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Using AI for Better Space Governance

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Key Points

- Recent developments in applied artificial intelligence (AI) research show that AI-driven tools can reliably characterize satellite behaviour in the near-Earth space environment.
- State- and international-level regulators are well-positioned to use these tools to uphold their responsibilities to promote safe and orderly use of the space domain.
- In the near future, AI could offer opportunities for even richer understanding of international space activities that could inform evidence-based space rulemaking across a variety of categories.
- Before adopting these AI-driven tools, the international space community should become familiar with their limitations and drawbacks, and advocate for changes that help make them more reliable and less likely to cause harm.

Introduction

As the near-Earth satellite population continues to grow, so too will the mountain of available data that describes international activities in outer space. Such a pattern paves the way for insightful analysis, driven by recent developments in AI, that can inform public understanding of how satellite operators behave in the space domain amid an overlapping network of space governance principles and goals. National and international space regulators tasked with administering the safe and orderly use of the space domain are particularly well-positioned to benefit from such advances as both incubators and consumers of AI-derived space data products. Before they turn to AI tools, however, informed members of the international space community — including those empowered to propose and advocate for new rules that govern a more congested space domain — should become familiar with their limitations and drawbacks.

Although there are some rules that incentivize operators to control their satellites in certain ways — geosynchronous (GEO) satellites, for example, must

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station-keep near the orbital positions assigned to them by the International Telecommunication Union (ITU) in order to be protected from harmful interference in the radio-frequency (RF) spectrum — there are none governing how or when operators should exercise their control authority on a day-to-day basis. If satellite trajectories are highways cutting through the near-Earth space environment, there are no rules of the road. Without such guidance, satellite operators have effectively established their own norms of behaviour over decades of operations, independently developing ad hoc definitions of key concepts along the way. Despite a number of efforts in multinational fora to establish agreed-upon definitions of responsible behaviour in space,[1] different operators have different ideas of what it means to be "too far" from a nominal orbit, "too close" to a nearby neighbour or "too risky" for on-orbit collision.

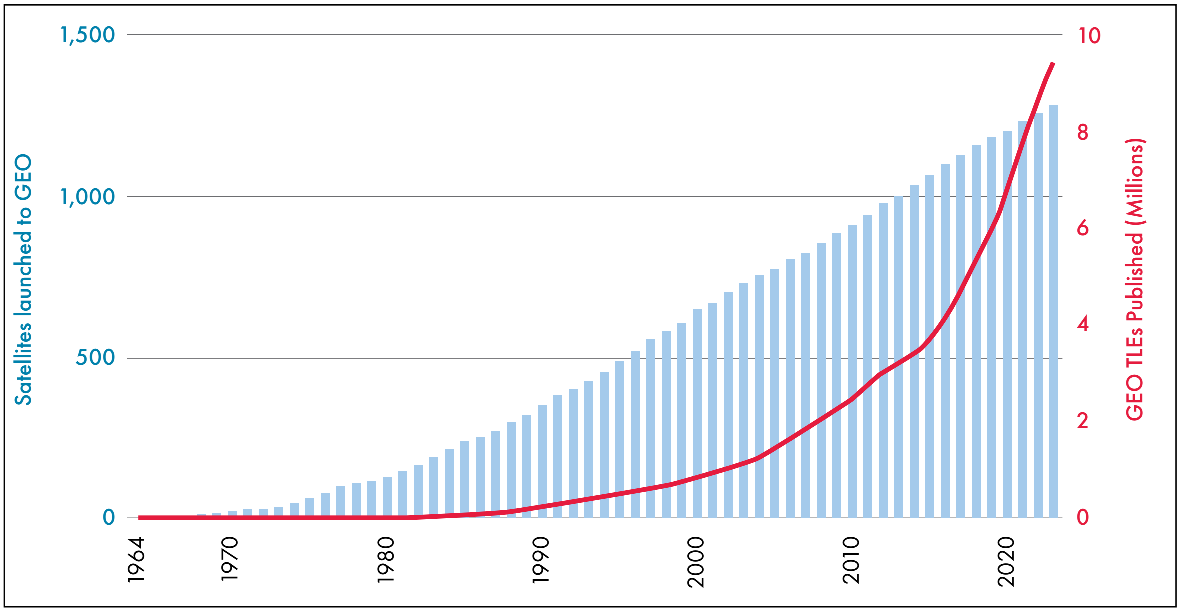
Analysis tools from the AI research community offer attractive opportunities to identify and characterize these operational norms of behaviour buried in both structured space domain awareness (SDA) data and unstructured natural language documentation.[2] Insights could be used as part of a wide variety of space regulatory affairs at both the state and international levels, such as determining whether operators are efficiently making use of their RF assignments, quantifying the degree to which states fail to register their new satellites on the United Nations' space objects registry or studying satellite operators' collision risk tolerances, among many others.

