A Mission-Oriented Framework for Evaluating Space Situational Awareness Data

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ABSTRACT

Space Situational Awareness (SSA) provides a characterization of the operating environment supporting informed decision-making processes for government and commercial space operators. Traditionally, the United States Government (USG) has relied on the Space Surveillance Network (SSN), a system of Department of Defense (DoD) owned and operated sensors, located terrestrially and in space, to detect, track, and catalog artificial objects in Earth's orbit. The commercialization of space has introduced an alternative source of SSA data—commercially operated sensors. These commercial systems offer a means of augmenting traditional military capabilities by employing diverse sensing technologies and increasing global coverage. However, integrating commercial SSA data presents a trade-off between the cost and value of observations. Differences in the capabilities of sensor technologies and architectures necessitate a structured framework for evaluating their contributions to mission impact.

This research proposes an operations research framework to evaluate SSA data from a wide range of sensor providers. Specifically, we focus on evaluating the effectiveness of SSA data in maintaining custody and detecting on-orbit satellite maneuvers, a key aspect of SSA. To achieve this, we introduce a suite of quantitative metrics designed to assess the performance of SSA providers.

The proposed framework is demonstrated on a month of real-world commercial SSA data from July 2025, including 14 million observations and 3.2 million derived products. By evaluating the contributions of SSA data providers using a common framework, data purchasers have a more holistic understanding of the product, which can inform contract decisions and operations. Additionally, by developing transparent and quantifiable performance metrics, the framework provides a mechanism for constructive feedback to SSA data providers, encouraging improvements that align with the user's objectives. The findings support U.S. Space Command and Space Systems Command's efforts to integrate commercial SSA data into existing workflows, ensuring that decision-makers have access to timely and actionable information. As the space environment becomes increasingly congested and contested, the ability to dynamically assess and prioritize sensor data will be essential for maintaining strategic advantage in the domain.

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1. INTRODUCTION

U.S. Department of Defense (DoD) doctrine defines Space Situational Awareness (SSA) as "the requisite foundational, current, and predictive knowledge, and characterization of space objects within the space domain" [11]. This study focuses on a central component of SSA—maintaining custody (i.e., tracking) of active satellites in Earth's orbit. Tracking has become increasingly important and challenging as the population of Resident Space Objects (RSOs) continues to grow. According to Space-Track.org, in August 2025, approximately 12,600 operational payloads were being tracked in the space domain [10].

In the 20th century, satellite operations were conducted by a limited number of government organizations, and orbital deconfliction was rarely required. Today, however, thousands of organizations—including governmental, international, civil, commercial, and academic entities—actively operate satellites in Earth's orbit. Although space is vast, specific orbital regimes such as Low Earth Orbit (LEO) and Geosynchronous Orbit (GEO) offer unique operational advantages and have consequently become increasingly congested. This congestion, combined with limited information sharing among operators, has elevated the risk of on-orbit collisions. The first major incident occurred in February 2009, when the American Iridium 33 and Russian Kosmos-2251 satellites collided, producing more than 23,000 trackable debris fragments and substantially increasing risks for other satellites operating in that orbital region [4]. In another example, on November 15, 2021, the Russians destroyed the COSMOS 1408 satellite in LEO while testing a Direct Ascent Antisatellite (DA-ASAT) rocket. The explosion resulted in 1,700 trackable fragments of debris, a severity sufficient to cause the astronauts in the International Space Station (ISS) to move to their escape pods in anticipation of a possible impact [9].

SSA data allows operators to verify that spacecraft are performing as expected, ensuring mission objectives are met efficiently. Conversely, SSA enables the rapid detection and diagnosis of anomalous behaviors indicative of potential system errors, component failures, breakups, or unexpected environmental interactions, including collisions. Comprehensive and timely SSA has therefore become a foundational capability for all space operators seeking to maintain effective, reliable, and sustainable operations in an increasingly complex orbital environment.

1.1 Augmenting the Space Surveillance Network with Commercial Data

The U.S. Government's approach to SSA has traditionally relied upon the Space Surveillance Network (SSN), a network comprising dozens of ground-based and space-based sensors [11]. SSN sensors, operated by the United States Space Force (USSF), detect, track, catalog, and identify artificial objects orbiting Earth (e.g., active/inactive satellites, spent rocket bodies, fragmentation debris).

The SSN provides critical advantages in data quality, reliability, and security. Nevertheless, U.S. Space Command has recognized the value of augmenting traditional SSN capabilities with commercially available SSA data, driven by the proliferation of advanced sensor technologies and commercial data providers. The USSF Commercial Space Strategy explicitly states, "The USSF seeks capabilities from the commercial sector that can contribute to the holistic generation of SSA" [14].

The National Space Defense Center (NSDC), a subordinate center of U.S. Space Command and the Combined Joint Force Space Component Command (C/JFSCC), coordinates military, intelligence, civil, and commercial space activities for unified space defense operations [13]. As early as 2016, the NSDC began exploring the use of commercial capabilities to augment military systems. Beginning in April 2019, the NSDC emphasized these efforts through the Sprint Advanced Concept Training (SACT) experiment series, designed to enhance collaboration among U.S. Space Command, its components, allied and partner nations, and commercial industry [2]. More recently, these efforts have transitioned to internal experiments known as the NSDC's Advanced Concept Experiments and Live Fly Experiments.

The success of these integration experiments led directly to the establishment of the Joint Commercial Operations (JCO) cell, which now acquires targeted SSA data and analysis focused primarily on adversarial or high-interest satellites, as well as select unclassified allied satellites, to support the NSDC's Protect and Defend mission. Unlike the SSN, the JCO does not aim to maintain comprehensive custody of the general RSO catalog, though it may serendipitously obtain data on general RSOs. The JCO's primary mission is to provide timely identification, analysis, and warnings of potential counterspace activities, leveraging non-classified industry and allied capabilities to facilitate broader distribution and strategic collaboration [2]. The JCO employs more than 150 commercial sensors to focus on approximately 800 high-interest satellites. In some cases, the JCO can maintain 24/7 surveillance, with measurement updates on satellites as frequently as once every three minutes. The JCO contributes more than 1 million independent

