SCN Ranging Reduction Study

Leon L. Lala Jr.
The Aerospace Corporation, Schriever SFB, Colorado, 80912

1st Lt. Marshall Thompson
United States Air Force, Schriever SFB, Colorado, 80912

1st Lt. Alexander Knoedler
United States Space Force, Schriever SFB, Colorado, 80912

Nate Crawford
Boeing Corporation, Schriever SFB, Colorado, 80912

Todd Brost
Numerica Corporation, Colorado Springs CO, 80919

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Abstract

The Aerospace Corporation and the 4th Space Operations Squadron (4 SOPS), Schriever Space Force Base (SFB), CO are analyzing the feasibility of utilizing commercial satellite state vectors for Wideband Global SATCOM (WGS) orbit determinations, orbit planning, and constellation management. Aerospace identified a capability within existing orbit analysis software that allows commercial orbital state vectors to be ingested, enabling operators to bypass traditional active track data collection using the Satellite Control Network (SCN). Working with Numerica, 4SOPS can now access WGS constellation state vectors collected from a commercial worldwide telescope network of visible staring arrays fixed at the equatorial plane. Access to the Numerica state vectors within the Unified Data Library (UDL) provides orbit analysts with the data necessary to accurately calculate orbital solutions. Analysis has shown that Numerica's optical array collection and algorithm processing solutions are generally within 400 meters of SCN orbit determinations. This solution set fits within the traditional WGS orbit accuracy covariances for orbital solution and maintenance. This paper outlines the accuracy of the orbital state vectors compared to SCN-generated state vectors, explains the process for accomplishing orbit planning with these commercially-provided vectors, and highlights the final orbital solutions of the commercial state vectors for use in orbit management. This new approach provides a more resilient process for spacecraft tracking while significantly reducing the operator workload for satellite orbit management.

4 SOPS MILSATCOM Overview

The 4 SOPS MILSATCOM constellations include Protected (Milstar/Advanced EHF/Hosted Enhanced Polar) and Wideband (Wideband Global SATCOM/Defense Satellite Communications System) constellations. 4 SOPS conducts daily command and control of 27 spacecraft supporting users in multiple areas of responsibility.

Specific to this study, the WGS constellation is capable of conducting tracking, command and control activities using Unified S-band (USB), Space-Ground Link System (SGLS) S-band, X-band, and Ka-band frequencies. The WGS satellite dual-banded transponder allows for switchable configurations between SGLS S-band and Unified S-band operations. The constellation is deployed world-wide, providing communications services to Department of Defense users in X-band and Ka-band frequencies.

4 SOPS Operations

Nominally, 4 SOPS conducts four SCN ranging contacts per day on every satellite to achieve a good estimate of the satellite location over a 24-hour period. In addition to ranging-only contacts, a number of satellite activities occur daily requiring the SCN, supporting housekeeping, maintenance and contingency operations. While WGS, Milstar, and AEHF leverage an in-band command and control system that is used for a majority of commanding requirements, significant use of the SCN is still required to support MILSATCOM daily operations. The SCN Reduction Study collected statistics on SCN use by all four 4 SOPS constellations during calendar year 2020. Table 1 shows the 4 SOPS SCN use outlined in the SCN Reduction Study.

Table 1: 4 SOPS SCN Usage (CY20xx).

Site	Number of Supports	Duration of Support (hr:min)
1	2	1:14
2	16	5:15
3	419	553:53
4	425	458:24
5	205	323:06

6	165	478:01

This extensive use of SCN resources has initiated efforts to examine alternate ranging solutions to reduce the overall usage of SCN resources for MILSATCOM tracking operations. By examining methods to collect state vectors through alternate ranging capabilities, 4 SOPS can effectively reduce SCN usage, allowing the network to be used for higher priority activities. These alternate tracking methods enhance resiliency for the constellations by providing alternative approaches to achieve mission requirements.

SCN Reduction and Usage

In 2020, the United States Space Force issued a memo directing operational units to reduce the SCN usage: *"AFSCN is oversubscribed and the overall utilization needs to be decreased to be able to support surge operations, maintenance, and upcoming satellite launches. In addition, due to increasing AFSCN load there is a potential that current users will not be able to fulfill mission requirements through AFSCN."*

The 4 SOPS SCN Reduction objective is to use no more than 37.07% of total time available per SCN site. In-band command and control capabilities assist with the offset of SCN usage; however, additional reductions are required to meet this objective while still ensuring mission success and resiliency. The following capabilities are being used by programs within Delta 8 and should be considered for 4 SOPS operations.

Numerica Overview

Numerica is a small commercial Space Domain Awareness (SDA) and tracking Research and Development company of ~75 employees based in Fort Collins, Colorado. Numerica's capability in SDA includes a worldwide telescope network to identify space-borne hazards and threats to government and commercial satellites. Numerica offers real-time data products for decision support, fusing third-party optical, radar, passive-RF measurements, and tracking of objects in geosynchronous orbit during daylight using small telescopes. Numerica currently supports government programs that include the Missile

Defense Agency and SDA data contracts with the National Space Defense Center and UK Space Agency. Numerica's telescope network includes visible staring arrays fixed at the equatorial plane, as well as taskable telescopes that can track inclined GEO objects and objects in LEO, HEO, MEO and GEO. The

Numerica Telescope Network includes a telescope network spanning 20 locations worldwide (14 OCONUS) and growing. The taskable systems include 20-inch Short-Wave Infrared (SWIR) day/night sensors, and 14-inch, and 11-inch aperture visible remote robotic telescopes with geographic diversity providing 100% coverage of the Geosynchronous orbit belt. Numerica has taken high end commercial components and has worked with manufacturers to custom-build them to optimize SDA performance. The hardware is then coupled with Numerica-developed Tasking, Collection, Processing, Exploitation, and Dissemination (TCPED) software to deliver accuracy of less than 1 arcsecond (RMS) for visible systems and less than 10 arcseconds (RMS) for SWIR systems. The TCPED software tasks the network, controls the sensors, and does sensor calibration, outlier removal, data association, and orbit generation.

