Supplemental General Perturbations (SupGP) Element Sets for Modern Space Operations and Space Flight Safety

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ABSTRACT

Traditional Space Situational Awareness (SSA) data alone is inadequate for modern space operations such as multi-satellite launches, close proximity deployments, and mega-constellation operations. Due to changes in the modern space operations environment, launches of more than fifty satellites at a time are now common, satellites are extremely small in comparison to the historical size that traditional SSA data and techniques were developed around, and satellites fly in formation clusters. These changes, in combination with the increase in overall congestion of the Earth Orbital Environment require more precise SSA data and processing techniques, with low latency, to support space operations and Space Flight Safety.

Supplemental General Perturbations (SupGP) Element Sets have proven effective in supporting modern space operations and enhancing Space Flight Safety. SupGP Element Sets are derived directly from owner/operator-supplied data. Until recently, all GP data provided to the public have been derived from radar and optical observations of the US Space Surveillance Network (SSN). This process can cause problems, particularly for deep-space objects (orbital periods greater than 225 minutes) which rely on optical observations. Limited geographic distribution of these optical sites, together with unpredictable weather conditions, can result in long intervals between observations, resulting in delays in cataloging objects, old and inaccurate data, and even difficulty in recovering objects.

While this uncooperative approach to tracking space objects is required for a large portion of the current satellite catalog, many of these objects are operational payloads which are routinely tracked by their owners or operators. Some of this orbital data, such as for the GPS constellation, is publicly available via the Internet. Working with owners, operators, and public data, platforms such as CelesTrak have been able to produce and share SupGP data with the public for 69% of the operational satellites on orbit. SupGP data has provided significant and measurable increases in accuracy, timeliness, and Space Flight Safety.

This paper discusses and provides recent and relevant examples and comparisons between SupGP data and traditional SSA data to illustrate the need for SupGP data incorporation across the Space Operations Community. One such example are the GALAXY 25 (G-25) maneuvers from GEO orbit to a circularized GEO Graveyard orbit from 2022 Dec 5-12. SupGP processes and data provided precision position information all throughout the maneuvers, to a level of detail where thruster fires were observed. Continuous situational awareness was provided to all other space operators who may have needed to make decisions for their own maneuvers or even conjunction avoidance.

By comparison, if a space operator had relied on the traditional SSA data alone it was not possible to know that G-25 was maneuvering. Using only the traditional SSA data, the first accurate orbit solution was not until 2022 Dec 19—14 days after the maneuvers began and 7 days after the maneuvers completed and G-25 was stabilized in the GEO Graveyard orbit.

The problems and risks of relying on such inaccurate and delayed data for space operations, maneuver decisions, and conjunction avoidance are obvious. The risks and potential for a catastrophic event are significantly greater when increased congestion and modern space operations are considered, such as: multi-satellite launches, close proximity deployments, formation flight clusters, and mega-constellation operations.

The SupGP data approach offers several advantages in accuracy, timeliness, redundancy, and ease of use over traditional SSA data. All SupGP advantages offer improvements in Space Flight Safety and increased precision required for modern space operations.

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SupGP data and processes have been rigorously tested, verified, and validated. Details of SupGP data, SGP4 fitting, convergence criteria, and RMS calculation results is discussed. Additional recent and relevant example comparisons between SupGP data and Traditional SSA data are provided with graphic illustrations to reinforce the benefits and the space community's need for adoption of SupGP data at present and in the future. There is a compelling necessity to share SupGP data across the space community in the interest of Space Flight Safety for all and to ensure the Earth Orbital Environment is preserved for future generations.

1. INTRODUCTION

The modern space operations environment, the unprecedented rate of change, and pace of operational activity has strained traditional SSA techniques and GP data processes to the point they alone are no longer fully effective. Traditional non-cooperative observation techniques do not provide orbital data at the accuracy and timeliness needed to support modern space operations such as: multi-satellite launches, close proximity deployments, formation flight clusters, and mega-constellation operations. In addition, modern space operations and the increased volume of data and satellite activity have negatively impacted traditional techniques and GP data by slowing GP data flow, decreasing accuracy, decreasing observation frequency, increasing errors, increasing satellite cross-tagging, increasing the number of lost satellites, etc.

SupGP data is a cooperative SSA technique using satellite owner/operator provided data and other public sources to augment traditional techniques. SupGP improves data accuracy, timeliness, robustness, and transparency. This in turn, improves SSA, Space Flight Safety, responsible use of space, and helps preserve the earth orbital environment for all.

2. METHODOLOGY

Each day, CelesTrak checks known sources of publicly available orbital data and produces GP data from that data using Satellite Tool Kit (STK). As an example, for the Global Positioning System (GPS) constellation, the latest GPS almanac provided by the 2nd Space Operations Squadron and posted in the GPS Data section on CelesTrak is propagated in accordance with Interface Specification (IS) for GPS, IS-GPS-200M, to produce ephemerides for the coming day [1]. A more detailed list of input source data for groups of satellites for which CelesTrak produces SupGP data for is provided in Table 1. Unlike in the standard GP queries, it is possible to get multiple SupGP elements for a single object. This is due to some objects having data produced by multiple sources (e.g., with the CPF data) or because there is data for multiple epochs (Intelsat data).