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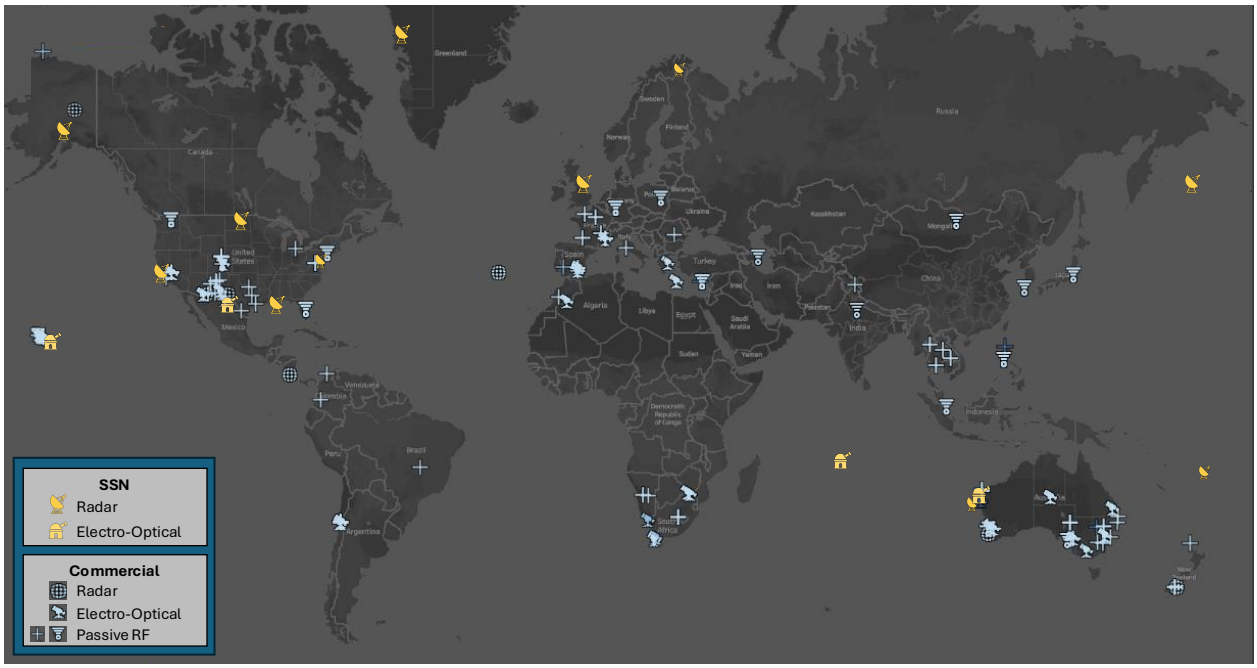

Fig. 1: Commercial sensor locations contracted by the JCO in blue overlayed with SSN locations in yellow.

space surveillance measurements to the NSDC daily, augmenting the data provided by the SSN.

Currently, the JCO supports the NSDC's Protect & Defend mission and operates as an extension of the NSDC operations floor, leveraging commercial providers to achieve diverse, timely SSA. The JCO's network includes allies, partners, academia, and industry, enabling near-continuous operational support.

Commercial companies contracted by the JCO offer global coverage using a range of sensor technologies. The commercial industry experiences rapid innovation as firms seek a competitive edge by developing new technologies and architectures. Commercial data provides an agile, flexible, and low-cost means to augment the SSN. However, the number of providers and the volume of data have grown to such an extent that the JCO must now make deliberate purchasing decisions.

1.2 Evaluating Space Situational Awareness Data

The three primary components of SSA are space weather, natural space debris, and orbiting space objects [8]. This study focuses on a critical subset of SSA: maintaining custody of active satellites.

The primary sensors for tracking space objects are radar, electro-optical telescopes (EO), and passive radio frequency (passive RF). Radar systems emit radio waves that are reflected by the target and measured by a receiver. These measurements of range and angle can be used to determine the location of space objects [3]. Radars can also collect specialized observations to characterize an object's size, shape, and orientation. They can operate at any time of day and are not limited by weather, making them a dependable, though costly, option. As terrestrial sensors, radars are more commonly employed at lower altitudes, such as LEO, due to the power required for higher orbits [11].

EO sensors for SSA operate similarly to telescopes used in astronomy: electromagnetic radiation emitted or reflected by an object is gathered and focused to form an image [16]. To track satellites from Earth, SSA EO sensors most commonly detect reflected sunlight, which limits their operation to clear, dark skies. EO systems are relatively simple compared to radar, with lower construction and operating costs and a smaller footprint. EO sensors provide angular measurements (azimuth and elevation) and can measure an object's brightness, referred to as visual magnitude. When visual magnitude is evaluated over time, it is referred to as a "photometric pattern of life." EO sensors cannot independently measure range. They are predominantly used to track satellites in orbits beyond LEO, such as Medium Earth Orbit (MEO) and GEO, where radar effectiveness diminishes with distance [1].

Passive RF uses multiple ground stations to detect and triangulate signals emanating from satellites. Like EO, this is a

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passive sensing method and less costly than radar. The primary measurement types for this sensor are time difference of arrival (TDOA) and frequency difference of arrival (FDOA). Ground-based passive RF sensors are operated in two to four geographically dispersed sites that use TDOA/FDOA as Doppler measurements. Passive RF is effective at a wide range of altitudes, including LEO, MEO, and GEO. As with radar, passive RF is robust to environmental conditions (i.e., weather and light). However, passive RF relies upon a satellite's active transmission of a signal to maintain track [11].

Choi et al. [3] analyzed radar-based SSA sensor systems, specifically their capability to detect and track objects in LEO. Their performance analysis showed that detecting a 1 m^2 radar cross-section (RCS) object at 2,000 km requires specific combinations of frequency, antenna gain, transmission power, and signal processing. Importantly, the authors highlighted the limitations of optical systems due to weather and solar exclusion, reinforcing radar's complementary role in ensuring persistent availability. This focus on the trade-offs between phenomenologies underscores the need for diverse sensor inputs in any evaluation framework, consistent with this study's emphasis on comparing heterogeneous providers.

Ackermann et al. [1] provided a systematic examination of ground-based versus space-based optical systems. Their evaluation emphasized differences in cost-per-observation, latency, global coverage, and sensitivity, concluding that a hybrid approach could reduce latency and broaden coverage. For the present study, their work highlights that sensor architecture and placement strongly influence operational timeliness, a factor directly tied to maneuver detection and custody metrics.

Felten [5] optimized GEO SSA architectures using genetic algorithms and high-performance computing. His research demonstrated that a hybrid architecture combining 1.0-meter aperture ground telescopes with small-aperture polar GEO satellites produced the most cost-effective solution, reducing overall system cost by 22.4% compared to alternative orbital regimes. This work illustrates the importance of cost-performance optimization across architectures, aligning with this study's goal of evaluating not only data quality but also the efficiency of different commercial contributions.

Fowler and Paley [6] extended SSA concepts into the cislunar domain, developing observability metrics for constellation design. Their analysis showed which orbit families provide the best observability of others, using numerical measures such as condition numbers to evaluate estimation quality. While their research addresses a different orbital regime, its emphasis on quantitative, metric-driven evaluation of tracking architectures parallels this study's mission-oriented approach to evaluating maneuver detection.

