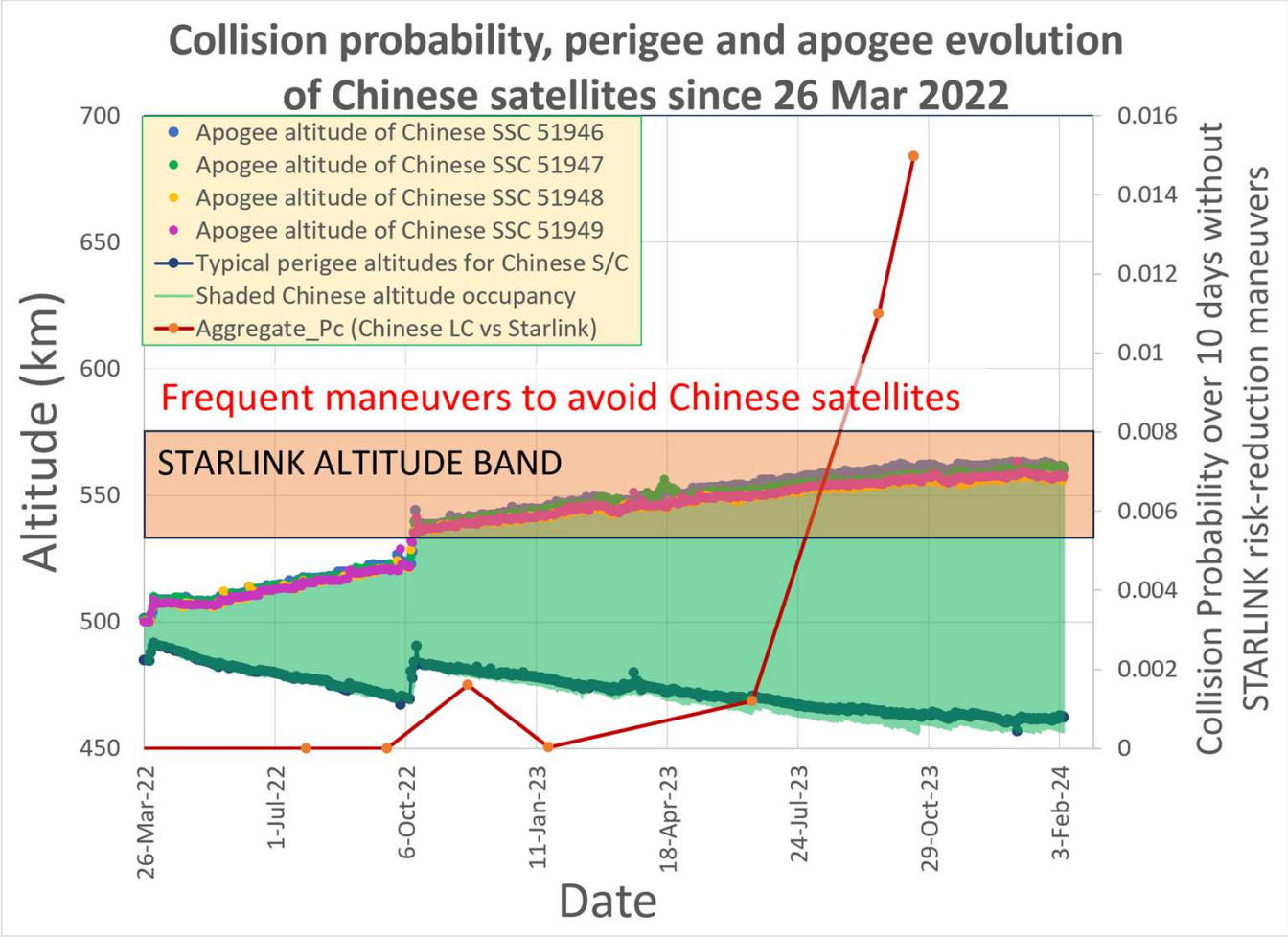
- Mismodeled/unmodeled maneuvers are single biggest degradation* to SSA accuracy
- Legacy approach (SP, TLEs, High-Accuracy Catalog) **fail to meet required accuracies**!