Table 1. Input Source Data for CelesTrak SupGP

Abbreviation	Description
CPF	Consolidated Laser Ranging Predictions
GLONASS-RE	GLONASS Rapid Ephemeris
GPS-A	GPS Almanac
GPS-E	GPS Ephemeris
Intelsat-11P	Intelsat 11-Parameter Data
Intelsat-E	Intelsat Ephemeris
Iridium-E	Iridium Ephemeris
ISS-E	ISS Ephemeris
ISS-TLE	ISS TLE [legacy data]
METEOSAT-SV	METEOSAT State Vector
OneWeb-E	OneWeb Ephemeris
Orbcomm-TLE	Orbcomm-Provided SupTLE
Planet-E	Planet Ephemeris
SES-11P	SES 11-Parameter Data
SpaceX-E	SpaceX Ephemeris
SpaceX-SV	SpaceX State Vector
Telesat-E	Telesat Ephemeris
Transporter-SV	Transporter State Vectors

Returning to the GPS example, those ephemerides are used as 'observations' to fit a GPE using the SGP4 orbital model in STK and described in detail in the paper "Revisiting Spacetrack Report #3" [2].

As a result, for the GPS constellation, where GPEs are generally released one to two days after they are generated, the uncertainty drops from several kilometers to several hundred meters (approximately an order of magnitude). A detailed analysis of the accuracy of GPS almanacs and GPS GPEs, is provided in paper "Validation of SGP4 and IS-GPS-200D Against GPS Precision Ephemerides." [3].

Within CelesTrak, each supplemental GPE can be distinguished from regular NORAD GPEs by looking at the Classification field in the data. GPEs provided by Space Track will have a "U" in this field (for Unclassified). Supplemental GPEs will have a "C" in this field (to identify the source as CelesTrak). GPS supplemental GPEs will use the GPS Week and day of that week as the Element Set Number (e.g., GPS Week 435, TOA 589824 yields Element Set Number 4356). Supplemental GPEs for other satellites will use similar methods to set the Element Set Number to allow users to track the SupGPE back to the source data.

For the Intelsat data, where both nominal ephemeris data is provided along with post-maneuver data, both GPEs are generated. That allows the user to use the nominal GPE up to the time of the maneuver and then switch to the post-maneuver GPE after the time of the maneuver. The post-maneuver GPEs are marked with [PM] at the end of the satellite name (CelesTrak data line 0).

Information is then produced on the accuracy of the SGP4 fit for each satellite, for each set of GPE data. SupGP data is fitted from the current epoch forward, as opposed to GP data which is fit to past observations.

Lastly, the final calculated RMS and the number of iterations required to meet the convergence criteria is produced as shown in Table 2.

Table 2. Results for GPS at 2023-08-31 15:40:07.835 UTC

NORAD Catalog Number	24876:	RMS =	0.374875	km,	Iterations =	3
NORAD Catalog Number	26360:	RMS =	0.39769	km,	Iterations =	2
NORAD Catalog Number	26407:	RMS =	0.380214	km,	Iterations =	2
NORAD Catalog Number	27663:	RMS =	0.377255	km,	Iterations =	2
NORAD Catalog Number	27704:	RMS =	0.29901	km,	Iterations =	2
NORAD Catalog Number	28190:	RMS =	0.354499	km,	Iterations =	3
NORAD Catalog Number	28474:	RMS =	0.283022	km,	Iterations =	2
NORAD Catalog Number	28874:	RMS =	0.356746	km,	Iterations =	2
NORAD Catalog Number	29486:	RMS =	0.31412	km,	Iterations =	2
NORAD Catalog Number	29601:	RMS =	0.37609	km,	Iterations =	3
NORAD Catalog Number	32260:	RMS =	0.4454	km,	Iterations =	3
NORAD Catalog Number	32384:	RMS =	0.356673	km,	Iterations =	2
NORAD Catalog Number	32711:	RMS =	0.324371	km,	Iterations =	3
NORAD Catalog Number	35752:	RMS =	0.383617	km,	Iterations =	2

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NORAD Catalog Number	36585:	RMS =	0.386543	km,	Iterations =	3
NORAD Catalog Number	38833:	RMS =	0.345985	km,	Iterations =	2
NORAD Catalog Number	39166:	RMS =	0.367509	km,	Iterations =	3
NORAD Catalog Number	39533:	RMS =	0.339057	km,	Iterations =	3
NORAD Catalog Number	39741:	RMS =	0.257094	km,	Iterations =	3
NORAD Catalog Number	40105:	RMS =	0.407027	km,	Iterations =	2
NORAD Catalog Number	40294:	RMS =	0.371353	km,	Iterations =	3
NORAD Catalog Number	40534:	RMS =	0.409387	km,	Iterations =	2
NORAD Catalog Number	40730:	RMS =	0.38275	km,	Iterations =	2
NORAD Catalog Number	41019:	RMS =	0.373891	km,	Iterations =	2
NORAD Catalog Number	41328:	RMS =	0.39749	km,	Iterations =	2
NORAD Catalog Number	43873:	RMS =	0.394859	km,	Iterations =	2
NORAD Catalog Number	44506:	RMS =	0.276646	km,	Iterations =	3
NORAD Catalog Number	45854:	RMS =	0.377879	km,	Iterations =	2
NORAD Catalog Number	46826:	RMS =	0.397019	km,	Iterations =	2
NORAD Catalog Number	48859:	RMS =	0.287126	km,	Iterations =	2
NORAD Catalog Number	55268:	RMS =	0.301236	km,	Iterations =	3

3. RESULTS

Initial CelesTrak SupGP work and concept development was accomplished and tested using GPS and GLONASS in 2007 and 2008.

