The TraCSS Consolidated Pathfinder: Leveraging Commercial Capability in LEO

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Abstract

The advent of commercial space situational awareness (SSA) data and services represents an exciting development in space traffic coordination. The proliferation of accurate, globally-proliferated space tracking radars and optical wide field-of-view searching sensors, both optimized for the low Earth orbit (LEO) regime, promises a wealth of additional SSA data. Similarly, the availability of enterprise-level orbit determination (OD) solutions, that can manage the maintenance of an entire space catalog and its attendant functions (e.g., maneuver detection and recovery), and the combination of existing LEO capabilities, provide the opportunity to explore the potential for the maintenance of commercial satellite catalog. Because improved orbital safety is a broad mandate, and furthermore the public-private partnership envisioned by SPD-3 is new paradigm for the space safety community, a number of different pathfinder efforts—-completed, in process, and planned-—have been selected in order to determine the desirable parameters of the public-private partnership; buy down technical risk; and understand contractual, legal, and cooperation challenges to this method of obtaining SSA data and services.

As the Office of Space Commerce advances the Traffic Coordination System for Space (TraCSS), it is mindful of the direction to leverage commercial data and services. The TraCSS capabilities in Phase 1 will include the purchase of commercial products to improve the solutions for conjunctions. To explore how the Office will procure, measure, integrate, and budget for the desired commercial SSA data and services, a short-term pathfinder activity with industry has been undertaken. The "Consolidated Pathfinder", announced earlier this year in January, exercised many of the capabilities planned for TraCSS, including obtaining additional data on secondary objects of conjunctions of interest, an orbit determination of those objects, data quality and integrity monitoring of the process, and insertion of the updated data into the conjunction screening process. In addition, the Consolidated Pathfinder provided an opportunity to explore the ability of the commercial sector to maintain a catalog focused on the LEO regime using commercial resources alone.

Three industrial providers were selected: LeoLabs, which provided LEO radar tracking; Slingshot Aerospace, which provided LEO optical search and tracking; and the COMSPOC Corporation, which provided enterprise catalog maintenance. Two data quality monitoring vendors, SpaceNav and Kayhan Space, were also selected to evaluate the data and products. A two-month preparation period ran from February 1 to March 31 2024. The pathfinder live data collection took place from April 1 to June 30 2024, and a post-pathfinder analytical period is still ongoing, but mainly completed in August 2024.

The paper will both describe the pathfinder activity and report on the interim results of the principal objectives, related to establishing metrics, understanding price and acquisition methodology, and the secondary objective of catalog maintenance.

1. INTRODUCTION AND BACKGROUND

In 2018, emerging national security space threats and the rise in commercial space traffic prompted the National Space Council to develop a national policy to transition space traffic coordination (STC) responsibility from the Department of Defense (DOD) to a civil agency lead. Space Policy Directive 3 (SPD-3) [7], among other things, directed the Department of Commerce (DOC) as that civil agency lead, and DOC delegated this responsibility to the Office of Space Commerce (OSC). Since that time, OSC has been working to develop the systems, processes, and relationships with industry to implement SPD-3 guidance.

The specific SPD-3 goals to develop an open architecture data repository and establish an on-orbit collision avoidance service are being addressed by developing a Traffic Coordination System for Space (TraCSS). TraCSS is a modern, cloud-based IT system that will provide space situational awareness (SSA) data and space traffic coordination (STC) safety services to space operators for spaceflight safety, space sustainability, and international coordination. There are three elements that make up the TraCSS system – TraCSS-OASIS to serve as the data repository, TraCSS-SKYLINE to host operational SSA application services, and TraCSS-HORIZON which contains a modeling, simulation, and research environment and a development and test environment. Currently the Office of Space Commerce is conducting pathfinder studies to explore how OSC will procure, measure, integrate, and budget for the desired commercial SSA data and services across the TraCSS components.

In 2023, OSC conducted a GEO Pilot[1], a predecessor to the pathfinders, that focused on orbital safety in the geosynchronous Earth orbit (GEO) regime. The outcomes of that study informed the planning and executing of the Consolidated Pathfinder, focused in the low Earth orbit (LEO) regime. The general purpose of this project was to further explore leveraging commercial capabilities and to develop metrics to inform future procurement of commercial data and services related to space object conjunctions and catalog maintenance. A foundational element of leveraging commercial capability for the TraCSS operational environment, and a notable aspect of this pathfinder, is to establish a construct where multiple industry competitors can operate effectively together. The Consolidated Pathfinder was a limited term developmental activity where five companies, through orders placed on the Global Data Marketplace (GDM)[2], came together under OSC leadership to gather SSA data, perform orbit determination (OD), and conduct data quality monitoring. In order for TraCSS to accomplish its STC functions, it must have accurate orbits in order to provide meaningful potential collision alerts to owner/operators, it must be scalable to accommodate the increase in space traffic, and it must be useful to an ever increasing, diverse set of users. The Consolidated Pathfinder sought to understand, using data-driven metrics, the means of further developing TraCSS in order to satisfy these attributes. As a consequence, the metrics used to measure this pathfinder address five broad categories: accuracy, timeliness, precision (repeatability), scalability, and completeness.

The purpose of this paper is to provide an overview of the Consolidated Pathfinder and to review the utility of various metrics developed to inform acquisition of commercial data and services for future TraCSS operations. It has been authored collaboratively between Government, supporting federally funded research and development centers (FFRDCs), and the industry participants. The paper is organized as follows: Section 2 describes how the pathfinder was set up and the responsibilities of the different actors. It includes subsections on tasking the commercial participants with high-interest targets, sensor calibration, catalog processing, and the mission planning algorithm. The metrics and their development are discussed in Section 3. Finally, some interim conclusions are made in Section 4.