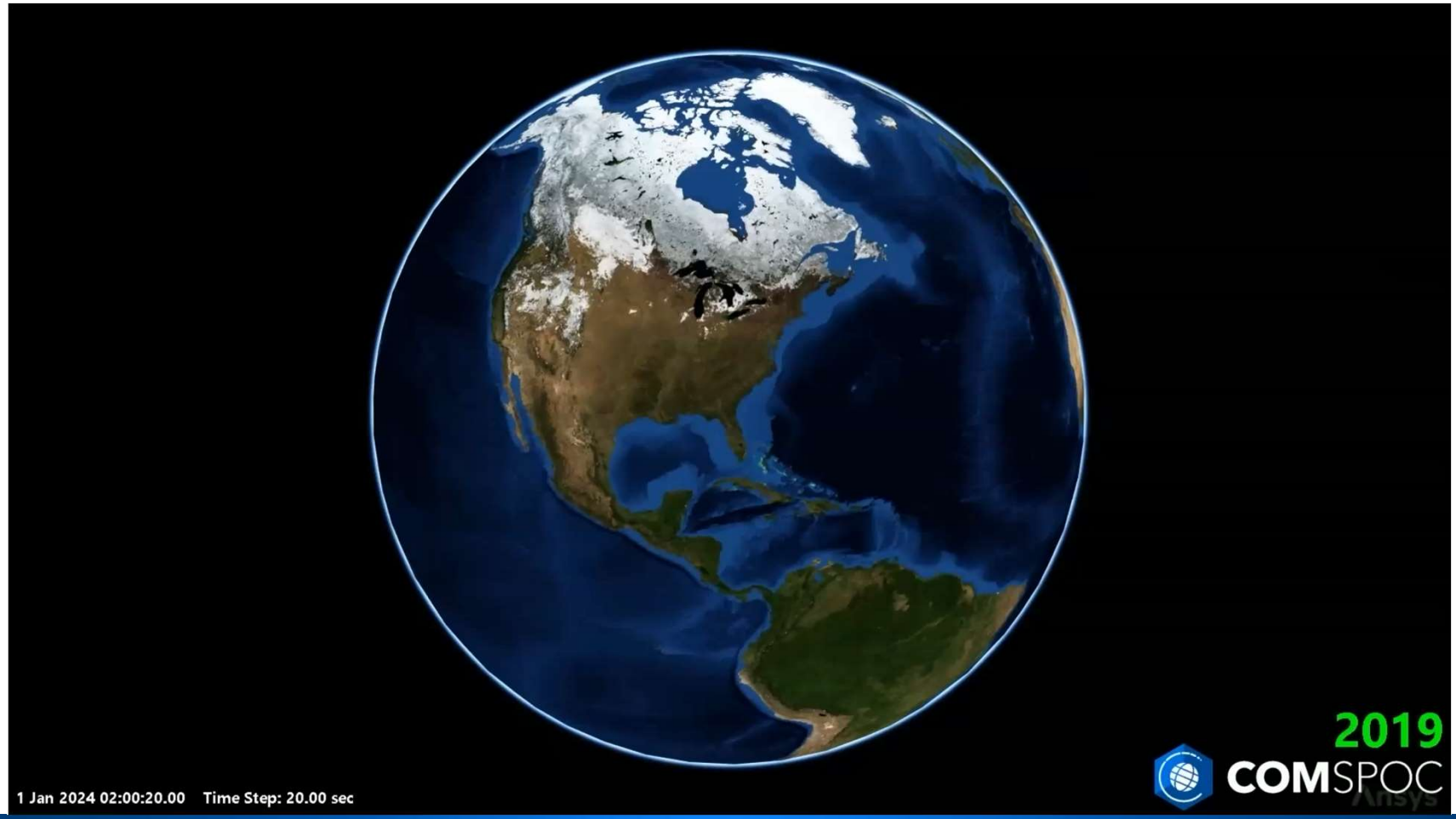


*COMSPOC technical performance assessment of DOC GEO/MEO Pilot

Lack of coordination between Large Constellation orbital shells

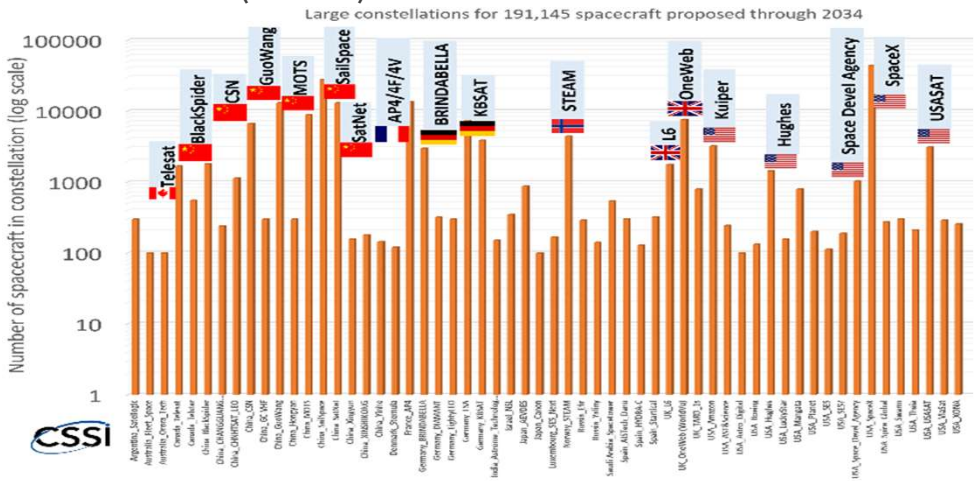


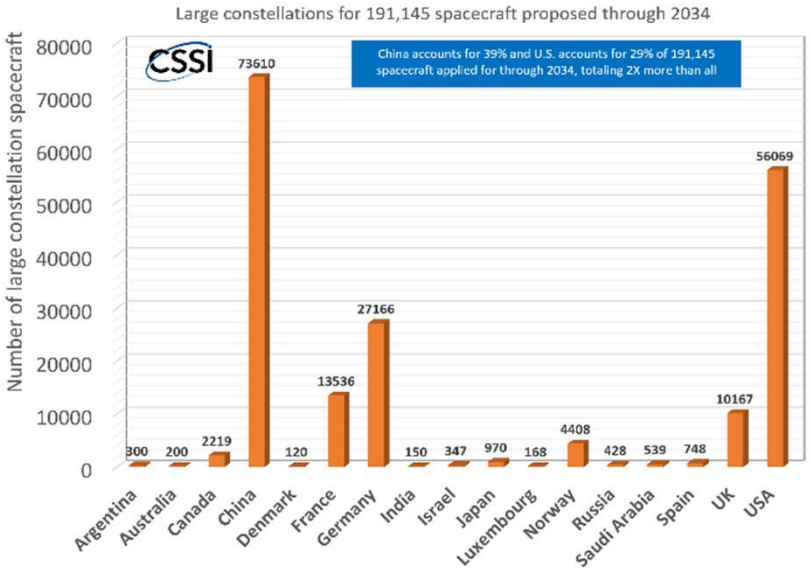
Updated Large Constellation applications: 191,000 by 2034

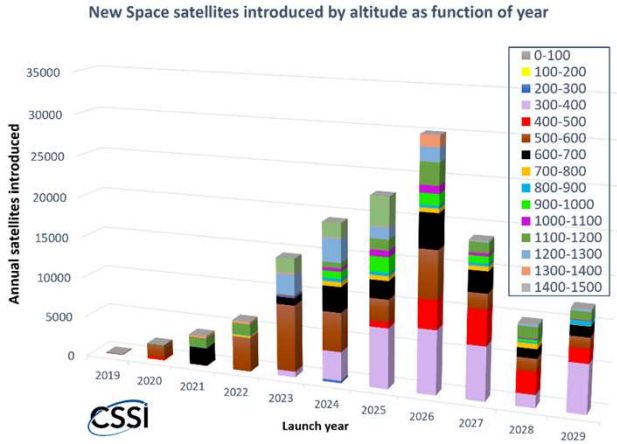


Large constellations (LCs)

- China has surpassed U.S. in LC applications
- Encounter rates are dominated by LCs
- Not a problem if **effectively** mitigated.
- Not currently **effective** because:
  - SSA is not good enough (accurate, timely, complete).
  - Some LCs (China) don't share or use shared data

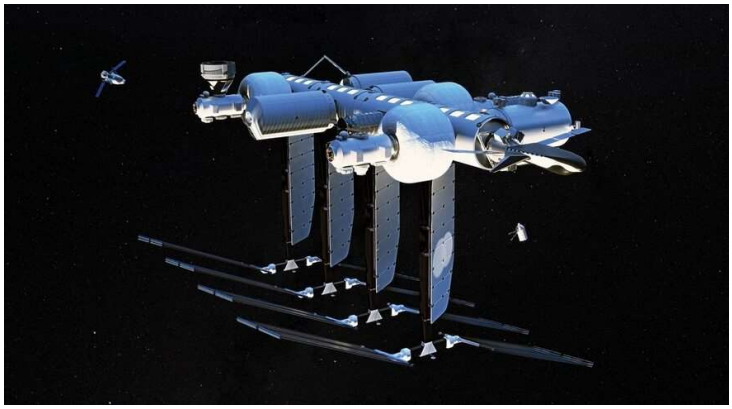






Human spaceflight transitioning from State Actor-led to commercial

- Once exclusively government-led… **Now open to commercial/private operators**.
- Many commercial companies developing human suborbital and space station systems
  - ✓SpaceX – Operational to ISS (2021)
  - ✓Blue Origin – Suborbital operations (2021-present)
  - ✓Virgin Galactic – Suborbital operations (2021-present)
  - ✓Axiom Space – ISS module (2024), then standalone station
  - Nanoracks/Lockheed/Voyager/Boeing/Redwire – Starlab (by 2028)
  - Blue Origin/Sierra Space/MHI – Orbital reef (beginning 2027)
  - X Orion Span – Aurora "Luxury Hotel" Station planned
  - Northrop Grumman – By 2029
  - Space Transportation Beijing – Suborbital space tourism + Hypersonic transport (~2030)*



Orbital Reef (SpaceNews)

- Happening coincident with deployment of large constellations!

http://www.parabolicarc.com/2022/07/13/suborbital-spaceflight-numbers/
https://spacenews.com/nasa-companies-reject-concerns-over-commercial-space-station-development-schedules/