3.1 GPS TEST CASE

Using GPS to demonstrate the improved accuracy available from SupGPEs, a comparison of the GPEs released by Space Track at 1300 UTC on 2007 Dec 31 was made to the supplemental GPEs generated from the System Effectiveness Model (SEM) almanac released that same morning at 1515 UTC. The comparison was made to the NGA GPS Satellite Precise Ephemeris for 2007 Dec 31, made available on the National Geospatial-Intelligence Agency (NGA) GPS Satellite Precise Ephemeris webpage on 2008 Jan 2, which is accurate to the centimeter level.

Fig 1 shows a comparison of the results for PRNs 1 through 6 and 8 through 32. The red curves show the error in the Space Track GPEs when compared to the NGA Precise Ephemeris on 2007 Dec 31 and the blue curves show the error in the SupGPEs. The plot demonstrates that the SupGPEs are far more accurate over this interval than the corresponding Space Track GPEs. The 31 Space Track GPEs show an average error of 7.54 km over this period with a maximum error (for PRN15) of 32.45 km compared to an average error for the supplemental GPEs of 0.87 km and a maximum error of 2.37 km, yielding approximately an order of magnitude improvement in the error.

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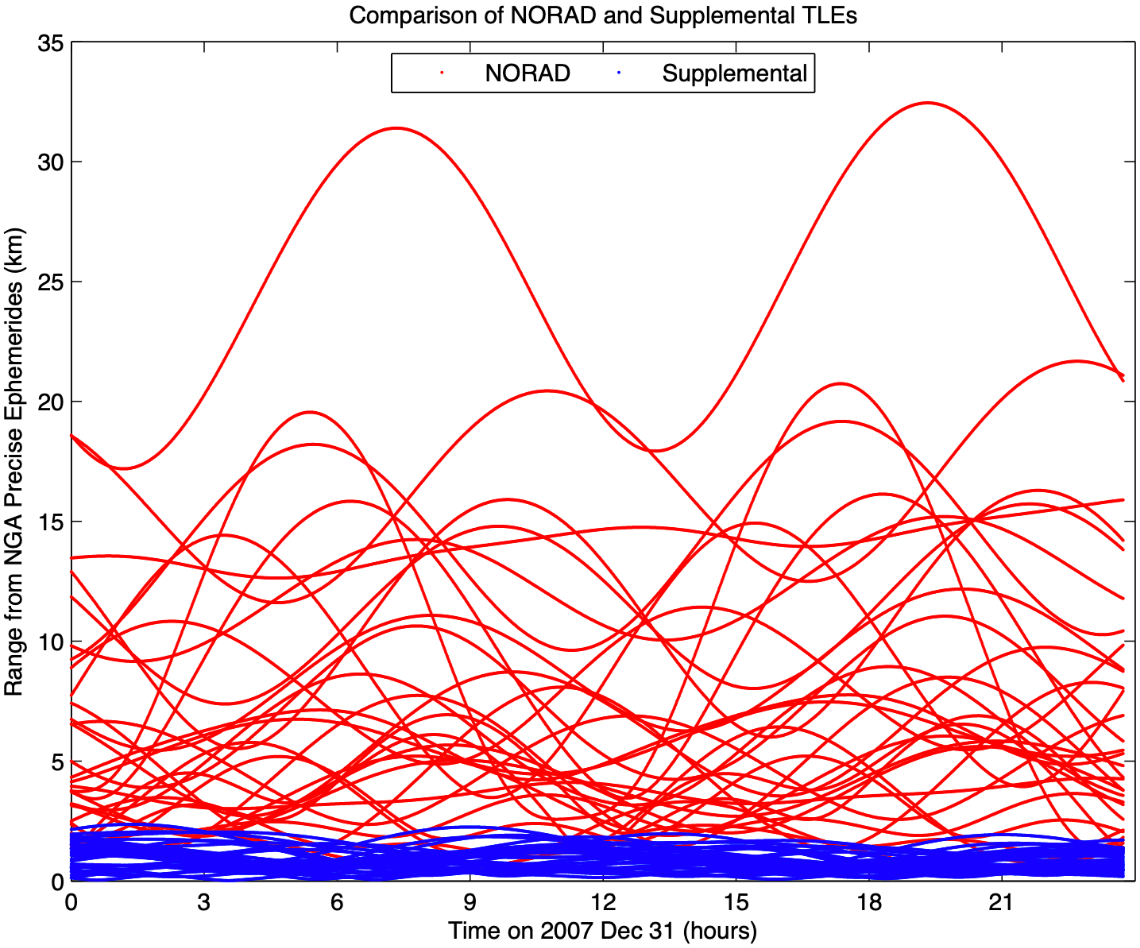

Fig 1. Comparison of GPEs (red) and SupGPEs (blue) for GPS to NGA Precise Ephemerides

3.2 GLONASS TEST CASE

Using GLONASS and repeating the process above, a comparison of the GPEs released by Space Track at 1300 UTC on 2008 Jan 25 was made to the SupGPEs generated from the GLONASS Rapid Precise Ephemerides released that same morning at 1311 UTC, covering the period from 2008 Jan 23 23:59:46.000 UTC (0000 GPS Time) to 2008 Jan 24 23:44:46.000 UTC. The comparison was made to the Final Precise Ephemerides for the day both data sets were released.