Harris [7] developed a mission-driven optimization framework for sensor network design, leveraging metaheuristics to produce networks that tripled observation capacity and reduced catalog gaps by 50%. His results demonstrated how network design can be tuned to fill geographic coverage gaps and improve estimation accuracy. For this research, Harris underscores the value of aligning evaluation criteria with mission outcomes—the same principle applied here to maneuver detection rather than raw revisit or coverage.

Vasso et al. [15] introduced a multi-objective optimization framework to evaluate SSA architectures that incorporate non-traditional and commercial providers. By simulating multiple architectures and applying Pareto analysis, they demonstrated threefold increases in capacity, a 55% improvement in coverage, and reductions in unobserved time. This finding reinforces the potential value of commercial data sources and highlights the importance of objective, quantitative trade-space evaluation, which directly informs the motivation for this study's proposed metrics.

In contrast to these foundational studies, this research contributes a unique perspective by proposing a set of metrics that can be used to evaluate sources of SSA data regardless of the sensor type or operator (i.e., government or commercial). By developing operationally relevant, quantitative metrics tailored explicitly to satellite maneuver detection, this study extends previous efforts and fills a critical gap. Overall, this research provides a structured, transparent, and practical framework aimed directly at enhancing SSA operations by aligning evaluation with mission objectives.

2. METHODS

To conduct this study, we employed an iterative approach combining insights from relevant literature, expert knowledge, and direct engagement with key stakeholders at U.S. Space Command. Initially, candidate metrics were identified through a review of existing SSA evaluation frameworks and the broader decision-support literature. These metrics were subsequently refined through discussions with subject matter experts and operational stakeholders at U.S. Space

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Command, ensuring alignment with the mission objectives of custody maintenance and maneuver detection.

2.1 Space Situational Awareness Data

For the purposes of SSA, an "observation" refers to a set of data points collected by sensors about a space object at a specific moment in time. Observations are the raw measurements that provide information on the position, velocity, or other attributes of an object in space, depending on sensor capabilities. They constitute the fundamental inputs used in the tracking process and are critical for building and refining tracks and calculating state vectors. This study focuses on observations from ground-based radar, EO, and passive RF sensors.

A "track" is a sequence of observations collected by a single sensor that behaves consistently with the expected orbital motion of a satellite (or other RSO). Tracks are developed by linking these individual observations into a continuous record from the sensor perspective, effectively showing the trajectory of an object through space. Tracks are commonly transmitted as a set of observations and used to update orbital states, either in batch or via filtering methods. In this paper, we use the term "orbital state" to refer to either a state vector or an orbital element set (e.g., a two-line element set (TLE)). Unless otherwise specified, these are considered interchangeable representations of the same underlying orbit.

A "state vector" is a six-dimensional Cartesian vector of position ($\mathbf{r}$) and velocity ($\mathbf{v}$) at a given epoch (t). Together, these values uniquely determine an object's trajectory under orbital mechanics. State vectors are created through the process of orbit determination, in which one or more tracks are processed using estimation techniques such as batch least-squares fitting or sequential filters (e.g., the Kalman filter). These methods iteratively adjust an initial orbital estimate until the propagated trajectory best fits the measured observations, within the limits of sensor error models [12]. Once established, a state vector can be propagated forward to predict a satellite's future position and support custody analysis, maneuver detection, and conjunction assessment.

For this study, a satellite "maneuver" refers to any deliberate change in velocity or trajectory. This is typically achieved by firing the satellite's onboard propulsion system, which imparts an acceleration and alters the orbit. Maneuvers are executed for various reasons, including orbital maintenance, plane changes, collision avoidance, or deorbiting procedures. Rapid detection and characterization of these maneuvers are crucial for maintaining accurate satellite tracking and for collision prediction models in SSA. Tracking maneuvers with ground-based sensors such as radar and EO systems involves detecting subtle deviations from the satellite's expected position or velocity, which may indicate that a maneuver has occurred.

The JCO maintains a list of high-interest satellites referred to as the "High Rate of Revisit" (HRR). In the context of SSA, "revisit rate" refers to how frequently a sensor or a network of sensors observes a specific space object or a particular region of space. The HRR includes the following fields: satellite catalog number (i.e., NORAD ID), common name, country, orbital regime, and rank. The rank of a satellite communicates the level of prioritization for custody and the desired revisit rate to the sensor providers. The current HRR rank objectives for satellites in GEO are identified in Tab. 1. Satellite rank is assigned based on assessments made by the JCO regarding satellite pattern-of-life behavior. The JCO operators reorder the HRR so that satellites exhibiting higher levels of activity or less predictable behavior are assigned higher priority (lower numerical rank). It is important to note that the JCO does not directly task sensors or providers. Instead, individual providers manage their own observation schedules and operations based on the routine publication of the HRR list.

SSA data providers are categorized into two types based on their contributions: (1) "sensor providers," which contribute direct observational data (e.g., radar, EO, and passive RF), and (2) "fusion providers," which produce derived products (e.g., state vectors and maneuver reports) by aggregating and processing data from multiple sensor sources. This distinction is critical for fair performance evaluation, as these provider types have fundamentally different operational capabilities and constraints.

2.2 Custody Metrics

Custody metrics evaluate a provider's ability to consistently monitor satellites, ensuring awareness of their orbital states and behaviors over time. Effective custody facilitates rapid anomaly detection, timely maneuver identification, and accurate long-term tracking. These metrics characterize observational persistence, revisit interval compliance, sensor network robustness, and unique contributions of individual SSA providers. Together, they provide critical insights into each provider's operational reliability and strategic value.

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2.2.1 High-Interest Satellites Persistently Observed

"Persistent observation" measures the continuity of satellite custody. Persistence is especially critical for high-interest satellites, where continuous tracking enhances operational awareness and strategic decision-making. Persistent observation enables timely detection and verification of on-orbit maneuvers and unexpected orbital behavior. High persistence also aids analysts in assessing satellite behavior and characterizing mission objectives and intent. This metric quantifies the proportion of high-interest satellites consistently monitored by individual SSA providers, stratified by orbital regime (LEO and GEO) and prioritization rank.

Persistence criteria were defined separately for LEO and GEO satellites, reflecting differing revisit expectations due to distinct orbital dynamics and observational constraints. For GEO satellites, revisit thresholds vary by prioritization rank according to the JCO standards (Tab.1). For LEO satellites we adopt a fixed revisit interval of 2-hours, chosen to approximate one collection per orbital revolution across typical LEO periods ($\approx$ 90–120 minutes).