AI-driven space domain analysis tools are likely to be adopted both nationally and internationally in the coming years because regulators already rely on similarly developed statistical space data products

1 *Prevention of an arms race in outer space: reducing space threats through norms, rules and principles of responsible behaviours,* GA Res 98(d), UNGAOR, 76th Sess, UN Doc A/RES/76/231 (2021), online: <https://documents.un.org/doc/undoc/gen/n21/417/21/pdf/n2141721.pdf>.

2 SDA, as defined by the US Space Force (USSF), refers to not just an understanding of space objects' behaviours in physical space, but also other portions of their operating environment, including along the RF spectrum (see www.space-track.org/).

Figure 1: Satellites launched to GEO versus associated number of two-line elements, 1964–2023



Source: Data gathered from www.space-track.org.

Note: While the number of satellites launched to GEO is growing nearly linearly, the number of two-line elements (TLEs) for those same objects is growing exponentially. There are fewer than 10 TLEs in the USSF catalogue that describe the first GEO satellite's first year in orbit. Satellites launched to GEO in 2022, on the other hand, have more than 600 TLEs available in the catalogue, on average, for the calendar year 2023 (Roberts 2024).

to make decisions today.[3] This policy brief previews a number of near-future opportunities stemming from the intersection of AI and space domain analysis, outlines the challenges inherent to using AI for such applications, and recommends steps for national and international space domain regulators to best make use of these new tools in a rapidly changing near-Earth space environment and state of the art.

Opportunities

AI algorithms thrive in data-rich environments. This section describes opportunities for AI-driven space domain analysis using a number of available data sources, including some that are highly structured and others that are completely unstructured.

Using Orbital Elements

The number of active satellites has increased over the course of spaceflight history, but the number of orbital elements published to space object catalogues describing those satellites' orbits has

3 The ITU, for example, uses space object orbital element data from the USSF (a national space data manager) and satellite mission data from Seradata (a commercial space data aggregator) to determine whether GEO satellites meet the requirements described in the ITU Radio Regulations for "bringing into use," after which they receive protections from harmful interference (Alexandre Vallet, chief of Space Services Department, ITU Radiocommunication Bureau, interview with author, August 8, 2023).

increased even more quickly.[4] Historical orbital elements are an example of a structured data set in which key information is stored in the same way over time, enabling a wide array of AI-enabled analysis methods to identify patterns.

Manoeuvre Detection and Characterization

AI algorithms have shown promise for efficiently and reliably detecting satellite manoeuvres from historical orbital elements (Varey et al. 2024; Perovich, Folcik and Jaimes 2022; Roberts and Linares 2022b). Such algorithms could be used to create a historical log of all satellites' past manoeuvres, from which analysts can estimate the degree to which operators allow their satellites to veer from their nominal orbits as part of their station-keeping practices. Currently unavailable in the public domain on a comprehensive scale, this knowledge could directly inform the debate surrounding space governance instruments such as keep-out zones (Acton and MacDonald 2021; Dickey and Wilson 2023). By studying a historical manoeuvre log, analysts can also better understand a satellite operator's risk calculus and even estimate the probability of collision that warrants a manoeuvre. This information can directly inform the evolution of collision risk thresholds already in place by state-level space agencies (National Aeronautics and Space Administration 2020; European Space Agency Space Debris Mitigation Working Group 2023). The same manoeuvre technology that might be used for station keeping and collision avoidance can also be used to more radically change a satellite's mission profile, perhaps to pursue an entirely different orbital trajectory in low-Earth orbit (LEO) or a different position along the geostationary belt in GEO. Detecting these sorts of manoeuvres — which are becoming more common in recent years (Roberts and Linares 2022a) — is paramount for measuring compliance with existing space governance systems such as RF spectrum-sharing agreements at both the state and international levels.