Fig 2 shows a comparison of the results for GLONASS Slots 1, 4, 6, 7, 8, 10, 11, 14, 15, 17, 19, 20, 23, and 24. The red curves show the error in the Space Track GPEs when compared to the GLONASS Final Precise Ephemeris on 2008 Jan 25 and the blue curves show the error in the SupGPEs. The plot demonstrates that the supplemental GPEs are far more accurate over this interval than the corresponding Space Track GPEs. The 14 Space Track GPEs show an average error of 3.30 km over this period with a maximum error (for Slot 7) of 9.39 km compared to an average error for the supplemental GPEs of 0.20 km and a maximum error of 0.54 km, yielding over an order of magnitude improvement in the error.

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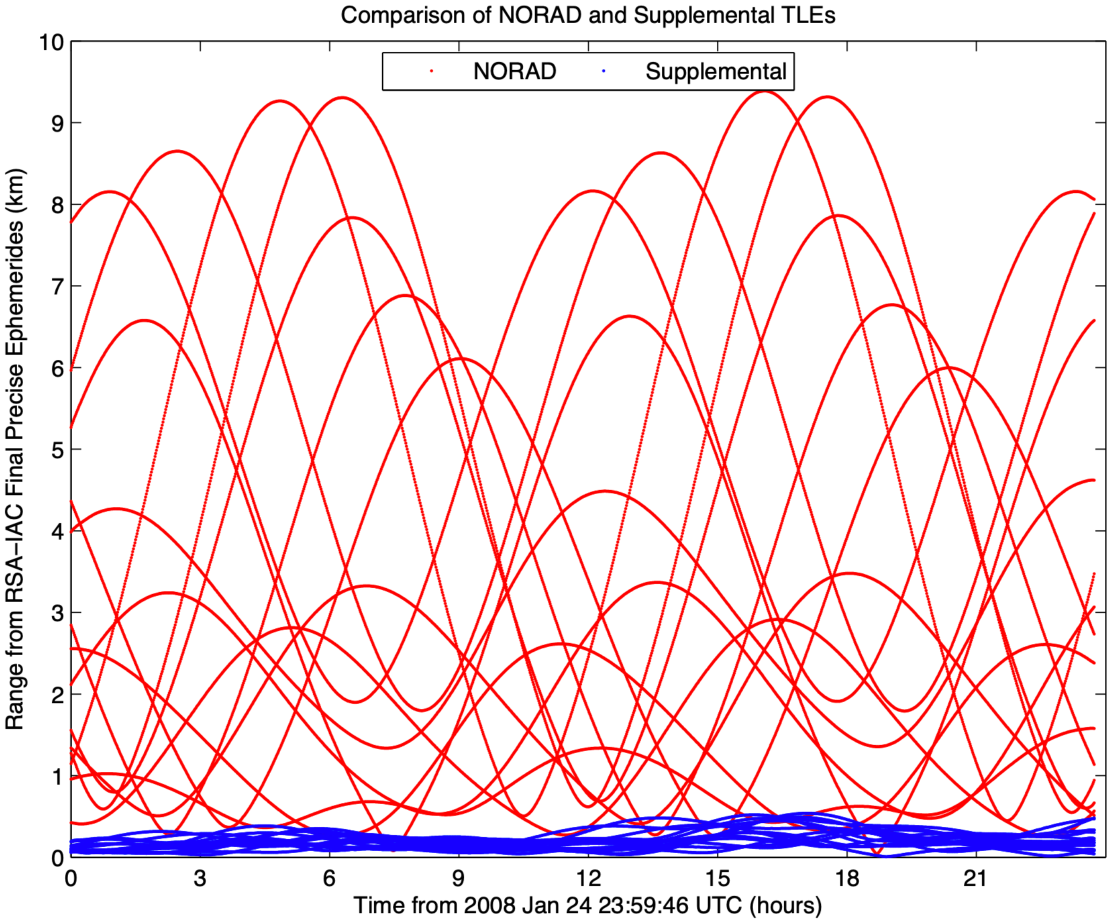

Fig 2. Comparison of NORAD and SupGPEs for GLONASS to GLONASS Final Precise Ephemerides

3.3 APPLICATION TO LEO AND GEO SATELLITES

Building on these early successes, recent work has focused on LEO and GEO satellites. This focus was driven by significant changes in the modern space operations environment. The increase in launches, increase in launch rate, increase of earth orbiting objects, increase of object per a launch, and increase in maneuvers within mega-constellations requires new techniques to support operators and space flight safety with more accurate and timely location, identification, and orbit propagation.

For a LEO example, Starlink results are provided. Prior to launch, CelesTrak produces pre-launch SupGP data for Starlink, using deployment state vectors provided by SpaceX. That data is propagated using numerical integration and the latest Earth Orientation Parameters (EOP) and space weather data. This is then fit with SGP4 to produce SupGP data for the initial stack to allow pre-launch planning by observers as shown in Fig 3.