2. THE CONSOLIDATED PATHFINDER CONSTRUCT

The Consolidated Pathfinder is the result of several individually planned pathfinders being combined into one pathfinder on the path to TraCSS phase 1 operations. The originally planned pathfinders included the introduction of commercial SSA data to TraCSS, data quality monitoring of the TraCSS data and data products, a mission planning algorithm for commercial tasking, and exploration of the GDM as a procurement path for commercial data and services for TraCSS. The studies were combined to allow better demonstration of integrated commercial capabilities and to reduce the need for overlapping activities in the planned studies. As the GEO Pilot was conducted in GEO regime, it was decided that this pathfinder should concentrate on the LEO regime. As a consolidated activity, the stated objectives of the pathfinder were:

1. To understand methods and develop metrics used for both assessing data quality in support of TraCSS operations and assessing future acquisition of commercial data and services for TraCSS.

[1] NOAA press release for the pilot: https://www.noaa.gov/news-release/commerce-department-awards-contracts-for-space-traffic-coordination-pilot-project.

[2] Global Data Marketplace is an online platform to purchase data and services and is maintained by Bluestaq LLC.: https://www.globaldatamarketplace.com

2. To develop a mission planning algorithm and OD quality indices required to execute "surge" data collection and evaluate resulting OD in order to meet the needed accuracy and precision levels for high-interest objects.

3. To exercise the mission planning tasking using the algorithm described in item 2 above, to obtain commercial sensor measurement data and perform orbit determination on conjunction assessment (CA) objects of interest in order to decrease ambiguity for the CA risk assessment process for such objects.

4. To gain insight into commercial capabilities and associated costs to inform future TraCSS acquisition related to

   (a) a mission planning tasking process to maximize utility of both radar and optical SSA tracking data

   (b) commercial LEO catalog maintenance

5. To explore the GDM as a commercial data procurement option and to develop order templates suitable for future use in TraCSS operations.

6. To exercise the catalog maintenance cycle of taking measurement data and performing orbit determination in order to keep all (or a designated section) of the LEO space catalog under reasonable regular maintenance commercially. This objective was secondary to the study, as there are no immediate plans to move to a fully commercial catalog.

The pathfinder was conducted in three phases:

1. Placing GDM orders and conducting planning and preparation to guide conduct of the pathfinder.

2. Data collection: resident space object (RSO) observation, catalog maintenance, and artifact collection for evaluation.

3. Wrap-up, analysis and production of the final report. This phase is still ongoing during the writing of this paper regarding final FFRDC analysis and reporting.

In January and February of 2024, the Office of Space Commerce partnered with NASA to place orders through the GDM as follows: LeoLabs and Slingshot Aerospace were brought in as SSA data providers, COMSPOC Corporation as the OD provider, and Kayhan Space and SpaceNav as commercial data quality monitors and to develop acquisitional and operational metrics. In coordination with these commercial providers, OSC conducted planning and preparation activities to guide conduct of the pathfinder from February 1 through March 30, 2024. This planning phase included a virtual kickoff, two in-person planning workshops, and formation of the following working groups dedicated to aspects of the pathfinder: mission planning, metrics, calibration, data flow, and strategic communications. These planning activities clarified architectural details, produced guidance to be used during data collection, and identified the need to begin data flow as early as possible in order to allow for maturation of data flow processes, perform initial sensor calibration and start and converge orbit solutions for the LEO catalog. Radar data flow to the catalog processing was initiated by mid-February, and optical data was flowing into the catalog by early March. This was essential to ensure the best results when the evaluation period began on 1 April.

The second phase started on April 1 when the data collection for the pathfinder was initiated. This was initially scheduled to run to May 31, but was extended through June 30, 2024, to collect additional data and further validate the metrics to be leveraged by the operational TraCSS system. Throughout the second phase, the combined team of Government, FFRDCs, and commercial providers participated in regular tag-ups to monitor pathfinder operations, to address emerging issues, and to ensure effective data collection. Separately, selected working groups from the planning phase remained active to continue development and refinement of mission planning, catalog maintenance, and other aspects of the pathfinder operation.

Finally, data collection completed on June 30 and the pathfinder team transitioned to the last phase of the study, which included data analysis for metrics validation, commercial provider submission of reports and other deliverables, and detailed documentation of the mission planner and catalog maintenance function and design. Final metrics analysis and selection is still ongoing by the Government and FFRDCs, and final reports on these and the study as a whole are still being produced.