4 Orbital elements are a series of parameters that together can be used to describe a satellite's orbital trajectory and its position within it. In the USSF's space object catalogue, made public on Space-Track.org, orbital elements are encoded in a format known as TLEs (see Figure 1). The process of orbit determination, in which each of the orbital elements within a TLE are derived via measurements of a satellite's position and velocity, requires more than one observation of that object.

Operational Status

AI algorithms deployed on orbital element data can also be used to assess satellites' operational statuses over time. Satellites' operational statuses can be partially deduced from manoeuvre histories — as derelict satellites cannot manoeuvre — and complemented using RF signal emission data sets created by passive observation. Knowledge of how satellites' operational statuses change over time could inform the development of post-mission disposal (PMD) principles. The dates at which satellites become non-operational effectively start the clock on existing PMD rules and guidelines, such as the US Federal Communications Commission's (FCC's) five-year rule and the Inter-Agency Space Debris Coordination Committee's (IADC's) 25-year guideline, in which satellites should de-orbit within five and 25 years of the end of their operational lifetimes, respectively (FCC 2022; IADC 2007).

Pattern of Life Characterization

As space activities become more routine, so too do satellite operations. Most satellites adhere to common patterns of life (PoLs) over the course of their operational lifetimes, which can be characterized in detail using AI-driven tools (Roberts, Solera and Linares 2023; Roberts et al. 2023). Well-documented satellite PoLs offer space governance architects a glimpse into an operational definition for "nominal" operations. Once nominal operations are algorithmically understood, the deviations from those operations may be considered "anomalous" behaviour. For example, an AI algorithm may identify an orbit-raising manoeuvre by a five-year-old LEO satellite as anomalous if that satellite has never previously demonstrated any propulsion capability before. Identifying statistically anomalous behaviour via PoL characterization can help delegations to multinational fora develop more detailed definitions for norms of responsible behaviour, including concrete examples in which historical behaviours may break those norms if they were to happen again.

Using Natural Language

Not all data describing international space activities is as well-structured as orbital element data. This subsection describes a pair of opportunities in which natural language data sources could serve as inputs to near-future concepts for space domain analysis using AI.

Launch Notification

In accordance with federal laws and international agreements, space launch providers must alert civil and commercial aircraft and vessel operators of their launch and re-entry activities via notices to airmen (NOTAMs). But because of the many use cases for NOTAMs, space launch providers do not adhere to standard language structures in their messages. Natural language processing (NLP) — a burgeoning subdiscipline of AI — is well-suited to identify patterns in historical NOTAMs and support algorithms that can predict otherwise poorly documented flight plans. Interrogating the use of notices for Earth-to-space traffic coordination has the potential to make the existing system of notification more efficient and serve as the foundation for new space governance recommendations for space-to-space traffic coordination in orbit.

Mission Purpose

Space operations inspire the publication of thousands of news articles, statements from operators and service providers, and third-party mission assessments. When combined, these resources can serve as an unstructured natural language database describing the purposes of various satellite missions, characterizations of those missions' success and important characteristics of satellites' capabilities. NLP tools could be used to maintain publicly available catalogues that describe satellite missions' purposes, such as that of the Union of Concerned Scientists, or those created and meticulously maintained by independent analysts.[5] Knowing the purpose of satellite missions can directly contribute to the development and assessment of compliance to rules, regulations and guidelines designed to govern only satellites with certain purposes.[6]

Challenges

AI algorithms are vulnerable to prejudices, which often stem from those existing in the data supplied to them. This section describes several examples of how these vulnerabilities may challenge the usefulness of insights gained from AI tools applied to space domain analysis.

Using Orbital Elements

While orbital element data sets are typically well-structured, they struggle with issues of availability and bias that threaten the validity of AI-driven tools trained on them.