Numerica Telescope Network data and information products are used operationally by multiple government and non-government organizations, and data is available via the Unified Data Library or custom API download. The data can include observations, state vectors, or Two-Line Element Set (TLEs) photometric change alerts, maneuver alerts, and conjunction notifications.

Unified Data Library Overview

The UDL is an enterprise data repository used for managing access, integration, and dissemination of data across disparate organizations and multiple levels of security. Many applications often require the analysis of large amounts of data, and the UDL is a helpful tool to simplify the process of collecting filtered data from a one-stop source in a timely manner. There are multiple, user-friendly APIs to choose from when performing data queries. The UDL is particularly significant for this project because Numerica already uses the UDL to upload data, providing barrier-free access to relevant state estimation data. With the USSF vision of an all-digital service, the use of the UDL for this highly technical project ensures its personnel are leveraging an asset to stay ahead in the competitive space domain.

Numerica granted 4 SOPS personnel access to their state vectors and sensor/observation data produced from coordinated collections on WGS vehicles. 4 SOPS used the Bulk Data Request API to query state vector and observation data based off time and satellite catalog number. The output of the query was filtered by x, y, and z position and velocity values for the state vector of the satellite in the ECI frame. Each query also includes sensor latitude, longitude, altitude, azimuth, elevation, and declination for the observation data. Boeing and 4 SOPS used their station-keeping planning software, Orbit Analysis System (OASYS), to run comparisons between Numerica's state estimates and 4 SOPS's native SCN ranging estimations.

Orbit Analyst Software

The software used for nominal WGS orbit analysis and maintenance is a commercial-of-the-shelf application called OASYS. OASYS is the high-precision orbit analysis system component of the EPOCH IPS software suite developed and managed by Kratos Defense & Security Solutions, Incorporated. This software is used by many different spacecraft operators for fleet management to include Intelsat, JSAT, Telesat, EchoStar, as well as various other NOAA and DoD assets.

OASYS can provide full spacecraft lifecycle support for spacecraft orbit and attitude determination and control. Spacecraft analysts and engineers can manage a single spacecraft or fleet in any earth orbit to include low earth, geosynchronous, and Molniya orbits. OASYS Version 10.1 added support for Boeing 702 spacecraft, to include models with Xenon Ion Propulsion (XIPS). The United States Air Force began orbit management of all WGS spacecraft in 2012 using OASYS Version 10.3.

4 SOPS Orbit Analyst Software Processing

The WGS constellation routinely performs orbit determinations (ODs) through the duration of a standard 14 day station-keeping cycle. Orbit analysts collect track data using the SCN over several days to perform normal satellite orbit determination. Each SCN track support collects ranging data over the course of several minutes through active ranging techniques. Prior to calculating the final orbit determination, orbit analysts reconstruct past maneuver activities to account for all orbital perturbations. This maneuver reconstruction converts raw maneuver telemetry and thruster performance metrics to accurately characterize nominal station-keeping maneuver performance. Once this conversion occurs, the data is incorporated into the OASYS software and applied to the data span used to determine the current spacecraft orbit.

The OASYS Orbit Determination Service provides an orbital estimate which best fits a set of input observations. This service can use most standard tracking data observation types including phase meter, range, turn around range, range rate, azimuth, and elevation. The WGS constellation specifically uses range, azimuth, and elevation samples acquired through routine tracking supports on SCN antennas. The raw observation is processed through a sigma filter, residual filter with a minimum value of -5 km and maximum value of 5 km, and finally a compression filter with an interval set at 50 seconds and maximum sample gap of 30 seconds. Once filtered, the available observations are passed to a statistical estimation algorithm based on a least sum of squared residuals fit to the observation set, using singular value decomposition. The epoch for these solves is nominally set at the end of a sequence of maneuver days and prior to upcoming burn days. During calculation, the algorithm completes multiple secant iterations to be taken between tangent iterations. The tangent iteration updates the tangent map of the first variation; the partials of the observations for the OD states are computed numerically. A secant iteration computes the parameter correction using the last tangent map computed. This secant method is guaranteed to converge to the same root as the full tangent method and is computationally more efficient.

Once the orbit determination is complete, various statistics are validated to ensure acceptability. An orbit determination with a final Weighted Root Means Square (WRMS) value of less than 5 and greater than 1, and a standard deviation for range less than 30 meters is considered acceptable for WGS operations.

Alternate Methods with Current Software

The only method of performing an orbit determination in OASYS is to use a nonlinear batch least squares based on singular value decomposition to minimize a chi-squared sum of squared weighted residuals performance index. Currently, the operational version of OASYS does not offer other differential correction techniques such as a Kalman filtering. Although the differential correction methodology is static based on operationally approved software, there are various filters and an ability to adjust fit spans of data to refine OD processing. Additionally, OASYS does have the ability to add new sensor and/or antenna sites; however, this requires additional software updates from the vendor.