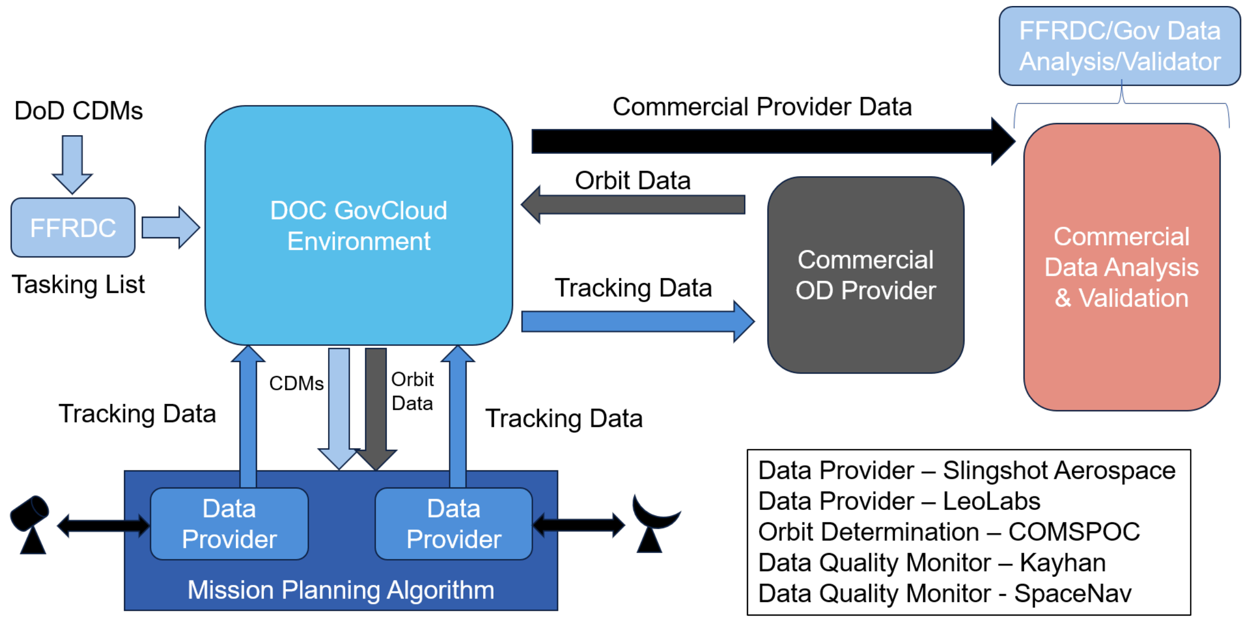

Figure 1: Consolidated Pathfinder Simplified Construct

Figure 1 is a simplified diagram of the pathfinder architecture and data flow. On a daily basis, current DOD conjunction data messages (CDM) were filtered to produce a tasking list of approximately 200 space objects for which additional SSA data was desired. This tasking list was then posted to a government cloud environment to which all pathfinder participants had access to. A mission planning algorithm developed jointly by LeoLabs and Slingshot took into consideration a number of factors, including existing orbital states, and produced a prioritized list of objects to be tasked for additional data collection by each participating data provider network. The resulting observation data was fed to the cloud environment and ingested by COMSPOC. This observation data was used to update space object states for OD and to feed the maintenance of the pathfinder LEO catalog. The updated states, maneuver information, orbit predicts, orbit post-fits, conjunction information, and track tagging summaries were then fed back to data providers to continue the process.

In parallel, the data quality monitors–Kayhan Space and SpaceNav–monitored data being collected, refined and validated the metrics developed by the other participants, and developed further metrics throughout the pathfinder. The data and OD providers were notified of any issues relating to operational activities, so that they could fix possible issues or provide more information to the data quality monitors. The analysis done by the data quality monitors is the primary basis for validating metrics to meet the primary pathfinder objective in the wrap-up analysis.

2.1 Tasking of High-Interest Objects

In order to demonstrate the ability for commercial data providers to surge additional observations for high interest conjunction events, the Aerospace Corporation developed a process to produce a daily list of conjunction secondary objects for prioritization for additional observation by the commercial data providers. This list was identified daily through a filtering and selection process using CDMs generated by the 18th Space Defense Squadron. Based on feedback from commercial data providers, a rough target of 200 secondaries on any given day were selected for additional tasking.

This process consisted of two steps: filtering and selection. First, candidate CDMs, numbering on any given day in the hundreds of thousands, were filtered in accordance with a number of criteria agreed upon by the Government, FFRDCs, and the commercial data providers and OD provider in the initial kickoff meeting. Only primary objects originating from owner/operator ephemerides were chosen to reduce complexity associated with unmodeled maneuvers that could complicate analysis. These filters are shown in Table 1.

Table 1: CDM Tasking Filters.

Title	Inclusion Criteria
Deduplication	Keep latest CDM within 15 minutes of first CDM, any primary/secondary order
Probability of collision	Probability of collision > 1e-7
Time of closest approach (TCA)	TCA < 4 days away from filtering time
Secondary apogee/perigee	Secondary apogee ≤ 2500km, perigee ≥ 300km
Secondary hard body radius	Secondary HBR > 0.1m
Secondary public TLE age	Secondary public TLE age < 30 days
Space Fence/analysts	Primary and secondary NOT a Space Fence or analyst object
Owner/operator ephemerides	Primary trajectory derived from O/O ephemerides

Next, CDMs were categorized. CDMs were deemed actionable or non-actionable based on the quality of their underlying orbit determination (OD), and 20% of the secondary object list was reserved for non-actionable but curable objects where more data might improve their actionability. The actionability criteria, their threshold, and whether they were considered curable is shown in Table 2. Weighted root-mean square (RMS) is the RMS of the OD residuals, weighted by the expected error in the measurements. Ideally, weighted RMS should be unity, but values are acceptable up to upper bounds established over time. The length of update interval (LUPI) refers to the fit-span of the observations used in the OD; long LUPIs increase prediction error, while short LUPIs produce poor drag solutions. The percent residuals accepted criterion measures the percentage of the residuals in the OD fit interval that are retained in the final iteration of the correction. This should be reasonably high unless extenuating circumstances exist (e.g., post-maneuver, cross-tagging). Non-positive definite covariances are simply covariance matrices that are non-positive definite, while default covariances are covariance matrices with default values of nine Earth radii squared, indicating the true covariance is not available. Curability refers to whether the quality of the object's state could be improved solely by additional tracking. [6]

Table 2: CDM Tasking Actionability Criteria.