The analysis period was divided into weekly intervals, with each week further subdivided into uniform time bins based on maximum desired revisit rates for each satellite. For each week, a satellite was considered to meet the persistence criterion if it received at least one observation from a given provider in at least 50% of the time bins:

$$\text{Weekly Persistence} = \begin{cases} 1, & \dfrac{B_{\text{observed,week}}}{B_{\text{total,week}}} \geq T_{\text{persistence}} \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

where $B_{\text{observed,week}}$ is the number of bins with at least one observation, $B_{\text{total,week}}$ is the total bins per week, and $T_{\text{persistence}}$ is the persistence threshold (0.5 in this study).

A satellite was considered "persistently observed" by a provider across the analysis period only if it met the weekly criterion for *all* weeks:

$$\text{Persistently Observed} = \begin{cases} 1, & W_{\text{persistent}} = W_{\text{total}} \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

where $W_{\text{persistent}}$ is the number of compliant weeks, and W_{total} is the total number of weeks. This strict requirement ensures that only satellites receiving consistent monitoring throughout the entire period are classified as persistently observed, preventing providers from inflating persistence scores with sporadic but intensive campaigns.

The persistence threshold is configurable to reflect operational needs and sensor constraints. A 50% threshold (0.5) was chosen here to allow equitable comparison across sensor phenomenologies, particularly accounting for EO sensors, which experience approximately 12 hours of daily solar exclusion.

The percentage of satellites persistently observed for each provider, orbital regime, and prioritization rank was calculated as:

$$\text{Percent Persistent} = \frac{N_{\text{persistent}}}{N_{\text{total}}} \times 100 \tag{3}$$

Table 1: The JCO uses the "HRR" to communicate importance and desired revisit rates to sensor providers based on satellite rank. These revisit rates are specifically for satellites in GEO. For the purpose of this study we apply a standard 120-minute maximum revisit rate for all satellites in LEO.

Rank	Num. of GEO Satellites	Desired Revisit Rate	Maximum Revisit Rate
0	2	Continuous stare	10 min
1	12	10–15 mins	15 min
2	26	30–45 mins	45 min
3	201	1–2 hrs	2 hrs
4	361	2–3 times daily	12 hrs
5	95	1 time daily	24 hrs

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where $N_{\text{persistent}}$ is the number of persistently observed satellites and N_{total} is the total number of high-interest satellites in the orbital regime and rank category. For provider-level calculations, N_{total} includes all high-interest satellites, even if a provider submitted zero observations for some satellites.

2.2.2 Total Violation Time

Timely revisit intervals are essential for rapid detection of maneuvers and orbital anomalies. Deviations from required revisit intervals, termed violation times, represent periods without observation during which maneuvers or anomalies may occur undetected. The "Total Violation Time" (TVT) metric quantifies the cumulative duration of these excessive gaps, providing a performance measure directly aligned with operational objectives.

Traditional revisit-rate metrics can unintentionally incentivize providers to collect multiple observations in rapid succession, yielding redundant data and reduced operational value. In contrast, TVT emphasizes minimizing gaps between observations, consistent with satellite rank requirements. This aligns more directly with the JCO's goal of rapid detection of maneuvers and anomalous behaviors, encouraging efficient sensor tasking and resource allocation.

To compute violation times, consecutive observation pairs of high-interest satellites were identified. The elapsed time between observations was compared against revisit thresholds (Tab. 1 for GEO, fixed at 2 hours for LEO). Violation time $V_{i,j}$ was defined as the excess duration beyond the threshold:

$$V_{i,j} = \begin{cases} \Delta t_{i,j} - T_{\text{threshold}}, & \Delta t_{i,j} > T_{\text{threshold}} \\ 0, & \text{otherwise} \end{cases} \tag{4}$$

where $\Delta t_{i,j}$ is the interval between consecutive observations and $T_{\text{threshold}}$ is the revisit threshold based on satellite rank.

TVT was calculated only for satellites where the provider met the persistence threshold (50% in this study), ensuring alignment between persistence and violation-based metrics. This prevents providers from being penalized for satellites they did not actively monitor. Results are presented alongside the number of satellites meeting the persistence criterion, and both should be interpreted jointly for meaningful provider comparisons.

2.2.3 Marginal Total Violation Time Reduction

"Marginal TVT Reduction" quantifies each provider's contribution to reducing custody gaps across the sensor network through leave-one-out analysis. This metric directly measures the operational impact of adding a provider to the enterprise by calculating the hours of violation time eliminated when that provider's observations are included.

The metric employs a counterfactual approach, computing TVT for the entire observation network with and without each provider. For provider p, let $\text{TVT}_{\text{without},p}$ denote the total violation time when provider p's observations are excluded from the network, and $\text{TVT}_{\text{with all}}$ denote the total violation time with all providers included. The marginal TVT reduction is:

$$\Delta\text{TVT}_p = \text{TVT}_{\text{without},p} - \text{TVT}_{\text{with all}} \tag{5}$$

Violations are calculated using rank-specific revisit thresholds for GEO and a standard 2-hour threshold for LEO satellites. The absolute reduction in hours directly quantifies operational benefit, while the percentage reduction provides normalized comparison:

$$\Delta\text{TVT}_p\% = \frac{\Delta\text{TVT}_p}{\text{TVT}_{\text{without},p}} \times 100 \tag{6}$$

To reflect operational priorities, the metric includes a rank-weighted summary that assigns higher weights to higher-priority satellites. Let w_r denote the weight for rank r, where $w_0 = 6$, $w_1 = 5$, $w_2 = 4$, $w_3 = 3$, $w_4 = 2$, and $w_5 = 1$. The weighted marginal TVT reduction is:

$$\Delta\text{TVT}_{p,\text{weighted}} = \sum_{r=0}^{5} w_r \cdot \Delta\text{TVT}_{p,r} \tag{7}$$

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where $\Delta\text{TVT}_{p,r}$ represents the marginal reduction for rank r satellites. The corresponding weighted percentage reduction uses the weighted baseline:

$$\Delta\text{TVT}_{p,\text{weighted}}\% = \frac{\Delta\text{TVT}_{p,\text{weighted}}}{\sum_{r=0}^{5} w_r \cdot \text{TVT}_{\text{without},p,r}} \times 100 \tag{8}$$

Results are stratified by orbital regime and prioritization rank to identify where each provider delivers maximum value. Providers with high marginal TVT reduction demonstrate critical contributions to closing custody gaps, particularly for high-priority satellites where continuous tracking supports mission objectives. This metric complements Unique Observation Capability by quantifying the temporal impact of each provider's contributions rather than just identifying unique coverage periods.

2.2.4 Sensor Contribution Density

"Sensor Contribution Density" quantifies the extent to which a provider leverages multiple sensors or extended observation time to sustain custody. This metric reflects sensor network robustness, redundancy, and allocation efficiency, offering insights into the provider's ability to maintain continuity despite potential outages or environmental constraints.