An orbit determination is not required to provide a starting state or vector for a specific spacecraft in OASYS, an external state can be either manually input or ingested from an ASCII ephemeris file. When conducting close approach analysis, orbit analysts often manually input Earth Centered Fixed or Earth Centered Inertial position and velocity vectors provided by an external source. This state vector is then propagated using the Bulirsch-Stoer Cowell propagator available in the Ephemeris Services menu in OASYS. There are additional types of propagators available in OASYS; however, the Bulirsch-Stoer Cowell uses rational function extrapolation and the modified mid-point method which is adaptive in step size and step order, making it the preferred propagator in OASYS. While this method is excellent for generating spans of ephemeris for dead or non-maneuvering objects, there are two significant issues associated with manually inputting vectors for WGS including errors caused by manual data entry, and propagation of the state through the standard station-keeping maneuvers of WGS spacecraft. Any minor error quickly grows during propagation. Most significantly these errors are observed in the nadir axis, resulting in an untrue east or west drift. These errors are mainly driven by the anti-nadir placement of WGS thrusters that provides the majority of delta-V in the positive nadir direction.

OASYS is capable of ingesting a single or multiple vector ephemeris ASCII data format files. This data file method reduces the risk of manual input caused by operators. Unfortunately, this method does require the user to manually verify and update the desired orbital element set and equinox prior to ingesting and processing the ASCII file.

Evaluation of Numerica State Vector Compared to SCN Track Orbit Determination

The initial evaluation of Numerica-provided vectors compared to internally generated vectors consisted of a basic sum of squares analysis on the differences of both positional and velocity components. Data was provided in the Earth-Centered Inertial reference frame with an equinox of MEME of Epoch, J2000. This data was then compared to OASYS orbit determination vectors in Microsoft Excel. Overall, the comparison revealed a total difference in vector magnitude ranging from 2.7 kilometers maximum to 120 meters minimum depending on spacecraft and epoch. The overall total difference average for all vectors was approximately 995 meters. The largest average difference was observed in the Z-axis at a value of 956 meters, while the X-axis resulted in the best average distance at approximately 97 meters.

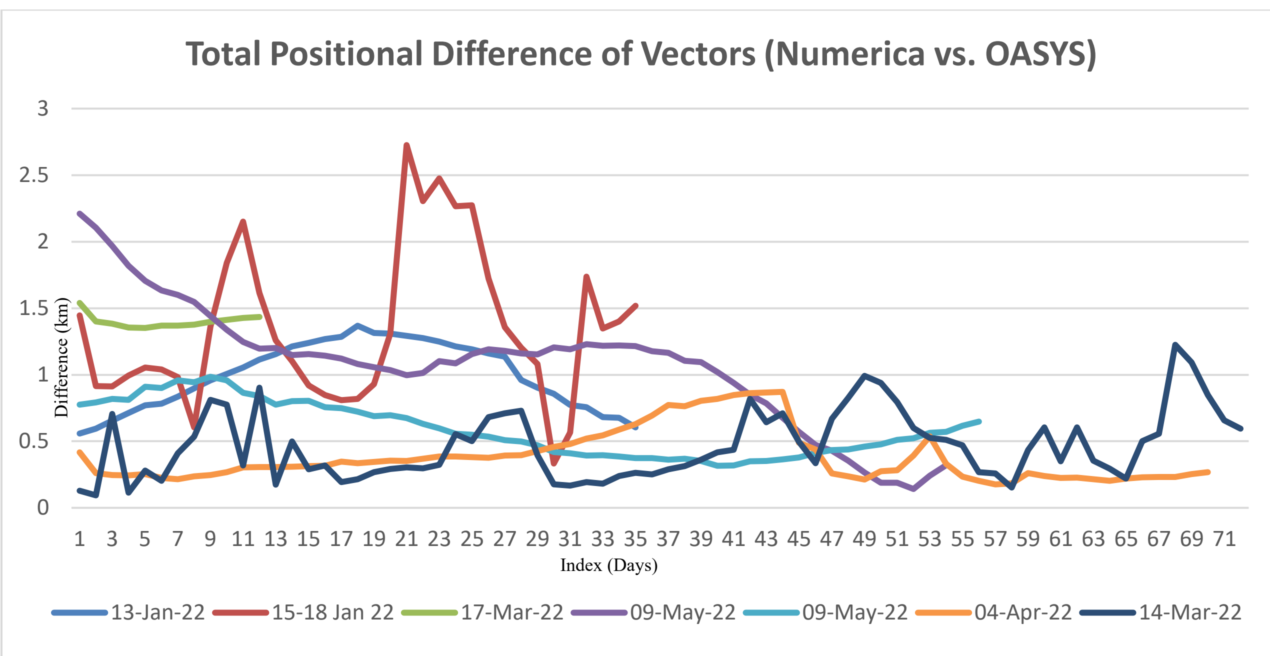

Figure 1: Total positional difference between OASYS and Numerica vectors (km)

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After comparing the total difference of position and velocity vectors, specific vectors were selected for propagation in OASYS based on accuracy and timing. The timing selection criteria is based on knowledge of the four maneuvers required by the spacecraft each day, and a time was selected after all burns for a specific day had occurred. The Numerica-provided vector chosen for use was manually inputted to OASYS and propagated with the predicted thrust considered during the ephemeris propagation. The overall vector was close in position to the OASYS starting state. Propagation of the orbit showed a consistent change pushing the spacecraft significantly east in longitude. This offset is likely a result of small errors in radial position and zenith facing thruster. The results of this propagation are shown in Figure 3.