Title	Inclusion Criteria	Curable?
Weighted root mean squared	Payloads: ≤ 1.5, rocket bodies: ≤ 2.0, debris/unknown: ≤ 5.0	No
Length of update interval	Dependent on energy dissipation rate and eccentricity; between 1.5 and 15 days	Yes, if high
% residuals accepted	≤ 80%	Yes
Non-positive definite covariance	Position covariance matrix is positive definite	No
Default covariance	Covariance provided are not default covariance, i.e., diagonal values ≥ 9 Earth radii squared	No

CDMs were subsequently placed into 1 of 7 priority categories derived from the CA dilution region concept [1, 2] and designed to give precedence to events that would benefit from more data. These categories are shown in Table 3. A conjunction is in the dilution region if the ratio of covariance size to miss distance is sufficiently high, representing a situation where the probability of collision (P_c) is small, but only because uncertainty is too large to truly know much about the situation. On the other hand, the robust region is one where the ratio of covariance size to miss distance is small enough to conclude that a low P_c represents reality. Between these two regions lies the max P_c. High-interest events, that are possible conjunctions, occur where the available knowledge indicates that the event is in the dilution region, but the P_c or max P_c are close enough to the mitigation threshold that a small amount of more data may alter the situation. This is the dynamic captured in the priorities shown in Table 3.

Table 3: CDM Tasking Prioritization Categories.

Priority	Title	Definition
1 (high)	Critically environmentally diluted	Event in dilution region, Max P_c greater than mitigation threshold, P_c less than mitigation threshold, P_c within 0.25 orders of magnitude of Max P_c and a collision would have catastrophic environmental consequences
2	Critically diluted	Event in dilution region, Max P_c greater than mitigation threshold, P_c less than mitigation threshold, P_c within 0.25 orders of magnitude of Max P_c
3	Robust, slightly sub-threshold	Event in robust region, P_c within 1 order of magnitude if mitigation threshold
4	Actionable, data desired	Event in dilution region, Max P_c greater than mitigation threshold, P_c greater than mitigation threshold
5	Robust, high risk	Event in robust region, P_c greater than mitigation threshold
6	High risk	Event in dilution region, Max P_c greater than mitigation threshold, P_c less than mitigation threshold, P_c outside 0.25 orders of magnitude of Max P_c
7 (low)	Low risk	Event in robust region, P_c well below mitigation threshold OR event in dilution region and Max P_c below mitigation threshold

Table 4: CDM Tasking Actionability Criteria.

Type	Values	Desired Proportion (%)
TCA altitude	[300-600] km	80
	[600-800] km	10
	[800-1000] km	5
	[1000-2500] km	5
HBR	Small: [.1, .15] m	40
	Medium: [.15, 0.5] m	30
	Large: [0.5,] m	30
Maneuverability	Is maneuverable	10
Starlink	Is Starlink	20
Priority	Critically environmentally diluted	50
	Critically diluted	10
	Robust, slightly sub-threshold	0
	Actionable, data desired	10
	Robust, high risk	0
	Low risk	10
	Non-actionable	20

Finally, a sampling process selected objects to be representative all of low Earth orbit with respect to object size, altitude, and maneuverability. These criteria (actionability, priority, representativeness) combined to form a highly constrained CDM selection problem, which was solved daily by an iterative optimization scheme. The desired quotas used with this optimization are shown in Table 4. One difficulty with this process was a dearth of high priority (i.e., priority 1, critically environmentally diluted) events during the pathfinder operation. As a result, the list consistently contained more low risk/low interest conjunctions than desired. Once a secondary object was placed on the list, it remained until time of closest approach (TCA).

This process produced lists of secondary objects and their associated CDMs, as well as other diagnostic plots and quantities. These products were provided to the mission planner. As secondary objects and their conjunctions persisted on the list until TCA, relevant CDM updates from the DOD were collected and provided to the data quality monitors to support analysis.

2.2 Sensor Calibration

Prior to attempting any orbit determination using tracking measurements, it is essential to properly calibrate the tracking sensors being used. This section outlines the calibration process used by COMSPOC in the pathfinder. For an in-depth discussion of the sensor calibration process, including a discussion of the McReynolds Filter-Smoother Consistency Test below, please refer to Johnson, 2015 [4].

The Extended Kalman Filter accounts for tracker white noise sigma, bias sigma and bias half-life, and offers a choice of using either a Vasicek or Gauss-Markov stochastic model. To initially set these values for each tracker, the observations are assessed against an independent high accuracy reference ephemeris. Examples of such spacecrafts are satellite laser ranging spacecraft, global navigation satellite systems spacecraft, etc. If needed, the list can be expanded to include well-tracked debris objects that do not maneuver, although it is preferable to use external reference ephemerides. When using external reference ephemerides, it is important to understand the accuracy of the reference data, e.g., some International Laser Ranging System sources may have larger errors at the end of the prediction period. The calibration process involves comparing the measurements from the tracker in question and assessing the residuals against the reference ephemeris. An initial coarse assessment identifies any issues with coordinate frame, site location, as well as identifying gross errors in initial bias or sigma values. The proper settings for the tracker data being received, in terms of what corrections should be applied (i.e., light time delay, ionosphere, troposphere, instantaneous doppler, aberration), were also confirmed.

Once the overall configuration is verified and any gross outlier behavior is understood, the filter solves for the biases (ensuring that the filter is not yet estimating the orbit). The process is repeated, allowing the noise sigma, bias sigma and half-life values to be refined. For each measurement type, it is ensured that the tracker bias consistency test passes. The Quantile-Quantile (QQ) plots [9] are also assessed to ensure that the residuals are Gaussian (for further discussion see Vallado & Seago 2010 [8]). If needed, the white noise sigma is adjusted to ensure the tracker bias consistency test is passed. Next, the filter and smoother are run to estimate the orbit. At this stage all consistency tests are evaluated as passing: satellite position, satellite velocity, ballistic coefficient, solar radiation pressure, transponder bias and tracker bias. The QQ plot is evaluated again as well.