For each provider, Sensor Contribution Density for provider p is calculated as:

$$\text{Sensor Contribution Density}_p = \frac{\text{Total Sensor-Hours}_p}{N_{\text{sat,observed}}} \tag{9}$$

where $\text{Total Sensor-Hours}_p$ is the cumulative sensor-hours contributed across all satellites within 24 hours, and $N_{\text{sat,observed}}$ is the number of unique satellites observed during that period.

2.2.5 Unique Observation Capability

"Unique Observation Capability" quantifies the extent of distinct contributions by each provider through bin-level temporal analysis, addressing the operational need to identify providers that fill critical custody gaps. This metric employs mission-aligned time bins to capture providers' abilities to deliver observations during operationally significant periods when other sensors cannot contribute. The metric evaluates custody at the satellite-bin level, where bins are defined according to satellite prioritization rank and orbital regime.

For GEO satellites, bin sizes correspond to maximum revisit requirements. LEO satellites employ uniform 60-minute bins across all ranks, reflecting operational revisit expectations. Analysis is restricted to Ranks 0–3, representing the highest priority satellites requiring persistent custody.

A provider is considered to satisfy a satellite-bin (s,b) if it contributes at least three observations within that temporal bin, ensuring sufficient evidence for a usable orbital update within the time window. Let C_p denote the set of satellite-bins covered by provider p. A satellite-bin is "unique" to provider p if p satisfies the bin and no other provider does:

$$U_p = \{(s,b) \in C_p : C_q \cap \{(s,b)\} = \emptyset \text{ for all } q \neq p\} \tag{10}$$

To avoid penalizing high-coverage providers, the metric employs a common denominator across all providers within each analysis slice. The denominator represents the union of all satellite-bins covered by any provider:

$$D = \bigcup_{p \in P} C_p \tag{11}$$

where P is the set of all providers. The Unique Observation Capability for provider p is then:

$$\text{UOC}_p = \frac{|U_p|}{|D|} \tag{12}$$

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This formulation ensures equitable comparison by using the same denominator for all providers within each orbital regime and rank combination. The coverage requirement (three observations minimum) applies uniformly to all providers, preventing gaming through sparse observation strategies.

Results are stratified by week, orbital regime, and prioritization rank to reveal temporal patterns and regime-specific performance. Higher UOC values indicate providers delivering critical observations during periods when other sensors cannot contribute.

2.3 Maneuver Detection Metrics

Maneuver detection metrics evaluate the responsiveness and effectiveness of SSA providers in detecting and characterizing satellite maneuvers. Timely maneuver detection and rapid state vector reestablishment are critical for maintaining accurate orbit determination and ensuring continuous domain awareness. These metrics measure the temporal responsiveness of providers, their contributions to orbit determination, and the sufficiency of observational data for maneuver analysis.

Most satellite maneuvers are benign; for example, satellites regularly conduct small thrusts to maintain their orbit, known as "station-keeping" maneuvers. Nevertheless, tracking all maneuvers provides valuable insight into a satellite's status, capabilities, and operating procedures. Some maneuvers may unintentionally threaten other satellites, especially when operators do not perform conjunction analysis or coordination in advance. Others may be executed with hostile intent, such as intelligence collection or malign operations.

In contrast to the custody metrics, maneuver detection metrics cannot be assessed on non-cooperative satellites. The application of maneuver detection metrics requires "validation satellites" for which confirmed maneuver data from the operator is available. Variations in data quality across providers, including missing or inconsistent timestamp fields, are addressed through standardized preprocessing. All temporal comparisons use timezone-aware UTC timestamps, and providers with incomplete temporal data are excluded from relevant calculations rather than penalized with zero scores.

2.3.1 Maneuver Detection Rate and False Positives

The effectiveness of each provider in reporting maneuvers is evaluated using two complementary measures: the "Maneuver Detection Rate" and the "False Positive Ratio". The Maneuver Detection Rate quantifies the proportion of known maneuvers successfully reported by a provider within an acceptable time window, defined here as up to 24 hours after the maneuver event. This metric captures the provider's ability to deliver timely, operationally actionable alerts.

Let N_{reported} represent the number of maneuver reports issued by a provider within 24 hours of a known maneuver (from reference data), and $N_{\text{maneuvers}}$ the total number of maneuver events in the reference set. Each reported maneuver was matched to reference events based on satellite identity and the 24-hour window; exact timestamp alignment was not required. Only maneuver reports with a status of "verified" are included. The detection rate is computed as:

$$\text{Detection Rate } (\%) = \frac{N_{\text{reported}}}{N_{\text{maneuvers}}} \times 100 \tag{13}$$

For sensor providers (contributing radar, EO, or passive RF observations), $N_{\text{maneuvers}}$ includes only maneuvers of satellites that the provider persistently observed. For fusion providers (producing state vectors and maneuver reports from aggregated data), $N_{\text{maneuvers}}$ includes all reference maneuvers, reflecting their broader access to observations. A higher detection rate indicates consistent and timely maneuver reporting.

False positives occur when a provider reports a maneuver not corresponding to any verified event. These false reports can increase analyst workload or mislead operations. A false positive is defined as any reported maneuver that does not fall within 24 hours of a verified maneuver for the same satellite. Multiple reports within the same 24-hour window following a verified maneuver are not counted as false positives, since providers may issue updates for the same detection.

Let N_{false} denote the number of such reports. Although a classical false positive rate requires knowledge of true negatives, which is not available, we define a practical "False Positive Ratio":

$$\text{False Positive Ratio} = \frac{N_{\text{false}}}{N_{\text{total reports}}} \tag{14}$$

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This formulation expresses the fraction of all reported maneuvers that are false. A lower ratio indicates greater precision and reliability. Together, the detection rate and false positive ratio provide complementary insight into timeliness, accuracy, and reporting reliability.

2.3.2 Time to Detect Maneuver

"Time to Detect Maneuver" quantifies the elapsed time between the actual maneuver event (from cooperative reference data) and the provider's first reported detection. Rapid detection is critical for timely SSA responses.

Only the earliest report submitted by each provider for a given maneuver is included in this metric, as well as in the detection rate. Multiple reports within 24 hours are considered updates and excluded from timing calculations; reports submitted after 24 hours are treated as false positives.

The time to detect a maneuver, ΔT_{detect}, is calculated as:

$$\Delta T_{\text{detect}} = T_{\text{first detection}} - T_{\text{maneuver}} \tag{15}$$

where $T_{\text{first detection}}$ is the system creation timestamp of the earliest maneuver report, and T_{maneuver} is the reference maneuver timestamp. Using the system creation timestamp captures both reporting and processing latency.