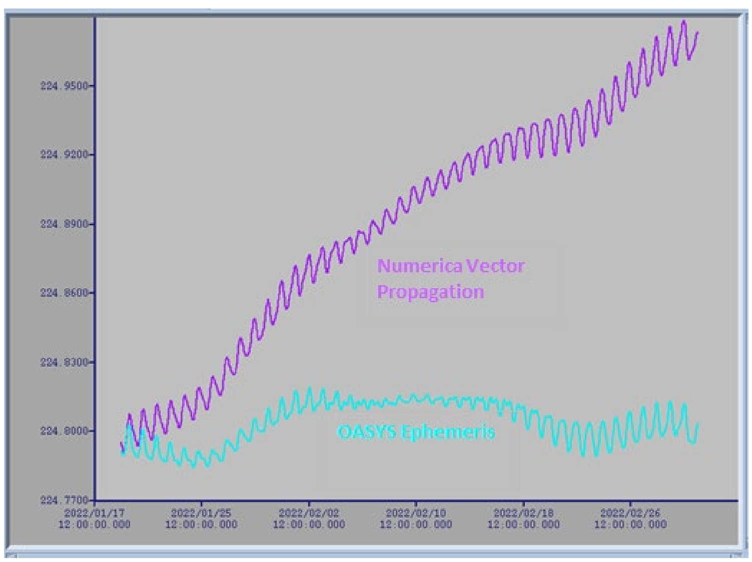

Figure 2: Numerica vector propagation compared to OASYS ephemeris in Longitude East.

The minor errors seen in radial position and thruster placement contribute to an inaccurate drift rate that is consistently higher (positive east) compared to actual drift calculated in OASYS. Once the orbit was propagated with the predicted maneuvers expected to occur over the next 40 days, a clear disparity between the OASYS orbit predict and the Numerica based propagation was observed. An additional test was performed to determine the feasibility of using a Numerica vector for station-keeping planning. This new method of orbit prediction showed the spacecraft maintaining on-orbit requirements within 0.1 deg of the target longitude. When the same thrust prediction was used to generate ephemeris using an OASYS starting vector, the OASYS prediction resulted in a significant West deviation as seen in Figure 4.

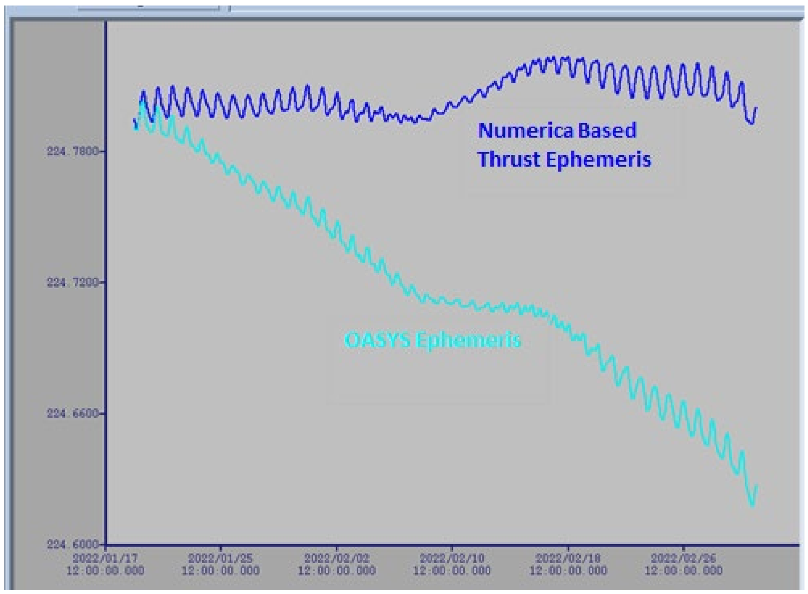

Figure 3: Numerica thrust prediction compared to OASYS ephemeris with Numerica thrust in Longitude

All propagation methods and tests based on a single Numerica vector resulted in the same deviation and significant easterly drift. A new method using a Numerica vector was propagated in OASYS and used as a reference ephemeris to perform an orbit determination to counteract this easterly drift error. Typically, WGS operations require around 20 track collection events spanning several days. This collection period is used as the reference ephemeris to solve an orbit determination in OASYS. Two different methods were used to determine feasibility of using Numerica-generated vectors as reference ephemeris. The first methodology used a 24-hour period of ephemeris data generated from a Numerica-provided state. This ephemeris was then used as a reference to perform an orbit determination using only four SCN tracking supports. The second method used a 14-day ephemeris span generated from a Numerica-provided state. This method was then used as a reference ephemeris for an orbit determination using only a single SCN support for every day of the ephemeris span (14 SCN track supports total, 1 per 24-hour period).

The single-day orbit determination was performed using both an OASYS vector and a Numerica vector. This change in orbit determination processing could theoretically reduce SCN requirements by approximately 90%. The orbit determination using this method resulted in a close longitude at the solve epoch. Unfortunately, internal propagation disparities within the OASYS software and a continued error in drift rate and semi-major axis resulted in an orbital state that could not support WGS station-keeping planning.