Data Availability

Although the USSF space object catalogue is available to the public, most space catalogues are not. The evolution of the global SDA industry has shown growth in both international partnerships and commercial ventures, creating new data sets only available to contributing states and customers, respectively (Borowitz 2022). When orbital element data sets are withheld from the public domain, fewer AI developers have the opportunity to train their algorithms on them, restricting their fidelity. Some databases are more accurate for certain orbital regimes due to the nature of the sensors deployed in the networks that inform them; applying AI algorithms trained on data with more accurate results for one particular class of satellites may lead to misleading results for other classes.

In addition, the USSF database does not publish measurement uncertainties alongside the orbital elements in their catalogue. While the USSF knows that some of its orbital elements are likely to be less accurate than others given their knowledge of how those orbital elements were determined, that information is not passed along to any algorithms trained on the public catalogue. AI-driven space domain analysis trained on data with uncertainty information, such as some privately managed space object catalogues, may lead to more accurate results.

Bias

Because various space object catalogues were created and maintained for different purposes, the priorities with which they track satellites are likely biased. The USSF space object catalogue, for example, includes a greater density of TLEs for Chinese and Russian space objects than they do for other objects, revealing that the US Space Surveillance Network may be tasked to observe those satellites more often than others in the catalogue (Roberts 2024). Worse yet, some space

5 See www.ucsusa.org/resources/satellite-database; McDowell (2020); https://space.skyrocket.de/index.html.

6 Military satellites, for example — those operated with the purpose of national defence — are effectively exempt from some existing regulations such as the ITU's Radio Regulations (ITU 1993, article 48).

objects — those associated with classified US military missions — are redacted from the USSF catalogue, allowing AI algorithms trained on the catalogue to entirely miss their behaviours. Catalogues maintained by other military services may be biased in other ways. Similarly, commercial space object catalogues may be biased to include more orbital elements for satellites of greater interest to their customers. These kinds of biases may lead to serious misrepresentations of the space environment by both AI-driven and traditional space domain analysis tools.

Using Natural Language

Although NLP tools are well known to produce hallucinations — text that conveys information not accurately contained in any of the documents used for training — results from those designed to better understand international space activities are also subject to other issues more unique to spaceflight culture and processes around the world (Ji et al. 2023).

Cultural Differences

While many space activities continue to be shrouded in a culture of secrecy, satellite operators are trending toward more transparency in their operations, regularly publishing high-fidelity orbital elements for their satellites, upcoming planned manoeuvres and details describing their mission profiles. This shift represents a real change in satellite operations, one that takes time and appears differently across different actors. NLP tools that rely on publicly available reporting describing international satellite activities would be trained on starkly imbalanced data. While much information is published about SpaceX's Starlink constellation, for example, much less is written about more recently declassified USSF satellites. These differences may challenge NLP tools designed to characterize underreported space activities; beneficiaries of these tools' insights should combat these challenges by prioritizing tools that cite their sources and can point readers to the documents that informed their characterizations.

Cultural differences from outside the space industry can also affect the nature of information available in publicly available documentation. For example, in some cultures and languages, the difference between success and failure is clear, and thus all missions are either entirely successful or entirely failed. In others, partially successful missions — those in which only a portion of the mission's objectives appear to be met — may be described using laudatory language in public reporting, which could challenge NLP tools tuned to understand the sentiment of natural language in order to report mission outcomes.

Disinformation Propagation

Some actors deliberately publish disinformation about their missions' characteristics. When the CORONA surveillance satellites were first launched in the late 1950s, the US government confirmed incorrect descriptions of the satellites' purpose, saying they were serving a scientific mission under a variety of dummy names (Perry 1973). More recently, in 2013, US officials noted an example in which the Chinese government's stated purpose for a particular space launch was scientific research, but instead followed a ballistic trajectory akin to a high-altitude anti-satellite weapon test (Weeden 2020). These kinds of conflicting reports — which may be noticeable to the seasoned human reader, but not an AI algorithm — are particularly dangerous to NLP tools, especially when newer information becomes available that contradicts older information.

Recommendations

The future in which AI technologies directly contribute to the space domain analysis concepts described in this brief is quickly approaching. To best leverage the insights of these technologies for a better-governed space domain, the international space community should:

- → advocate for comprehensiveness in space object catalogues;
- → incentivize satellite operators to publish more information about their space missions; and
- → demand transparency for how and when AI tools are used by government and intergovernmental agencies.