Finally, the resulting ephemeris from the smoother is compared to the reference ephemeris, and the position difference is evaluated. The tracker-specific settings are then updated in the system database, the tracker is enabled, and subsequent catalog processing uses the measurements from the calibrated sensor. Following the initial calibration, all trackers are reassessed periodically to ensure no changes in behavior. This is often accomplished weekly, with each iteration presenting an opportunity to further adjust the calibration settings.

2.3 Catalog Processing

The ingestion and processing of the sensor tracking data was performed by COMSPOC using its commercial catalog architecture and data fusion capabilities, to perform the orbit determination for the pathfinder. A separate pathfinder catalog was instantiated to track and monitor the LEO population as defined for the Consolidated Pathfinder effort (i.e., perigee >300 km and apogee <2500 km). Following an initial sensor calibration for every new sensor (see Section 2.2), the LEO catalog was initialized using DOD two-line elements (TLE) and subsequently refined and solved using sensor data from either or both of the data providers.

The catalog automation utilized the commercial extended Kalman Filter to perform observation association, OD and maneuver detection and processing. The observation association process includes automatic attempts to re-tag any observations that fail initial association, but certain constraints specific to this study prevented most attempts to re-tag, meaning only the de-tagging was done if observation association failed. The OD process updated orbit states with each new set of measurements, producing an updated state vector multiple times per day. If a maneuverable satellite exhibited signs of having performed a maneuver, the maneuver processing updated the orbit instead, and also provided maneuver metrics including time of maneuver and maneuver magnitude.

As part of the catalog processing, a quality metric was computed in order to convey an assessment of each object's OD. This metric combines numerous OD parameters such as position and velocity errors, covariance size, force model parameters, tracking data acceptance and historical behavior for the object. The OD quality metric was delivered to the Mission Planner (see Section 2.4) to help determine proper follow-on action.

Following every catalog orbit update, conjunction assessment was automatically performed. Relevant conjunction information was communicated back to the Mission Planner via CDMs. In addition to the data sets produced throughout the day, catalog processing delivered predicted ephemerides for each object daily along with post-fit ephemerides for each object weekly.

2.4 Mission Planning and Catalog Maintenance

LeoLabs and Slingshot Aerospace were tasked to jointly develop and implement an integrated, radar-optical OD support mission planning algorithm (the Mission Planner), whose core responsibility was to optimize resources of the commercial tracking networks in pursuit of improved CDMs for select high-interest events and general catalog maintenance. A set of CDMs for high interest events was selected daily by the Aerospace Corporation algorithm developed for this study and a list of objects of interest, containing roughly 200 secondary objects from the CDMs, was delivered to the Mission Planner on a daily cadence (see Section 2.1).

The Mission Planner ran automatically on a daily cadence to generate scored, provider-specific observation collection requests, which were output to a scored list and delivered to each provider to use in their internal prioritization algorithms. The process first determined how much each object would benefit from additional tracking data by evaluating several parameters from the latest commercial catalog state including the epoch age, OD confidence (a metric from the OD provider), and covariance size to compute a score. The score was scaled based on the time remaining until TCA of the relevant CDM, more heavily weighting objects with less time remaining. Each scaled score was then augmented based on each provider's self-reported ability to collect observational data on the object.

One challenge faced when developing the Mission Planner was accounting for each observation provider's different capabilities, such as object detectability, sensor viewing windows, staring vs. tasked sensors, phenomenology, and coexisting requirements on the network. The Mission Planner needed to account for the fact that each provider has their own collection prioritization scheme that is highly nuanced for their network's specific capabilities and needs. It was discovered that the mission planning concept must differentiate between need and priority. The fact that an object is in need of additional information does not mean that it is prudent for a given provider to prioritize tasking that object. Perhaps the object is not detectable, has unfavorable viewing opportunities, conflicts with other collection requests, or conversely is sufficiently observed without an increased prioritization.

To better address the nuances in each provider's network, an update was made to the Mission Planner to directly incorporate the provider's ability to successfully collect on each object. This update helped account for cases where an object's provider-specific score could be very high even when that provider reported no or low detectability for the object. The Mission Planner was updated to perform a simple weighting of each score by the provider's detectability value, to account for this discrepancy. This change caused objects with low detectability to be scaled down to a lower score, and consequently, objects that may have been in desperate need of information, would receive low provider-specific scores if they were difficult to detect. This update enabled the Mission Planner to function more in line with how each provider's internal prioritization algorithms behaved.

Preliminary results from the data quality monitors show that utilization of the mission planning tool resulted in additional observations for some objects of interest. Rate of increase depended strongly on tasking methodology of the data providers, sensitivity of the systems, and availability of additional tracks on the objects of interest. More investigation is necessary to understand the impact of additional tracking on uncertainty reduction and prediction improvement. Early results show large variation in improvement depending on existing track quality, and object type and size.

For catalog quality, the Mission Planner also determines which objects from the commercial catalog would benefit from additional observations and incorporates those objects into the scoring scheme described above. When selecting objects for tracking improvements for catalog maintenance, a down selection or filtering process was employed to achieve the desired number of objects from the hundreds or thousands of candidates. Ultimately, the goal was to identify the objects that would benefit most from increased prioritization. The process used to select the catalog maintenance object set, described below, ran daily for the latter half of the pathfinder along with the Mission Planner.