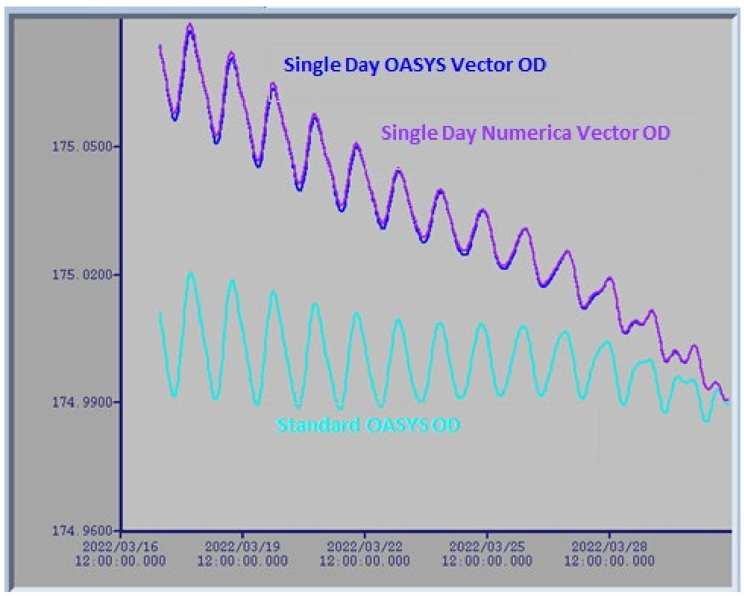

Figure 4: Longitude East after single day span orbit determination using Numerica vector.

The standard orbit determination process was modified by increasing the span of the orbit determination to 14 days while at the same time reducing SCN tracks to only one track per orbit. This approach resulted in reducing SCN track supports by up to 75% over current processes. By using a Numerica vector as a reference state for the OASYS orbit determination, analysis showed nearly identical orbit accuracy to the OASYS-based orbit determination techniques. These results showed equally acceptable performance using an OASYS-based state and performing an orbit determination across the 14 days span with only one SCN track per day. It is equally important to understand that limiting SCN data could result in less accurate orbit determinations over time as any inaccurate SCN samples would be weighted more in the OD calculation. This specific scenario resulted in a solved orbit state useful for generating a new WGS station-keeping plan.

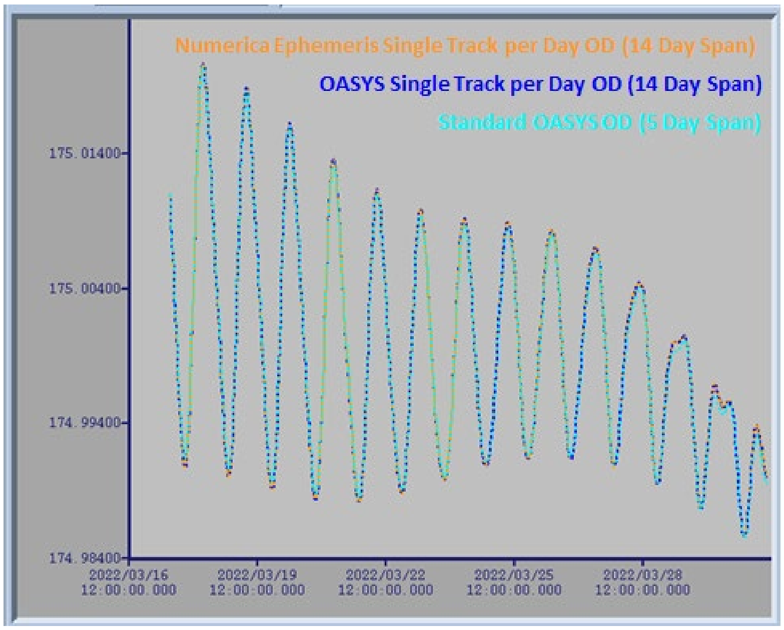

Figure 5: Longitude East after 14-day span orbit determination using Numerica vector

All orbital components of this study fell into acceptable limits. Mean geodetic longitudinal drift is an important component when propagating a state with WGS-predicted maneuvers or when using the state to plan future station-keeping maneuvers. Along with positional accuracy, the drift rate was overlapping on all three studies in this process as shown in Figure 7 below. A nominal WGS MGL Drift value is usually –0.0007 degE/day for standard station-keeping.