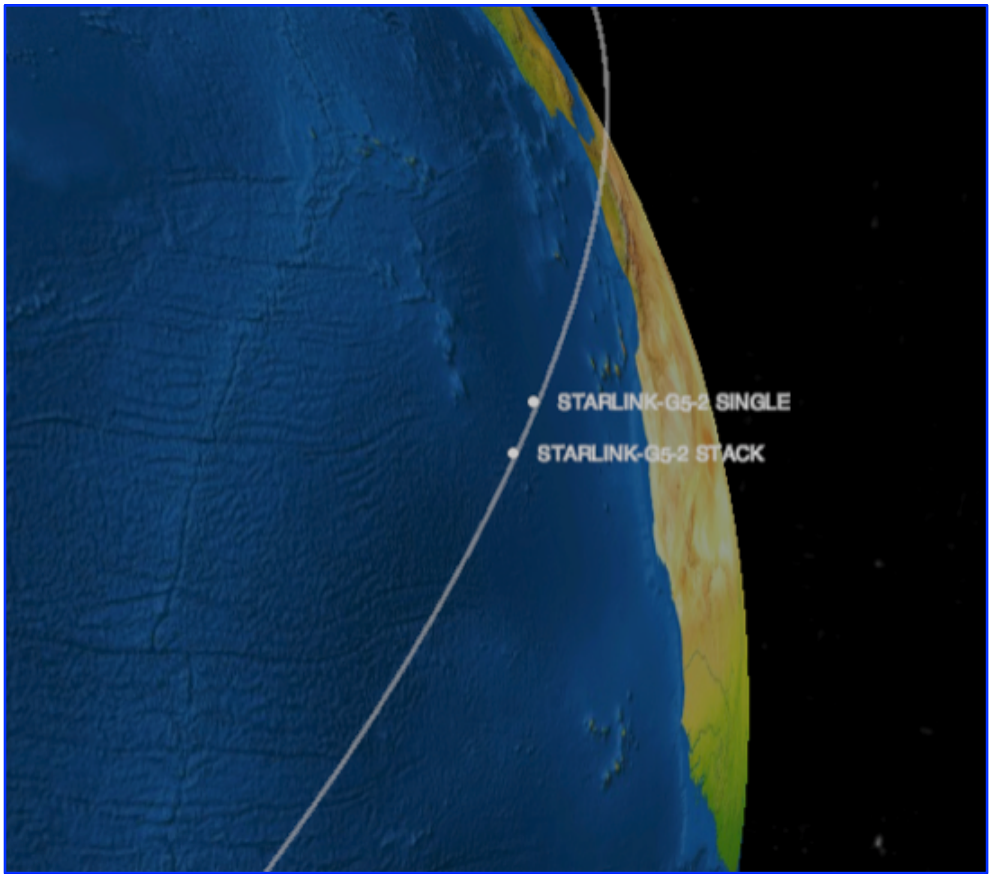

Fig 3. CelesTrak Pre-Launch SupGP Data for SpaceX Starlink G5-2 Launch

Post-launch, CelesTrak produces ephemeris-based SupGP for all satellites on the launch, generally within 8 hours of deployment. Positive identifications are made of each satellite using the GPS tracking data that is explicitly transmitted by a specific satellite. Comparatively, traditional non-cooperative observations, such as the SSN can day 7 days or more. As the Starlink satellites slowly separate, non-cooperative techniques take significant time to associate observation data to individual tracks to produce GP data of sufficient quality for public release. Mis-association of observations to tracks regularly occurs and results in poor orbit solutions which extends the time needed to produce suitable data. Following this, another day or two is required to produce satellite identifications correlated to each orbiting object, resulting in a total of 8-10 days after launch in the best cases. SupGP data produced within 8 hours of deployment can significantly augment and assist traditional methods.

For Starlink standard constellation operations, CelesTrak uses the latest ephemeris and fits the first 8 hours (the interval between updates) using SGP4. Data is limited to the update interval to avoid including maneuvers outside of the interval from ‘fuzzing up’ the solution close to the current time. Users should use the most current data to ensure it includes the latest actual (solved for) maneuvers provided by the satellite operator, as well as pending maneuvers. This approach is especially important for low-thrust maneuvers, like those used by Starlink and OneWeb, which can occur over extended periods of time.

Lastly, RMS values produced for matches of both CelesTrak SupGP data to 18 SDS (Space Track) GP data and the inverse, 18 SDS (Space Track) GP data to CelesTrak SupGP data. This raw data is compiled and provided as a summery highlighting “NO MATCH” satellites and cross-tagged satellites as this information is most critical for operators and identifying data problems. Fig 4 shows the large number of unsuccessful matches for the Starlink constellation between SupGP and GP data in the midst of a 4-day total outage of GP data updates on 2023 Jul 23.