The initial implementation of catalog maintenance identified a small population of objects, dictated by a set of criteria defining bounds on epoch age, OD confidence, and covariance size. Specifically, these conditions were joined by "AND" statements to bound the population of objects with an old epoch, poor OD confidence, and a large covariance. Limits were imposed for each criterion such that lost objects were not prioritized, but ones near the edge of becoming lost were. These thresholds were set such that the population they bound consisted of a reasonable number of objects for the purposes of the pathfinder, somewhere in the 75−200 object range varying day by day.

An update was made to change the "AND" statement to an "OR", and enforced a hard limit to keep only the top 100 objects, sorted by score. Changing the statement to an "OR" expands the criteria to consider objects that meet any of the criteria (i.e., having an old epoch, a poor OD confidence, or a large covariance). Sorting the objects by score prioritizes those that are most in need of maintenance. Additionally, a filter was imposed on the selection process to exclude objects that one or both providers report zero detectability, so only objects with reasonable detectability expectations will be attempted. The selected set of objects was then scored through the process described above, with the amendment of using a static scale factor, rather than a TCA based one.

A centralized catalog maintenance strategy must account for the fact that each commercial data provider has unique sensors, capabilities, processes, and customer requirements, and thus the collection strategy will vary from one provider to another. This problem was solved by delegating that responsibility to each provider separately. The centralized Mission Planner serves an oversight role to monitor the catalog and request surge scheduling when appropriate. The surge scheduling requests are kept minimal to allow existing provider-specific catalog maintenance software to work as intended across the entire catalog.

Preliminary results from the data quality monitors suggest that utilization of the mission planning tool through increased object prioritization of the catalog maintenance list resulted in reduced uncertainties for these objects and an improvement in the overall health of the catalog.

3. METRICS DEVELOPMENT

A critical component of the pathfinder was the development of key metrics for tracking data and outcomes throughout the course of the experiment. These metrics are designed to inform critical metrics for inclusion in the Office of Space Commerce TraCSS operational system that is under development. Metrics fell into two rough categories:

- Operational metrics – useful for monitoring system performance in real time and identifying issues, and assessing degree of operational improvement.
- Acquisitional metrics – to be used in future contracting of similar services, particularly for determining occasion and amount of additional data needed and for quantifying amount of operational improvement realized.

The following sections describe the development of the metrics for the Consolidated Pathfinder. The initial set of metrics defined by the Metrics Working Group is described in Section 3.1 and the work of the data quality monitors are addressed in Section 3.2.

3.1 Initial Metrics Development by the Metrics Working Group

An STC system consists of diverse sensors and sensor types, data fusion, and astrodynamics algorithms and tools. To assess the effectiveness of such a system, and consequently, the Consolidated Pathfinder, the quality and performance of each part must be evaluated. Unfortunately, a set of mutually understood, clearly defined, and harmonized metrics to evaluate capabilities of an STC system did not exist, posing a challenge to the Consolidated Pathfinder team.

The Metrics Working Group was formed to collaboratively collect and define a base for the metrics to be used to evaluate the success of the pathfinder. The working group began by reviewing the many lessons learned from participation in and execution of the previous GEO Pilot. This review helped to identify and apply a portion of the necessary relevant metrics. The three commercial SSA companies responsible for the operational component of the pathfinder partnered with OSC and FFRDCs to further augment this set with metrics designed to provide additional insights into the operational readiness and maturity of the commercial SSA data and algorithms used in the Consolidated Pathfinder. The collaboration yielded an initial set of metrics categories as follows:

- Measurement throughput statistics measured by tracks/day, observations by region, number and distribution of sensors, track utility rate, and SSA latency statistics;

- Observation association measured by retag/untag rate and rate of observations outside range of values;
- Conjunction confidence measured by percentage of actionable CA;
- OD confidence including OD confidence history and confidence cumulative distribution function (CDF);
- Maneuver detections and solutions measured by number of maneuvers found/day;
- Sensor calibration measured by number of calibration sets/day;
- Predicted ephemeris accuracy measured by accuracy vs. 3rd party reference and accuracy vs. smoothed reference;
- Covariance metrics measured by 1σ errors vs. time and covariance realism (Mahalanobis Distance, χ^2) [3, 10];
- Catalog latency measured by OD age history and CDF;
- Catalog completeness and "freshness" measured by number of RSOs vs. on Space-Track and percentage of RSOs on the attention list; and
- Tasking measured by number of track taskings, number of tracks achieved, number of tracks failed, OD latency per track, CDM actionability, and number of CDM improved.

This initial set of metrics served as a starting point for OSC in developing requirements for the data quality monitors. To aid in this task, the Metrics Working Group assembled a working document that helped to interpret requirements in the context of the overall set of metrics and shared examples that the data quality monitors could use during the pathfinder.

3.2 Final Metrics Development by Data Quality Monitors

Metrics development for the pathfinder was conducted by two companies, Kayhan Space Corporation and SpaceNav, who were responsible for monitoring data quality during the experiment in conjunction with a government appointed contact from MIT Lincoln Laboratory. The data quality monitors received an outline of categories of metrics that the OSC wished for them to calculate in the form of a project work statement at the beginning of the pathfinder. They also received, as outlined in Section 3.1 above, a suggested set of metrics for the data quality monitors, derived from industry best practices and the other commercial participants' understanding of the experimental design.

Using these two input documents, along with weekly metric review feedback sessions with MIT Lincoln Laboratory, and the body of experience each data quality monitor came in with, each data quality monitor was asked to put together their own independent package of metrics that they believed best assessed the performance of the pathfinder. This set needed to include measuring individual commercial participant contributions and performance, performance of the output catalog relative to the DOD catalog as a reference, and assessment of the utility of the developed metrics for future OSC systems. The data quality monitors did not communicate with each other about the individual metrics that they were employing until after the pathfinder had concluded and the metrics being generated had solidified. Allowing the data quality monitors to develop the specific metrics generated based on general categories of metrics resulted in a surprising amount of variation between the two products, allowing the OSC to better understand the variety of implementations that they could employ and the usefulness of each.