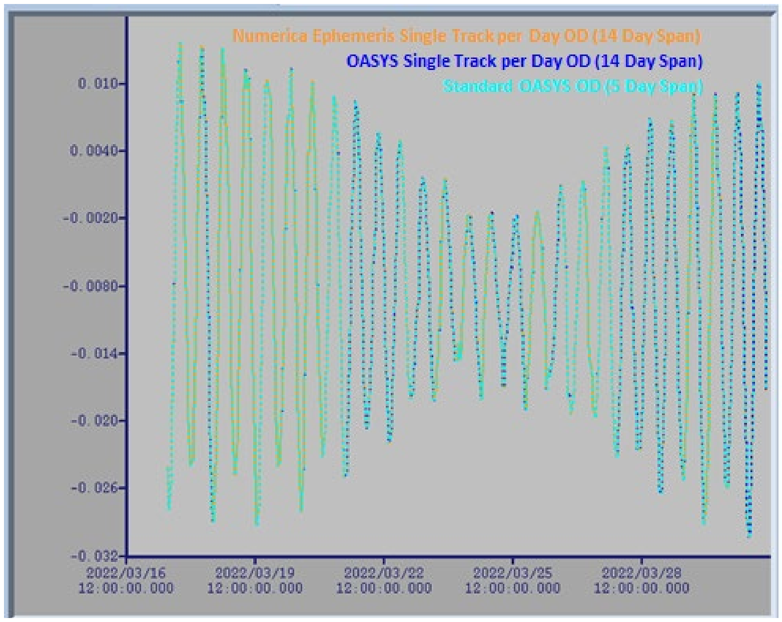

Figure 6: MGL Drift rate for Numerica-based and OASYS based orbit determinations

After completing the 14-day orbit determination with Numerica-based reference ephemeris, predicted maneuvers were added to the ephemeris and propagated. Both the single day and 14-day Numerica OD ephemeris with predicted maneuvers were compared to OASYS operational ephemeris. The single day orbit determination propagation showed significant western deviation out of station-keeping requirements during the 14-day period. The Numerica-based 14-day OD resulted in a very close prediction when compared to the operational ephemeris and would be operationally acceptable in all orbital parameters.

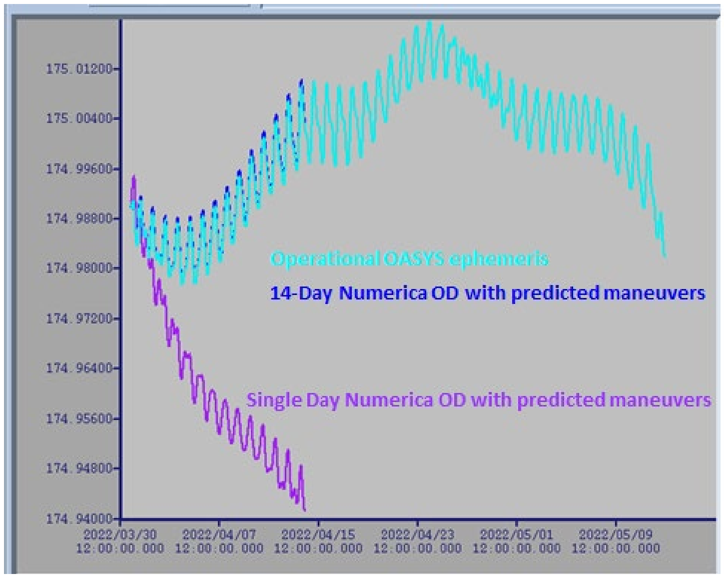

Figure 7: Longitude East OASYS operational ephemeris, Numerica 14-Day and 1-Day OD propagation

A similar study was performed on a different spacecraft with stereo observations. As stated earlier, reducing SCN observations can induce risk into the performance and accuracy of an orbit determination in OASYS. The OD performed in this scenario only used 7 days of ephemeris for the OD span. The statistical analysis of operational values used to determine the quality of orbit determinations fell outside of operationally acceptable limits. However, the positional results of the orbit determination were accurate as seen in Figure 9.

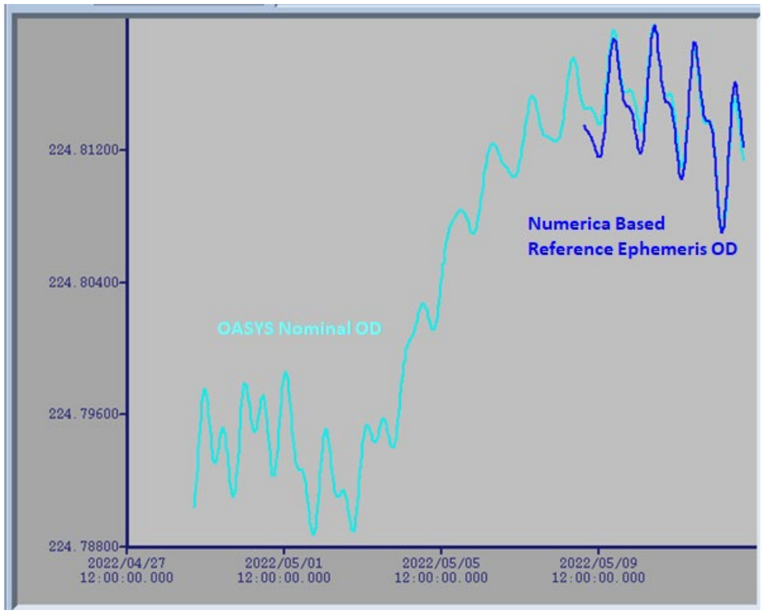

Figure 8: Longitude East OASYS OD, Numerica reference ephemeris with one SCN track per day OD.

During the period of this study, a WGS spacecraft was relocated to a different operational longitude. Standard WGS relocation operations include periods of drifting below or above the geosynchronous altitude for a set duration. Numerica observations were collected and processed during one of these drift periods where nominal station-keeping maneuvers did not occur. These observations were collected in stereo with multiple sensors collecting at the same time. The best vector showed a difference from the OASYS state of 176 meters. The highest difference between the OASYS vector and the Numerica vector was only 871 meters. The vector with the lowest deviation from the internal vector was then propagated using the nominal operational methods. The result of this propagation was identical to propagated orbits internal to OASYS.