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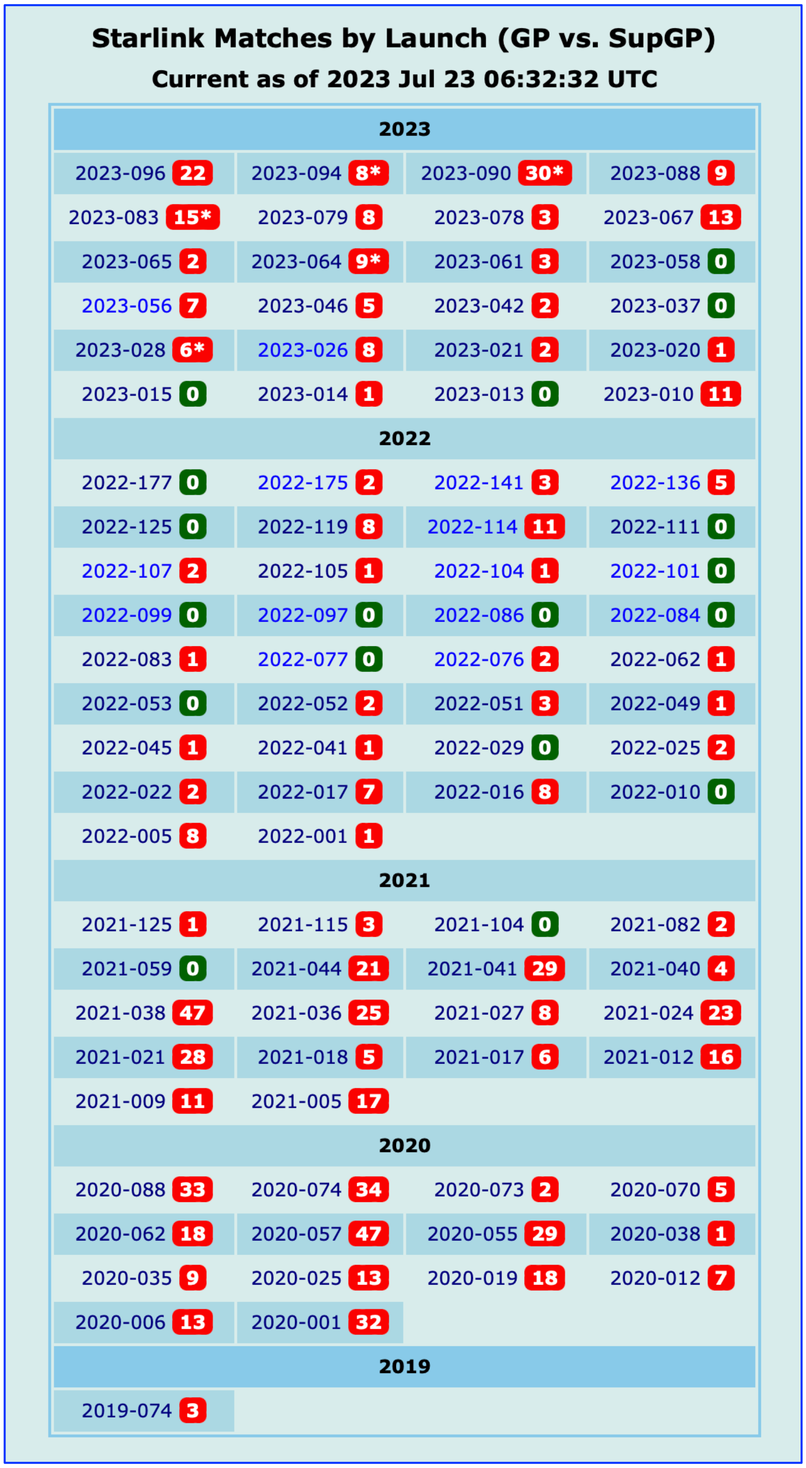

Starlink Matches by Launch (GP vs. SupGP)

Current as of 2023 Jul 23 06:32:32 UTC

2023			
2023-096 22	2023-094 8*	2023-090 30*	2023-088 9
2023-083 15*	2023-079 8	2023-078 3	2023-067 13
2023-065 2	2023-064 9*	2023-061 3	2023-058 0
2023-056 7	2023-046 5	2023-042 2	2023-037 0
2023-028 6*	2023-026 8	2023-021 2	2023-020 1
2023-015 0	2023-014 1	2023-013 0	2023-010 11
2022			
2022-177 0	2022-175 2	2022-141 3	2022-136 5
2022-125 0	2022-119 8	2022-114 11	2022-111 0
2022-107 2	2022-105 1	2022-104 1	2022-101 0
2022-099 0	2022-097 0	2022-086 0	2022-084 0
2022-083 1	2022-077 0	2022-076 2	2022-062 1
2022-053 0	2022-052 2	2022-051 3	2022-049 1
2022-045 1	2022-041 1	2022-029 0	2022-025 2
2022-022 2	2022-017 7	2022-016 8	2022-010 0
2022-005 8	2022-001 1		
2021			
2021-125 1	2021-115 3	2021-104 0	2021-082 2
2021-059 0	2021-044 21	2021-041 29	2021-040 4
2021-038 47	2021-036 25	2021-027 8	2021-024 23
2021-021 28	2021-018 5	2021-017 6	2021-012 16
2021-009 11	2021-005 17		
2020			
2020-088 33	2020-074 34	2020-073 2	2020-070 5
2020-062 18	2020-057 47	2020-055 29	2020-038 1
2020-035 9	2020-025 13	2020-019 18	2020-012 7
2020-006 13	2020-001 32		
2019			
2019-074 3			

Fig 4. CelesTrak SupGP data and Space Track GP data matching results for Starlink satellites

For an example of CelesTrak SupGP results and benefits in a GEO orbit, the December 2022 Galaxy 25 (G-25) maneuver is used. From 2022 Dec 5-12, G-25 maneuvered from its GEO orbit to a circularized GEO Graveyard orbit. CelesTrak SupGP data was able to provide precision position information all throughout the maneuver, to a level of detail where thruster fires can be observed. SupGP data provided continuous situational awareness to all space operators regarding the maneuver as shown in Fig 5.