At the conclusion of the pathfinder activities, MIT Lincoln Laboratory is performing validation of the calculated metrics, working in conjunction with the data quality monitors and the other commercial participants to replicate each of the metrics that the data quality monitors generated and identify sources of error if the results deviated from expectation. This process was implemented both to vet that the performance metrics accurately reflected experimental performance and to capture the necessary knowledge to ensure that the metrics can be implemented within the TraCSS system if desired.

The following outlines the categories of metrics assessed during the pathfinder and found to be of high utility by each of the data quality monitors, providing a short description of each. Examples of said metrics is out of the scope of the current document but are planned to be released at a later date, after the OSC analysis and validation process has concluded.

Catalog completeness: The goal of this metric is to quantify how many objects were adequately maintained during the pathfinder by the commercial providers compared to the public DOD catalog. This goes beyond measuring the total number of objects present in the pathfinder and DOD catalogs, which is also a relevant metric, as an object must be consistently tracked with consistent OD updates for it to be considered well-maintained. Variations on this metric can be displayed including tracking data coverage statistics, state coverage percentages, or as joint statistics requiring both tracks and states to be defined as maintained. Additional variations were investigated, e.g., varying update rates including using the average, median, and minimum rates of 1 update and 1 track per day, as well as an average of 4 updates and 4 tracks per week.

Predictive Ephemeris Accuracy: One of the most important metrics collected during the pathfinder is the aggregate accuracy of the predictive ephemerides. This is evaluated by comparing the predicted state vectors to the definitive or reference "truth" trajectories. For each object, the accuracy assessment begins by differencing multiple predictive ephemeris files against a reference definitive trajectory to generate a set of position differences (ephemeris overlaps). This error allows the examination of both the quality of the orbit determination as well as the fidelity of the prediction which produced the predictive ephemeris. This metric can also be broken down by object into categories to gain insight into the impact that various object characteristics have on the catalog's quality. For example, the metric can be split out by object size, by orbit regime, and by maneuverability.

Covariance Realism: Following the ephemeris accuracy assessment, another relevant metric is the realism of the predictive covariances from the Consolidated Pathfinder. This metric evaluates the extent to which the covariance in the predictive and definitive ephemerides published by the OD provider realistically described the error observed when comparing the trajectories of overlapping predictive and definitive ephemerides. Covariance realism was evaluated by comparing the squared Mahalanobis distance of the residuals to the theoretical χ^2 distribution with 3 degrees of freedom using a goodness of fit test (in this case, the Cramér–von Mises test) [3, 10, 8]. Because uncertainty has a large impact on computation of probability of collision for conjunction assessment, covariance realism is a critical statistic on which to evaluate a catalog. If the uncertainties are unrealistic, they could fuel unrealistic estimations of risk when predicting close approaches between satellites. Covariance realism can also serve as a metric of predictive ephemeris accuracy itself. If there are systematic issues during OD or prediction such as dynamics mismodeling or undetected maneuvers, they may impact the Mahalanobis distribution's conformity to the theoretical distribution.

Data Flow Metrics: This class of metrics captures several individual metrics aimed at capturing the flow of data within the system. This allowed for identification of flow issues during the course of the pathfinder, as well as provided an understanding of the quantity of data feeding in and out of the system. The following metrics of this type were generated:

- ***Total Tracks over Time:*** This metric captures the number of observation tracks flowing into the system, where a track is defined as a collection of observations on an RSO. The tracks can be categorized in different ways to assess the composition of tracks regarding object type (i.e., payload, debris, rocket body, unknown) and originating sensor or provider. As a simple metric to compute and understand, it is useful in preliminarily validation of the raw data flow highlighting possible data gaps and/or operational issues. While examining the track count distribution by object type category is a critical component in understanding catalog completeness and health, it does not fully encapsulate either.

- ***Tag Report Tracking:*** Another metric related to the tracking data consists of displaying the quantity of objects originally associated by the data providers, but later marked as uncorrelated tracks by the OD provider's observation association process. It is important to present these metrics alongside the total tracks per day to get the full picture of the quantity of observations feeding into the OD process.

- ***Observation Latency:*** This metric measures the time delay between an observation data production (measurement "epoch") and data delivery time. Observation delivery latency is an important component of the total system latency. If an observation is collected but not delivered in time for an OD run, then the quality of the OD solution and subsequent predictive ephemeris could be negatively impacted.

- ***OD Product Production over Time:*** This metric monitors the overall production rate for the OD outputs, i.e., number of ephemerides, state vectors, and objects for which data was produced per day. As with other data flow metrics, it does not capture catalog completeness and its usefulness is limited to troubleshooting high-level process-related issues.

Tracking Gain in Support of Conjunctions of Interest: To evaluate the performance of the mission planner algorithm implemented during the Consolidated Pathfinder and designed to increase tasking for objects involved in high-interest conjunctions, a metric was needed that compared the current tracking of the selected objects compared to a baseline from before they were added to the interest list. This metric was designed slightly differently by each of the data quality monitors, but at the core, each metric was designed to measure the response to sensor tasking by considering the number of tracks collected for a given object on an individual day when said object received surge tasking compared to the baseline revisit rate from an analysis period when it did not receive surge tasking. These metrics were found to help build understanding of the effectiveness of the mission planner implementation.

State Quality Improvement on Conjunctions of Interest: Related to the above tracking gain metric, this metric allows evaluation of the change in the OD solution quality in terms of RMS uncertainty from before the object was added to the list to after it was prioritized, allowing improvements in catalog quality to be assessed. Variations of this metric include splitting objects up by size, altitude, or object type.