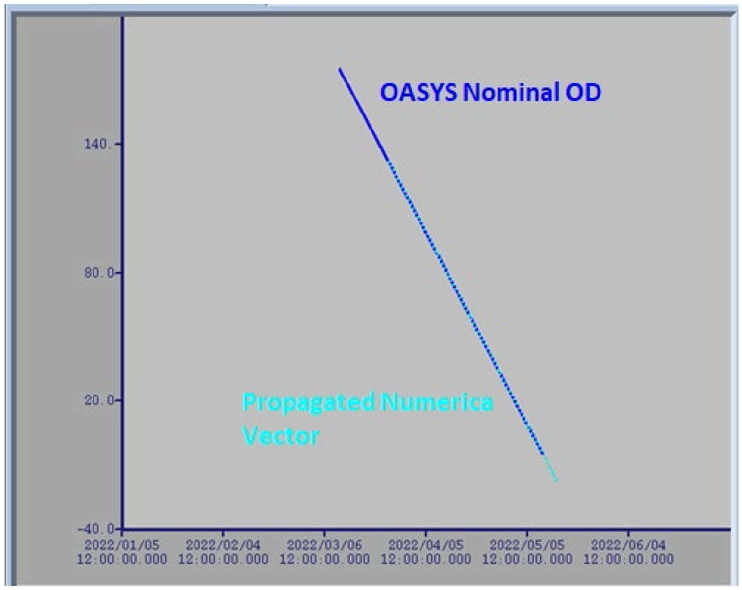

Figure 9: Longitude East OASYS OD, Numerica-propagated vector during drift

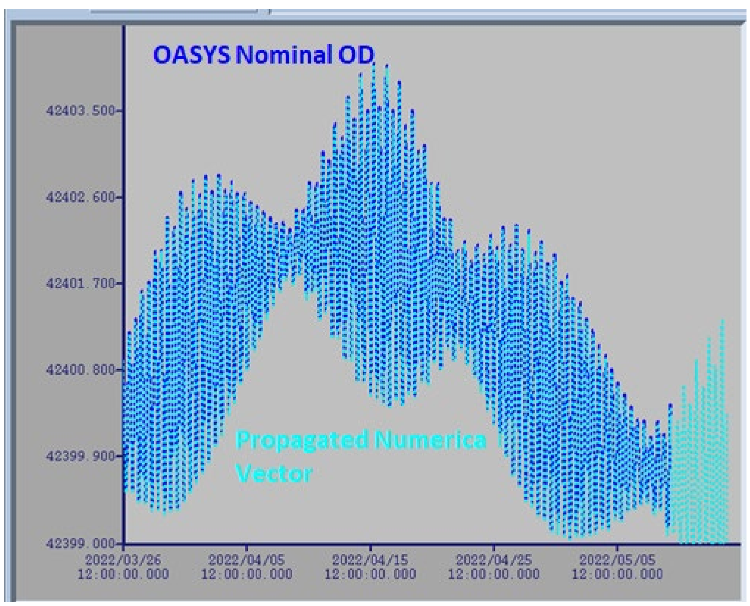

Figure 10: Semi-Major Axis (km) OASYS OD, Numerica-propagated vector during drift.

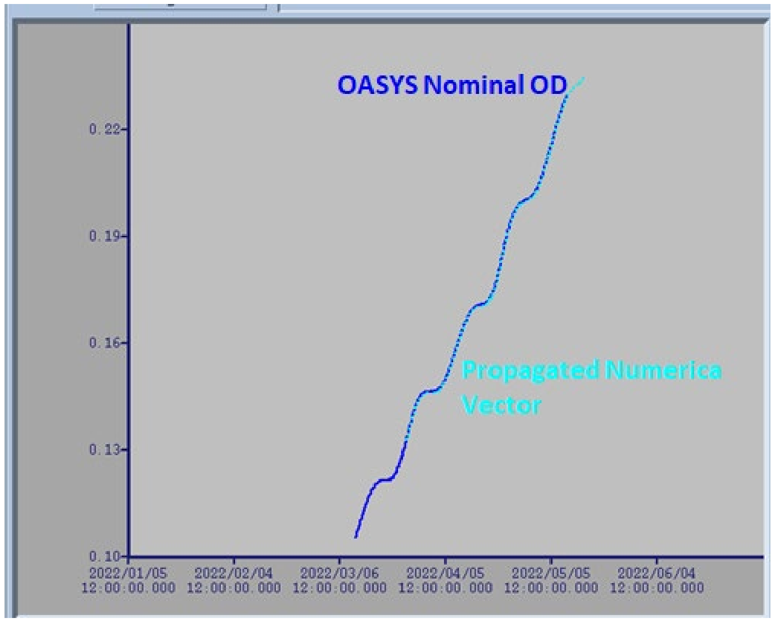

Figure 11: Inclination (deg) OASYS OD, Numerica-propagated vector during drift.

After initial comparison with the propagated vectors during drift, the upcoming maneuvers that reduced drift rate from 3 deg/day to 0.3 deg per day were added to the orbit and propagated. The results of propagation post-drift with maneuvers resulted in identical orbit states.