2.3.3 Time to Post-Maneuver Observation

The metric "Time to Post-Maneuver Observation" measures the responsiveness of a provider's sensor network following a maneuver. It is defined as the elapsed time from the maneuver end time to the provider's first observation after the maneuver:

$$\Delta T_{\text{obs}} = T_{\text{first post-maneuver obs}} - T_{\text{maneuver}} \tag{16}$$

where $T_{\text{first post-maneuver obs}}$ is the timestamp of the first observation submitted after the maneuver event. Rapid post-maneuver observations support timely orbit updates and responsiveness.

2.3.4 Time to Post-Maneuver State Vector

"Time to Post-Maneuver State Vector" quantifies the elapsed time between a maneuver event and the first valid post-maneuver state vector (e.g., TLE or Cartesian vector). Prompt state vectors are critical for maintaining orbit knowledge and informing operational decisions. A post-maneuver state vector is defined as the first provider-submitted state vector timestamped after the maneuver end time:

$$\Delta T_{\text{state}} = T_{\text{state vector published}} - T_{\text{maneuver}} \tag{17}$$

where $T_{\text{state vector published}}$ is the timestamp when the state vector becomes available in the database.

2.3.5 Observation Sufficiency for Maneuver Resolution

"Observation Sufficiency for Maneuver Resolution" evaluates whether providers contribute sufficient observations to characterize maneuvers. Specifically, it measures the percentage of maneuvers for which a provider contributed at least one observation both before and after the maneuver event within a ± 12 hour window:

$$\text{Observation Sufficiency} = \frac{N_{\text{sufficient}}}{N_{\text{maneuvers}}} \times 100 \tag{18}$$

where $N_{\text{sufficient}}$ is the number of maneuvers with sufficient observations and $N_{\text{maneuvers}}$ is the total maneuvers analyzed.

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2.4 Statistical Reporting, Stratification, and Metric Design Considerations

For each temporal metric, descriptive statistics (minimum, maximum, mean, median, and standard deviation) are computed and stratified by orbital regime (LEO, GEO) and satellite prioritization rank. Stratification reveals performance variations across subsets of satellites, while aggregate statistics provide broader assessments. Distributions reveal operational consistency: for instance, violation metrics with low maximum values and small standard deviations indicate reliable coverage, while high variability suggests sporadic coverage.

The metrics are deliberately structured to resist gaming behaviors that might optimize scores without enhancing operational value. For example, persistence is assessed through distributed coverage across weekly time bins, violation time directly measures coverage gaps, and maneuver metrics count only the first valid report per event. These design choices align provider incentives with operational objectives.

Effective provider evaluation requires interpreting metrics holistically while accounting for limitations. While the 50% persistence threshold reflects phenomenology constraints (e.g., EO solar exclusion), providers with lower persistence may still deliver high-value, unique coverage in critical temporal or environmental windows (e.g., daylight opportunities, weather-resilient passes) that reduces custody gaps. Environmental factors, sensor modality differences, and the 24-hour detection window all introduce variability that must be considered alongside quantitative results. Complementary metrics—such as detection rate paired with false positive ratio—create a robust evaluation framework, where strong performance across multiple dimensions demonstrates genuine custody and maneuver detection capability.

Taken together, these metrics provide decision-makers with quantitative tools for optimizing SSA resource allocation. The emphasis on consistency, responsiveness, and robustness, combined with stratification across satellite subsets, enables a nuanced assessment of provider contributions while resisting metric manipulation.

3. CASE STUDY RESULTS

To demonstrate the application of the proposed metrics, we analyzed commercial SSA data collected during July 1–31, 2025, from 17 providers listed in the JCO HRR list. The dataset comprised more than 14 million direct sensor observations and over 3.2 million derived products (e.g., state vectors, maneuver reports). Twelve providers contributed as sensor providers—delivering radar, EO, and passive RF observations—while five served as fusion providers, producing value-added products through aggregation and analysis of multiple sensor sources. This composition provided a representative cross-section of commercial SSA capabilities for evaluating custody and maneuver detection performance.

Custody metrics were evaluated on all satellites in LEO and GEO included on the JCO's HRR during the analysis period. Maneuver detection metrics cannot be evaluated on the full HRR since they require verified maneuver data. To assess maneuver detection metrics, we leveraged a collection of 46 "validation satellites" in GEO for which we received confirmed maneuver data from the satellite operator. These satellites collectively executed 752 maneuvers during the analysis period using a range of thruster types: chemical, stationary plasma thruster (SPT), electric hall thruster (EHT), electrothermal, and xenon ion propulsion system (XIPS).

It is important to note that these results were influenced by the scope of JCO contracts during the experiment period and do not necessarily reflect a provider's full operational capacity. Some commercial providers supply observation data for only a subset of the satellites they are capable of tracking, based on budget and contractual priorities. The following results, therefore, represent apparent performance during the analysis period rather than unconstrained technical potential. The purpose of the case study is to demonstrate application of the proposed evaluation framework—not to evaluate specific providers.

3.1 Custody Metrics

Tab. 2 summarizes custody performance over four weeks for all ranks and orbital regimes. D demonstrated consistently high persistent observation counts (495–603 satellites), reflecting broad coverage and sustained custody. In contrast, Providers N (56–90 satellites) and G (72–80 satellites) maintained smaller but relatively stable persistence levels. Providers F and M showed moderate persistence with limited temporal variation.

Tab. 3 shows violation time performance for ranks 1–3 satellites. Provider M achieved the lowest mean violation times ($\sim$0.08–0.12 hours), reflecting revisits aligning closely with the JCO objectives, while Provider D maintained moderate violation times ($\sim$7.45–9.13 hours) with stable performance across a larger set of persistently observed

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Table 2: Provider custody metrics by week for all ranks and orbits. Sensor contribution density is expressed in total sensor-hours per observed satellite. ISO-aligned week start dates are listed.

	Persistently Observed Sats (#)				Sensor Contribution Density				Unique Observation Capability			
Provider	**Jun 30**	**Jul 7**	**Jul 14**	**Jul 21**	**Jun 30**	**Jul 7**	**Jul 14**	**Jul 21**	**Jun 30**	**Jul 7**	**Jul 14**	**Jul 21**
D	495	603	562	589	22.19	23.48	22.62	21.40	0.887	0.885	0.896	0.880
F	21	21	19	19	59.88	61.11	64.97	65.47	0.000	0.000	0.000	0.000
G	72	77	74	80	11.04	10.95	10.51	11.12	0.210	0.205	0.235	0.275
M	27	32	32	32	113.83	136.61	128.90	140.78	0.024	0.005	0.011	0.000
N	67	90	65	56	12.71	12.02	8.28	5.74	0.396	0.330	0.322	0.264

Table 3: Violation time in hours by provider and week for satellite ranks 1–3 in all orbits. Count indicates the number of persistently observed satellites. ISO-aligned week start dates are listed.