Metrics relevant to Conjunctions of Interest: Multiple metrics were investigated to assess the operational impact of additional data on objects of interest that were prioritized by the Mission Planner. This family of metrics attempts to capture meaningful changes to the filtered CDMs, that served as inputs to the pathfinder tasking (i.e., original CDMs), if they were to be updated (recomputed) using the pathfinder derived catalog data, i.e., predictive ephemerides. CDM recomputation involves taking each original CDM and updating their secondary object's state vector with one from the predictive states produced by the pathfinder on that same day. With the updated state, a new time and geometry of the closest approach based on the changed state is found to recompute the CDM.

Among the many comparisons that can then be drawn from the recomputed CDMs, the most useful include the count and reason for recomputation failure, the distribution change of risk assessment metrics such as miss distance and probability of collision, and the improvement on dilution and actionability of a CDM. Additionally, the differences in probability of collision between the original and recomputed CDMs were examined at select risk mitigation maneuver commit points to evaluate how many conjunctions would have resulted in different operational decisions had the Consolidated Pathfinder secondary catalog been used instead. The usefulness of these metrics was found to be limited by the fidelity of the model used to represent the TraCSS operational system, e.g., they are impacted by surge tasking capability and catalog health and coverage. As such, they require careful interpretation that decrease their usefulness in the pathfinder. For example, while a CDM dilution improvement in this metric might seem to indicate optimistic results, it is ultimately tied to the covariance realism difference between the DOD and the catalog of the pathfinder. With catalog health and coverage issues addressed, and outside the delayed context of tasking, these metrics could prove useful in operations or future pathfinders.

Sensor Calibration: Finally, the data quality monitors independently assessed sensor calibration, using the same calibration data provided to the COMSPOC. The following metrics were assessed as part of that process.

- ***Bias Estimation:*** This metric provides an independent assessment of sensor calibration quality and outlier rates during the pathfinder. It is computed based on an independent bias modeling technique over the already corrected observations produced in the pathfinder. The metric can be useful in evaluating sensor quality/outlier issues but could not be easily used for direct validation of the sensor calibration effort since the OD provider used a different bias model.
- ***Calibration Satellite Track Counts:*** This metric records the number of calibration satellite tracks observed per sensor during a given "Bias Estimation" period to help in assessing the coverage and validity of the "Bias Estimation" metric. This metric is limited in usefulness, because it does not quantify the impact of calibration satellite lack of coverage or observation quality. However, it might be useful as a high-level binary check.

4. CONCLUSIONS

In light of the transformation taking place in space activity and the policy guidance from SPD-3, OSC is developing a Traffic Coordination System for Space to preserve the safety and sustainability of the space operating environment. The Consolidated Pathfinder was a limited term developmental activity where five companies came together under OSC leadership and with FFRDC support and established an architecture designed to collect commercial data to follow-up on space object conjunctions and maintain a commercial catalog focused on the LEO regime. The primary objective of this activity was to develop metrics to inform future procurement of commercial data and services in support of TraCSS operations.

This paper provided an overview of this activity and briefly reviewed the utility of various relevant metrics. In brief, Aerospace provided a daily list of projected conjunctions. In addition to providing observational data on all objects in LEO they were tracking, the two SSA data providers (LeoLabs & Slingshot) developed a mission planning algorithm to prioritize objects collected from their respective sensor networks. These observations fed an orbit determination provider (COMSPOC) for refinement of object states and update of the pathfinder LEO catalog. Two data quality monitors (Kayhan and SpaceNav) monitored all data in light of a proposed list of metrics, and performed analysis of that data to support post-activity assessment of those metrics.

Full assessment of the Consolidated Pathfinder data and metrics analysis is ongoing and will be the subject of a final report. However, all indications at this stage are that sufficient data was collected to successfully define the metrics list and specify the parameters of the desired metrics. Such metrics will inform OSC's acquisition processes as a Government customer of commercial SSA data and services, to the thresholds needed to support spaceflight safety. Additionally, the metrics will support TraCSS operators in monitoring and improving the TraCSS operational system and support stakeholders in international coordination efforts. The specific metrics and the assessment of those metrics will be documented in more detail in the final report.

In addition to this study, there are other related pathfinder efforts conducted by OSC to give more insight for integrating commercial services and improving the CA process. The CA disambiguity study [5], which focuses on the nature of the diluted events and what can be done to make them more actionable, is currently being wrapped up. Another incipient pathfinder effort engages the commercial SSA industry to assist selected owner/operators in the production of quality owner/operator ephemerides that include planned maneuvers and, thus, can constitute a highly-accurate statement of their expected future positions. OSC is also examining the feasibility of whether an on-board GNSS transponder device would be effective in improving satellite position reporting and prediction accuracy and precision. Should the concept prove feasible a new study may be initiated. Other pathfinder efforts are presently under discussion within OSC and are likely to be announced in the coming months. In short, the intention is to execute several of such efforts in order to assemble a portfolio of tested and understood commercial options for meeting TraCSS orbital safety data and algorithmic needs.

While the final report will be documented at the conclusion of the assessment phase, the Consolidated Pathfinder was a successful public-private partnership–both in terms of organizational and technical architecture collaboration–that enabled multiple industry competitors to cooperatively tackle spaceflight safety, space sustainability, and international coordination challenges. The Consolidated Pathfinder will enable OSC to accelerate efforts to integrate commercial capabilities into the TraCSS operational system in support of fulfilling SPD-3 direction and addressing the evolving spaceflight safety needs for a growing space operator community.

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