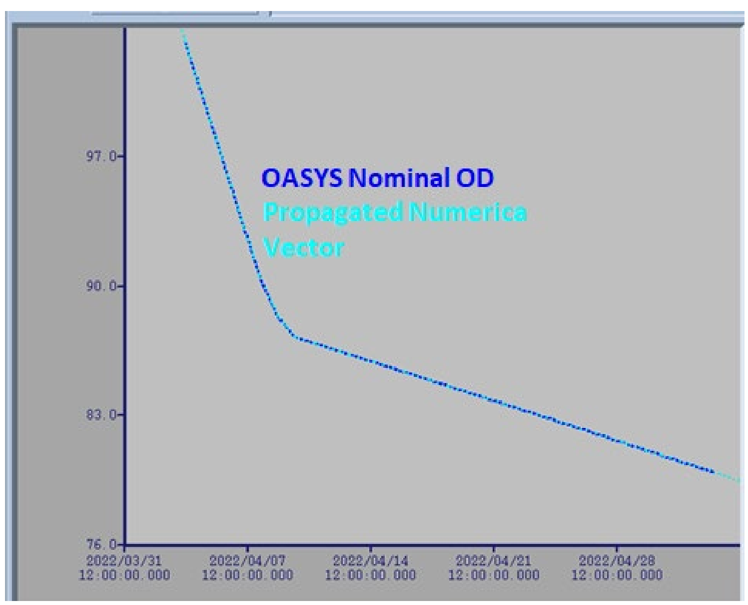

Figure 12: Longitude East OASYS OD, Numerica-propagated vector with relocation maneuvers.

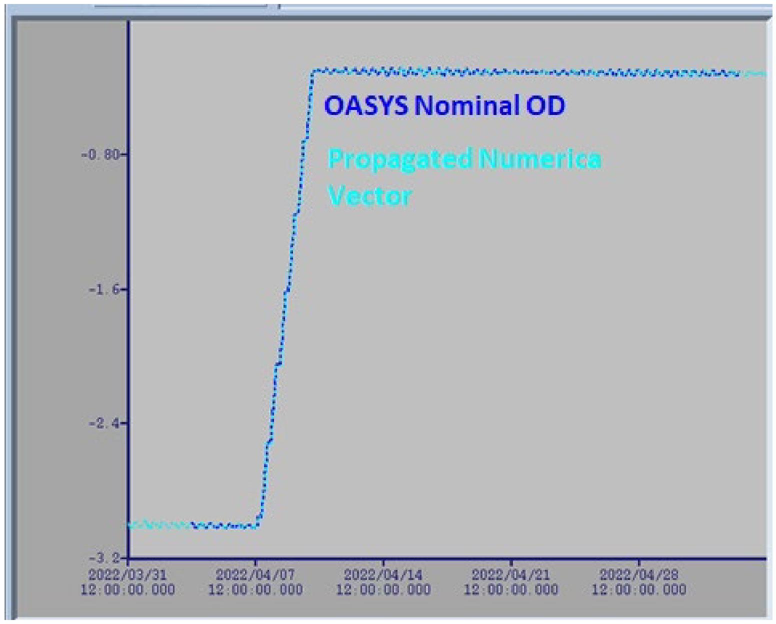

Figure 13: Drift Rate (DegE/day) OASYS OD, Numerica-propagated vector with relocation maneuvers.

The results of the active station keeping studies performed showed significant error directly correlated to WGS maneuver operations, position of the thrusters on WGS spacecraft (zenith face), and the resulting higher semi-major axis which can cause inaccurate drift propagation and predictions. The studies performed on a drifting WGS proved that outside of the station-keeping issues, it is feasible to use an orbit state provided by an external source to propagate and acquire the spacecraft orbit in current software.

A hybrid methodology of using interpolated external vectors converted into an ASCII file could be ingested into OASYS and used as a reference ephemeris with limited SCN tracks to converge on an acceptable orbit. This methodology is not currently part of operational procedures and further analysis and testing would be recommended to ensure feasibility. Numerica data also consists of the azimuth and elevation values of the collection sensor. This data could be extracted and used as supplemental data in the current orbit determination process; however, it would require the addition of Numerica sensor information to the current OASYS antenna database for testing.

This paper shows there is potential for 4 SOPS to use commercial, optical observations to create viable orbital states for station-keeping operations. Successful integration of optical state estimation into operational use requires adjustments to station-keeping burn plans, software baselines, networking hardware, mission planning, and training. A commercial, optical state estimation concept of operation may be considered along with other alternatives such as in-band ranging, S-/L-band ranging at in-band commercial control sites, or upgrades to the SCN to improve satellite tracking capabilities.

Successful integration of commercial, optical state estimates for WGS requires work on a several fronts. Optical collection times must be coordinated with satellite maneuver schedules to ensure that the final error in the commercial state vector would be accurate to support plan future maneuvers. Collections must be frequent enough to maintain a tight mission boundary (+/- 0.05 deg E-W and N-S) and to create new, low-error states for collision avoidance (COLA). 4 SOPS could include a diurnal period without burns at the beginning and end of the burn planning periods (approximately every 2 weeks) to perform more accurate state vector collections. If state estimate accuracy diverges from mission requirements, maneuver planning periods could be shortened. The trades between current estimation and planning and the integration of optical collections may require adjustment to space-vehicle software to meet DoD-level weapon system autonomy requirements.

Data flow from the UDL to the Command and Control System-Consolidated (CCS-C) ground system and orbit determination/planning software (like OASYS) should be improved to allow simple data transfer among multiple systems. Upgrades to the OASYS software will allow streamlining of planning activities, track collection and maneuver events.

Summary

The Numerica state vector study has demonstrated that non-maneuvering spacecraft can reduce SCN tracking requirements through the use of optical telescope data. While ion-propulsion spacecraft that maneuver multiple times a day result in optical radial uncertainties, there are 75% and 90% SCN usage reductions that can be gained through changes to satellite operation processes. The techniques outlined in this paper are applicable to other spacecraft currently using the SCN for track data collection.

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