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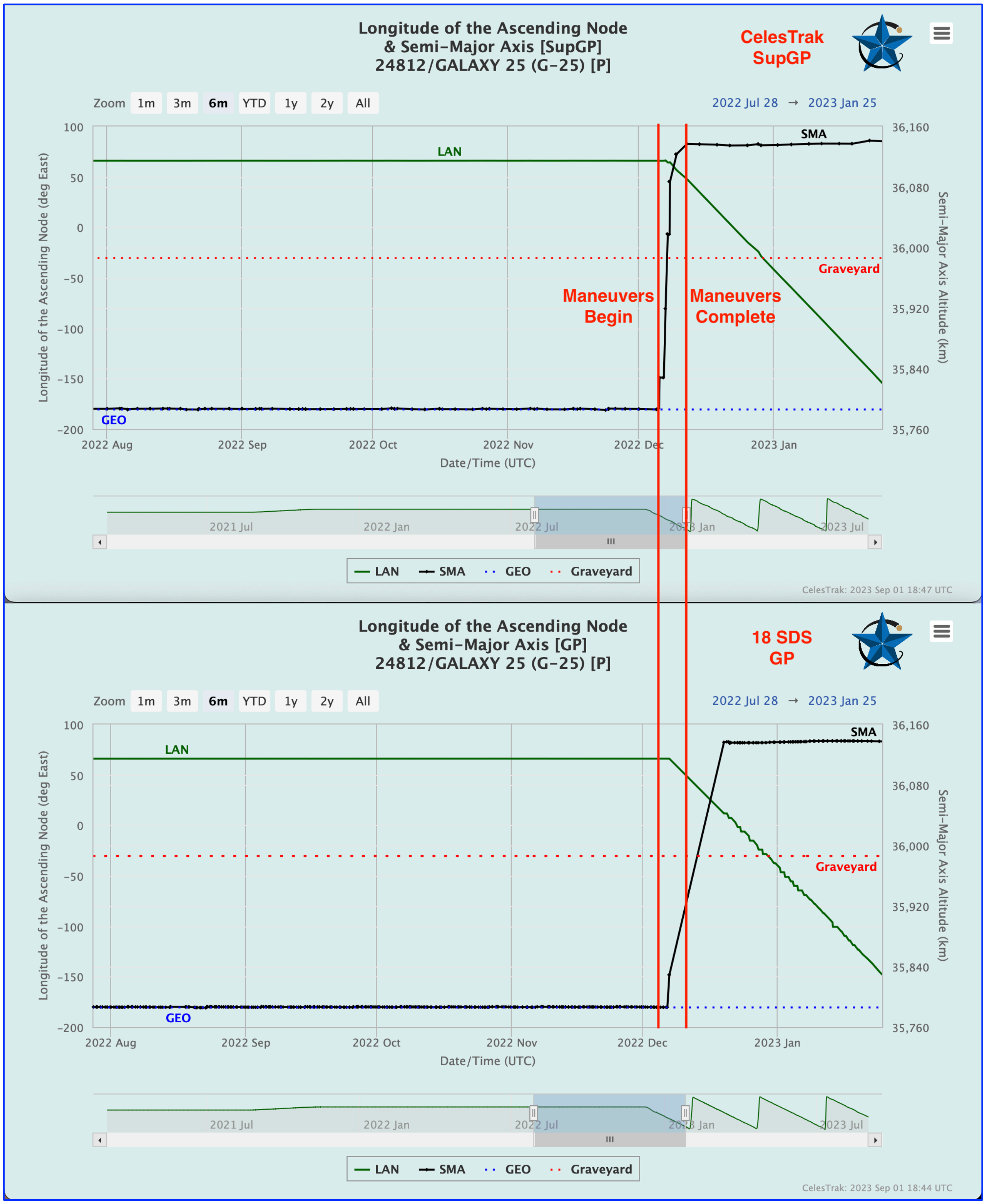

Fig 5. CelesTrak SupGP data of G-25 GEO graveyard maneuvers 2022 Dec 5-12 compared to 18 SDS GP.

By comparison, using the 18 SDS (Space Track) GP data alone, the G-25 maneuvers were not observable. It took until Dec 19 before a valid orbit was produced—14 days after the maneuvers began.

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4. OPERATIONAL IMPACTS

Utilizing SupGP data and/or augmenting traditional GP data with SupGP data increases Space Situation Awareness, improves Space Flight Safety, and identifies data discrepancies within the space community that need to be resolved. Fundamental Advantages of SupGP data include:

- ***Accuracy:*** Not only is the data available from satellite owner/operators more accurate than the uncooperative tracking data available from the SSN, but since the SupGPEs are produced with a known version of SGP4, the predictions using those SupGPEs with that same version will be more accurate.

- ***Timeliness/Latency:*** Satellite owner/operator orbital data is generated routinely as part of their normal operations and is not typically subject to the limitations of optical observing systems. This provide more reliable, timely, and consistent updates.

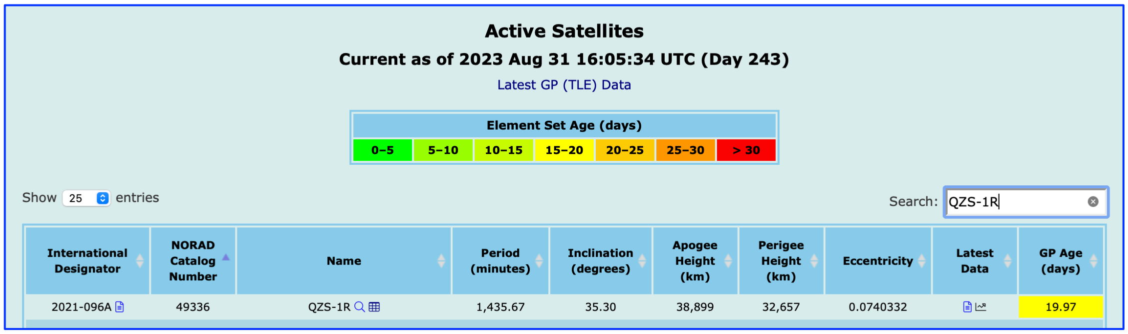
- ***Redundancy:*** Space Track GPE outages, corruption events, and data duplication events are known to occasionally occur. In instances where GP data is unavailable or seems to be producing anomalous results, SupGPEs are a backup source of orbital data that can be used for verification/validation, reconstitution, and operations.