Make Space Catalogues More Comprehensive

AI models are only as good as the data they are given. Because space object catalogues are likely to be principal data sources for AI-driven space domain analysis tools, it is critical that they are trusted by space domain regulators.

Today's most-cited space object catalogues — those created and maintained by national government agencies from around the world — give users pause because of their well-identified biases, as discussed previously. Although the practice of obscuring space activities stretches back to the earliest days of the first space age, when more than 70 percent of all satellites launched were operated by military services (Harrison et al. 2017), more recent patterns of declassification demonstrate a promising trend toward more transparency in space object catalogues.[7] But that evolution is slow and more can be done today to deepen trust in the catalogue management process.

The international space community should advocate to make existing catalogues more comprehensive by supporting initiatives that make meaningful progress in this regard, including customers paying more for commercial space surveillance data that includes covariance information, legislators endorsing national governments' efforts to establish civilian-run space object catalogues, and satellite operators contributing high-resolution orbital elements to non-governmental organizations' data-sharing platforms.

Ask Operators for More Information about Their Satellites

No one knows more about a satellite than its operator. Regulators should support proposals that increase the richness of the information they receive from operators as part of licence application processes and input that new data into in-house tools to assess compliance with agency rules or publish them to offer AI development opportunities to the broader international space community.

Important data that could be collected and published by regulators includes satellites' operational statuses over time, high-resolution records of past manoeuvres and future plans to adapt orbital profiles. In addition to compliance assessment within regulatory agencies, independent analysts could also use this information to better understand operators' adherence to space sustainability guidelines and predict harmful interference or risk of collision. While already important today, these issues are on track to become yet more critical in a more congested near-Earth space environment.

Although some operators already share detailed information about their satellites publicly in the name of good space stewardship, others will likely need to be mandated to do so. National regulators should consider mechanisms similar to what the ITU calls "administrative due diligence," codified in Resolution 49 of the Radio Regulations, in which member states must submit paperwork describing the satellite systems that will make use of RF assignments before being granted protections from harmful interference.[8]

Be Clear about When AI Is Being Used

As AI-driven space domain analysis tools become commercially available (Erwin 2023), national and international space regulators must be clear about how and when they are adopted into practice. This transparency ensures that satellite operators understand the decision-making processes that authorize their missions and protect their operations, while also helping them to build trust in regulators' execution of authority.

To achieve this clarity, officers at space regulatory agencies such as the FCC and the ITU do not need to become AI specialists, but rather hold their likely commercial developers to the highest standards of transparent software architecture: open-source access to the algorithms' codebase, clear citations for training data sources and detailed descriptions of how the algorithm is updated over time. Without these safeguards, AI-driven tools could systematically misrepresent behaviour, and repeatedly consider the same behaviours as anomalous when they are observed in one operator but nominal when observed in another. In state-level scenarios in which regulatory agencies have enforcement authority — such as when the FCC issues fines to actors that fail to meet certain space sustainability guidelines in the United States — satellite operators must be treated fairly, even when their behaviour is evaluated by AI tools before human analysts (Rainbow 2023).

AI is poised to make dramatic contributions to our understanding of outer space activities in the coming years. With mindful adoption, policy practitioners can harness those contributions to foster a safer and more orderly space environment, ensuring the peaceful and sustainable use of outer space for generations to come.

7 One example of the US military trending toward comprehensiveness in their publication of space object data stems from the declassification of the Geosynchronous Space Situational Awareness Program, which was once completely redacted from the Space-Track.org catalogue (Clark 2014).

8 See www.itu.int/en/ITU-R/space/plans/Pages/Res49.aspx.

Acronyms and Abbreviations

AI	artificial intelligence
FCC	Federal Communications Commission
GEO	geosynchronous orbit
IADC	Inter-Agency Space Debris Coordination Committee
ITU	International Telecommunication Union
LEO	low-Earth orbit
NLP	natural language processing
NOTAM	notice to airmen
PMD	post-mission disposal
PoLs	patterns of life
RF	radio frequency
SDA	space domain awareness
TLE	two-line element
USSF	United States Space Force

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