	Jun 30				**Jul 7**				**Jul 14**				**Jul 21**			
Provider	**Count**	**Mean**	**Max**	**Std**	**Count**	**Mean**	**Max**	**Std**	**Count**	**Mean**	**Max**	**Std**	**Count**	**Mean**	**Max**	**Std**
D	62	9.13	10.72	2.29	59	8.10	15.20	4.61	54	7.45	19.39	5.69	58	8.36	17.93	5.62
F	5	0.51	9.00	1.15	4	0.50	14.08	1.48	12	0.53	6.08	1.10	2	0.25	5.50	0.46
G	23	1.59	7.87	1.47	23	2.12	33.92	3.07	22	1.96	6.92	1.53	23	2.21	27.65	2.96
M	8	0.12	6.66	0.45	8	0.08	0.63	0.09	9	0.10	5.55	0.30	9	0.12	5.91	0.46
N	11	5.88	17.44	6.47	14	5.85	15.05	4.53	10	3.57	9.08	3.94	9	5.10	9.56	3.66

satellites (54–62 satellites). Provider N exhibited moderate violation times (∼3.57–5.88 hours) with higher variability (max 17.44 hours), while Provider G balanced moderate violation times (∼1.59–2.21 hours) across 22–23 satellites with occasional wider maximum gaps (up to 33.92 hours). Provider F showed excellent mean violation times (∼0.25–0.53 hours) with variable persistence counts (2–12 satellites).

Across all custody metrics, Providers D and M emerged as strong performers in either breadth or revisit frequency, while Providers N and G offered moderate persistence but meaningful unique coverage.

3.2 Maneuver Detection Metrics

Maneuver detection results were limited to only two providers that submitted maneuver reports for the validation satellites during the analysis period. Provider E, a fusion provider, achieved a verified detection rate of 24.7%, identifying 186 of 752 known events within 24 hours. Provider M, operating as a sensor provider, demonstrated a notably higher detection rate of 63.2% of the satellites it persistently observed, successfully detecting 24 of the 38 relevant maneuver events within its persistent observation coverage. Note that as a fusion provider, E was evaluated on the full set of validation satellites, whereas the sensor provider, M, was only evaluated on the satellites it persistently observed.

Provider E reported a false positive ratio of 94.9%, and Provider M exhibited a false positive ratio of 79.9%. This means that both providers submitted a relatively high volume of maneuver reports more than 24 hours after the validation satellites' maneuver start times. This may reflect numerous revisions as the providers refine their reports with updated post-maneuver observations.

Median time to detect for Provider E was approximately 13.3 hours (mean 15.0 hours), with some detections occurring in under a minute but substantial variability across events.

Tab. 4 and Tab. 5 present post-maneuver observation and state vector availability. Provider G achieved the fastest median post-maneuver observation (0.19 hours) and state vector posting (0.19 hours), though with a limited sample size of 3 events each. Provider M demonstrated competitive performance with median times of 0.45 hours for observations and 0.46 hours for state vectors across a larger sample (30 events). Among providers with substantial event counts, N showed strong state vector responsiveness with a median of 3.99 hours across 395 events, while D maintained consistent performance with a median observation time of 2.88 hours (409 events) and a state vector time of 8.15 hours

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Table 4: Time to post-maneuver observation by provider in hours. Performance evaluated on 46 validation satellites.

Provider	Min	Max	Mean	Median	Std Dev	Count
G	0.15	3.33	1.23	0.19	1.49	3
M	0.02	38.31	4.89	0.45	10.72	30
D	0.00	59.86	4.87	2.88	5.77	409
N	0.15	4.53	2.56	3.01	1.82	3
P	8.84	56.60	24.81	9.00	22.47	3
A	8.22	60.60	26.38	16.82	17.61	20
K	0.61	71.92	32.03	24.45	24.48	17
B	4.09	50.23	27.19	27.23	21.49	4
C	0.16	51.15	32.27	45.49	22.82	3
All Providers	**0.00**	**71.92**	**7.12**	**3.85**	**11.45**	**492**

Table 5: Time to post-maneuver state vector by provider in hours. Performance evaluated on 46 validation satellites.

Provider	Min	Max	Mean	Median	Std Dev	Count
G	0.15	3.33	1.23	0.19	1.49	3
M	0.05	38.41	5.95	0.46	11.64	30
N	0.00	66.36	6.01	3.99	9.17	395
J	0.01	70.79	9.21	6.92	11.34	401
D	0.00	59.88	9.04	8.15	8.36	404
O	0.03	69.77	14.39	12.41	12.21	214
E	0.01	71.71	21.68	19.94	19.29	247
All Providers	**0.00**	**71.71**	**10.82**	**8.48**	**12.66**	**1694**

(404 events). Network-wide medians were 3.85 hours for post-maneuver observation and 8.48 hours for state vector publication, with means of 7.12 hours and 10.82 hours, respectively.

Overall, the maneuver detection metrics reveal that while some providers excel in rapid follow-up observations and state vector posting, consistent, accurate detection of maneuver events remains a significant challenge across the commercial SSA sector.

3.3 Comparative Summary

When comparing custody performance with maneuver detection effectiveness, no direct correlation emerged between high persistence and accurate maneuver reporting. For example, Provider D demonstrated exceptional persistent observation and high unique coverage, yet did not appear among the providers submitting maneuver reports. Conversely, Provider E, a fusion provider with no direct sensor observations, achieved a 24.7% detection rate despite lacking custody metrics entirely. Notably, Provider M exhibited contrasting performance profiles: while showing limited persistence (27–32 satellites) and minimal unique coverage, it achieved the highest detection rate (63.2%) among the two providers reporting maneuvers, though only for its 38 persistently observed satellites. This divergence underscores that maneuver detection effectiveness is not solely dependent on continuous custody, but also on specialized processing, fusion of multi-source data, and timely analytical workflows. The combined interpretation of custody and maneuver metrics, therefore, offers a more complete operational assessment than either measure in isolation.

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4. DISCUSSION

4.1 Trade-off Analysis Between Cost and Value

The metrics presented in this study highlight different aspects of value to the SSA data consumer, specifically U.S. Space Command and its subordinate elements. Among these, violation time is particularly emphasized due to its direct impact on operational responsiveness and effectiveness. To illustrate the trade-off between cost and performance, we calculated the cost per persistently observed satellite for each provider and plotted this against mean violation time (Fig. 2). This section uses artificially generated data for demonstration purposes only. The actual provider costs are not disclosed.