- ***Ease of Use:*** Rather than each user having to implement a variety of orbital propagation models to meet their needs, users can continue to use the standard SGP4 orbital propagation model, which is already implemented in most orbital tracking software packages.

The above advantages easily translate into space operations needs and activities such as:

- Identifying and resolving cross-tagged satellites
- Post-deployment satellite location and identification for multi-satellite launches (e.g., Starlink)
- Maneuver detection
- Locating lost satellites
- Conjunction avoidance
- Improved conjunction false-alarm and missed-alarm rates

For a specific example of locating a lost satellite, a comparison between tradition GP data and SupGP data for QZS-1R is shown below. As seen in Fig 6, the GP data is obsolete at over 19 days old and the orbital information is inaccurate, resulting in a lost satellite.



Active Satellites

Current as of 2023 Aug 31 16:05:34 UTC (Day 243)

Latest GP (TLE) Data

Element Set Age (days)						
0–5	5–10	10–15	15–20	20–25	25–30	> 30

Show 25 entries

Search: QZS-1R

International Designator	NORAD Catalog Number	Name	Period (minutes)	Inclination (degrees)	Apogee Height (km)	Perigee Height (km)	Eccentricity	Latest Data	GP Age (days)
2021-096A	49336	QZS-1R	1,435.67	35.30	38,899	32,657	0.0740332		19.97

Fig 6. 18 SDS (Space Track) GP data for QZS-1R

However, SupGP data is available, provided by the QZSS network as part of the ILRS (International Laser Ranging Service). This data and the SupGP data is less than 3 days old and has an RMS solution just over 1 km as shown in Fig 7. Thus, this satellite can be recovered by using the latest SupGP data. Any lost or cross-tagged satellites for which SupGP data is produced are resolvable discrepancies.

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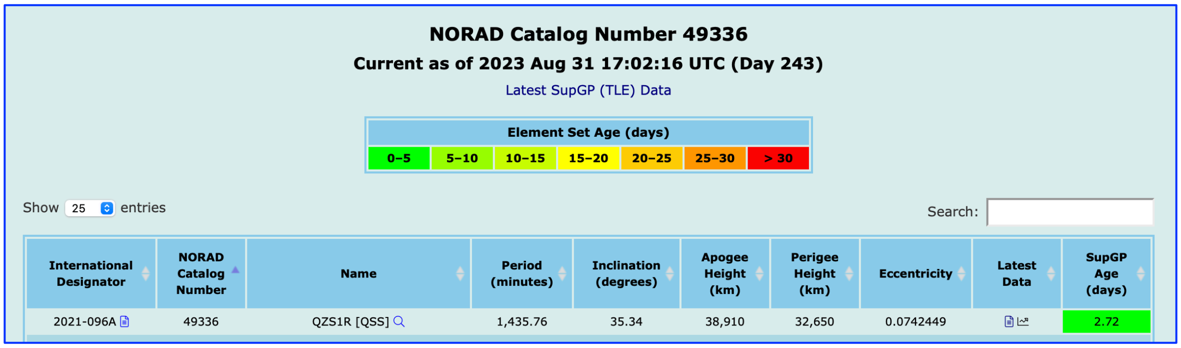

NORAD Catalog Number 49336

Current as of 2023 Aug 31 17:02:16 UTC (Day 243)

Latest SupGP (TLE) Data

Element Set Age (days)						
0–5	5–10	10–15	15–20	20–25	25–30	> 30

Show 25 entries

Search:

International Designator	NORAD Catalog Number	Name	Period (minutes)	Inclination (degrees)	Apogee Height (km)	Perigee Height (km)	Eccentricity	Latest Data	SupGP Age (days)
2021-096A	49336	QZS1R [QSS]	1,435.76	35.34	38,910	32,650	0.0742449		2.72

Fig 7. SupGP data for QZS-1R produced from the ILRS (International Laser Ranging Service)

5. CONCLUSION

SupGP data is an additional data source that provides significant enhancement to SSA and augments traditional GP techniques. Implementation of SupGP improves all aspects of space operations, space flight safety, SSA, responsible use of space, and preservation of the earth orbital environment. SupGP techniques were developed and implemented as a result of global need due to the significant change in space operations within the modern space operation environment. Traditional observation capabilities and GP data processes were not designed with the modern space operation environment in mind. Thus, data problems have emerged related to increased data volume, launch rates, mega-constellations, low-thrust maneuvers, and close proximity operations. SupGP data provides solutions to many current SSA data and catalog maintenance problems and significantly augments other data sources for the benefit of all.

As of 2023 Aug 31, CelesTrak now provides SupGP for over 5,900 of the 8,500 active satellites (with GP data) currently in Earth orbit. This constitutes 69% of all active satellites with GP data (i.e., does not include national security satellites for which no data is available). CelesTrak SupGP data is only possible because satellite operators like SpaceX, OneWeb, Planet, Iridium, Intelsat, NASA/JSC (ISS), GPS, GLONASS, and ILRS share data to increase transparency and improve overall safety of flight. CelesTrak remains committed and prepared to work with any satellite operator to use their independent orbital data for the same.

6. REFERENCES

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