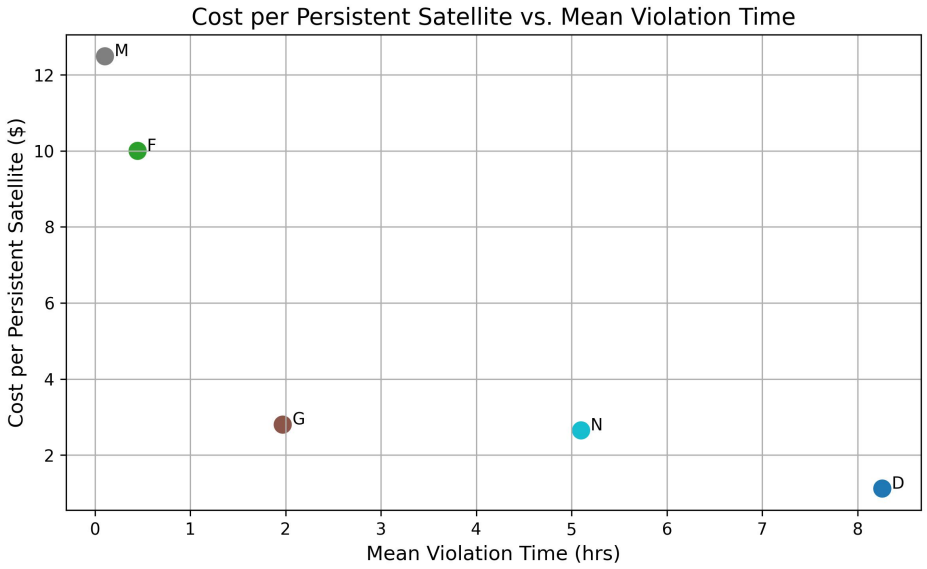

Fig. 2: Cost versus mean violation time for SSA data providers, based on artificial demonstration data. Providers near the origin notionally represent an ideal cost-performance balance. Actual provider costs not disclosed.

The resulting scatter plot demonstrates the cost-performance landscape across providers. The ideal position is near the origin, indicating both low cost per persistently observed satellite and low violation time—representing the highest overall value to the consumer. Providers M and D exemplify contrasting approaches: M achieves exceptionally low violation time (0.10 hours) at a higher cost ($12.49 per satellite), whereas D offers highly competitive cost efficiency ($1.12 per satellite) with moderate violation time (8.26 hours).

Provider G demonstrates moderate costs ($2.80 per satellite) with strong violation performance (1.97 hours). Despite the higher per-satellite cost than some competitors, Provider G provides consistent coverage of approximately 76 satellites, which may justify the investment for high-priority targets. Provider F shows excellent violation time performance (0.45 hours) but at a substantial per-satellite cost ($10.00) across a smaller set of 20 satellites. Provider N occupies a middle position with moderate cost ($2.65 per satellite) and moderate violation time (5.10 hours) across approximately 70 satellites.

This analysis underscores the need for a comprehensive evaluation framework, integrating multiple performance metrics to holistically assess the cost-effectiveness and operational value of SSA providers. The wide variation in both cost efficiency and performance suggests that optimal procurement strategies may involve a diversified portfolio of providers, each contributing distinct strengths to the enterprise.

4.2 Interpretation of Key Metrics and Insights

The custody and maneuver detection metrics developed here provide nuanced insights into provider capabilities. Metrics such as persistent observation and violation time directly influence operational effectiveness by identifying which providers deliver the most reliable custody coverage. Providers with low mean violation times and low variability

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demonstrate operational consistency essential for timely maneuver detection. Conversely, providers with high variability or sporadic coverage pose greater risks of undetected events.

Unique observation capability emerges as a critical complementary metric, capturing marginal contributions that enhance overall custody. Providers such as D, with high unique observation capabilities, significantly improve robustness by filling coverage gaps unaddressed by other networks.

4.3 Implications for SSA Operations

These metrics have practical implications for SSA planning and resource allocation. Decision-makers can use them to balance performance with budgetary constraints, optimizing provider mixes to ensure persistent and comprehensive custody. Providers demonstrating consistently high performance across multiple metrics represent strategic assets that enhance reliability and responsiveness.

Considering cost-performance trade-offs alongside complementary metrics such as unique observation capability supports well-rounded procurement strategies. Recognizing provider strengths and limitations across orbital regimes and satellite ranks allows for tailored sensor tasking and efficient allocation, maximizing operational effectiveness while minimizing inefficiencies.

Equally important, transparent evaluation criteria foster a constructive feedback loop between users and commercial providers. Sharing results enables providers to identify improvement areas and adjust practices to better align with user needs. In this way, the evaluation process itself contributes to the maturation of the commercial SSA ecosystem, enhancing data quality and operational alignment.

4.4 Limitations

While robust, the metrics have inherent limitations. Environmental and operational constraints affecting different sensor types are reflected indirectly but not explicitly distinguished. Providers relying on weather-dependent sensors (e.g., EO) may show variability unrelated to operational performance.

Maneuver detection metrics, though operationally relevant, use a 24-hour detection window that may not fully differentiate rapid initial detection from comprehensive characterization. Providers excelling at rapid detection may differ from those offering more detailed but slower analyses. Similarly, sensor contribution density, while indicative of network robustness, may be inflated artificially through redundant sensor deployment or switching.

These limitations highlight the need for holistic interpretation. Analysts and decision-makers must combine quantitative results with qualitative operational knowledge to draw meaningful conclusions and actionable strategies.

5. CONCLUSION

This study introduces a structured evaluation framework for assessing commercial SSA providers using operationally relevant metrics. By quantifying contributions across multiple dimensions (such as persistent observation, violation time, unique observation capability, and sensor density), the framework supports data-driven decision-making for resource allocation and tasking in space operations.

The results reveal meaningful differences in provider performance across orbital regimes and satellite priorities, highlighting trade-offs between cost and operational effectiveness. This outcome enables decision-makers to strategically select provider combinations that align with mission objectives and budgetary constraints.

Beyond internal decision-making, the framework also serves an external function. The transparent application of these metrics—when shared with providers—creates a positive feedback loop that encourages continuous product improvement and closer alignment with user requirements. In this way, the evaluation process contributes to the maturation of the commercial SSA ecosystem.

Future work should extend the analysis to longer timeframes, incorporate additional sensor types (e.g., space-based sensors), and explore dynamic weighting schemes that reflect evolving mission priorities. Ultimately, this framework lays the foundation for a rigorous, accountable, and mission-aligned approach to integrating commercial data into national SSA architectures.

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6. ACKNOWLEDGMENTS

This research was conducted in part while the first author was affiliated with the Operations Research Center at the United States Military Academy and supported by the U.S. Space Command's Academic Engagement Enterprise. The authors thank Jason Broussard, Scott Daw, Barbara Golf, Derek Ho, Jason Randolph, and Michael Taylor for their thoughtful comments on drafts. Any remaining errors are the authors' alone. The views expressed are those of the authors and do not necessarily reflect the official policy or position of U.S. Space Command, the Department of Defense, or the U.S. Government.

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