The Space Object Ontology

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***Abstract*—Achieving space domain awareness requires the identification, characterization, and tracking of space objects. Storing and leveraging associated space object data for purposes such as hostile threat assessment, object identification, and collision prediction and avoidance present further challenges. Space objects are characterized according to a variety of parameters including their identifiers, design specifications, components, subsystems, capabilities, vulnerabilities, origins, missions, orbital elements, patterns of life, processes, operational statuses, and associated persons, organizations, or nations. The Space Object Ontology provides a consensus-based realist framework for formulating such characterizations in a computable fashion. Space object data are aligned with classes and relations in the Space Object Ontology and stored in a dynamically updated Resource Description Framework triple store, which can be queried to support space domain awareness and the needs of spacecraft operators. This paper presents the core of the Space Object Ontology, discusses its advantages over other approaches to space object classification, and demonstrates its ability to combine diverse sets of data from multiple sources within an expandable framework. Finally, we show how the ontology provides benefits for enhancing and maintaining long-term space domain awareness.**

Keywords—Basic Formal Ontology; Common Core Ontology; space domain awareness; space situational awareness; resident space object; Resource Description Framework; realist ontology; data integration; data mining

I. Introduction

Space domain awareness (SDA) – also called space situational awareness (SSA) – is, roughly, knowledge of the objects located in and events occurring in outer space. Specific definitions of space domain awareness tend to vary based on the interests of the defining organization [1-4]. For our purposes, space domain awareness is understood as broadly as possible. Maintaining SDA requires continuously updated knowledge of the number, types, identities, locations, and trajectories of both natural and artificial space objects including functional spacecraft, orbital debris, asteroids, and meteoroids. It would also require detailed characterization of the composition, functionality, behavior, and missions of such objects, as well as knowledge of the space environment including space weather, planetary atmospheres, and magnetospheres. Additionally, knowledge of ground-based space systems and atmospheric weather is needed due to their importance for observing, controlling, or potentially interfering with space operations.

SDA enables the sort of accurate prediction of space object behavior and space events that is critical for the identification of threats and the protection and continued operation of space assets. This is especially important as the quantity of Earth-orbiting space objects continues to grow due to increases in both the number of active and defunct spacecraft as well as orbital debris created largely by intentional antisatellite testing activities and accidental explosions or collisions. Avoiding accidental space object collisions is a major motivation for developing SDA capabilities. Building and launching spacecraft involves a large financial investment and months to years to complete, loss of service can affect millions of users, and resulting debris increase the risk to future missions. The threat of collision is significantly increased by the limits on those portions of space that are best suited for space operations. This results in the clustering of spacecraft and orbital debris in the most operationally valuable regions of space, including locations of geostationary orbits.

The Space Object Ontology (SOO) is designed to facilitate the attainment of SDA by enabling enhanced characterization of space objects, integrating multisource datasets to overcome data silo impediments, and enabling more robust entity tracking. The SOO is a domain ontology that represents objects located in outer space, the processes in which these objects participate, the outer space environment, and the entities that interact with space objects, such as ground-based sensors, launch sites, and launch vehicles. The SOO is built as an extension of the Basic Formal Ontology (BFO) and the suite of Common Core Ontologies (CCO), which respectively form its upper- and mid-levels.

The SOO currently contains more than 700 classes that represent entities of a wide range of different types, including: natural and artificial resident space objects (RSOs); spacecraft design specifications; spacecraft parts including subsystems, modules, and sensors; spacecraft functions, capabilities, and vulnerabilities; spacecraft processes including orbits, orbital maneuvers, missions, and launches; temporal intervals; spatial regions and frames of reference; space object identifiers, descriptions, measurements, and orbital elements; as well as the entities involved in the construction, launch, operation, or ownership of spacecraft. Space object data are aligned with classes and relations in the SOO and stored in a dynamically

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updated Resource Description Framework (RDF) triple store, which can be queried to support SDA and the needs of spacecraft operators.

This paper presents the core of the SOO, discusses advantages it provides over existing approaches to space object classification, and demonstrates its ability to combine diverse sets of data from multiple sources within its expandable framework. We conclude by highlighting benefits the SOO provides for enhancing and maintaining long-term SDA.

II. METHODOLOGY

Individual ontologies are representations of domains of interest. When taken together with other ontologies that represent neighboring domains of interest, ontologies form an information ecosystem. To ensure interoperability and avoid creating data silos, the design of the ontology must relate its content to the content of other ontologies within the entire ecosystem. The SOO achieves cross-domain integration by drawing on BFO, an upper-level ontology that classifies the fundamental entities, properties, modes, and aspects of the world, and defines how they are related to one another [5]. The SOO expands on the benefits of the BFO by using the suite of Common Core Ontologies to provide its mid-level structure. The CCO represents entities that are common to many domains in much greater detail than the BFO. The use of common higher-level ontology structures facilitates data integration because every ontology that shares the same upper levels re-uses their patterns of expression in a consistent manner.

Prior efforts to create an ontology, taxonomy, or other classification system of space objects have neglected the principle of consistent development because they have been designed to address specific, local application needs. The authors of [6] utilized a Linnaean approach to develop a taxonomy of resident space objects (RSOs) with classification based on a taxonomy tied to the somewhat idiosyncratic requirements of a specific application. While it is true that a well-formulated taxonomy is an important part of an ontology, the taxonomy derived there offers little opportunity for reuse in general SDA applications. [7] offers a taxonomy that specifies properties and attributes of RSO classes, but fails to account for the relationships between the objects and attributes. A properly built ontology should however provide not only a taxonomy of types of entities but also a system of logically defined relations between these types which enables the ontology to be used to support reasoning over associated data.

A well-constructed ontology will be based not on a specific data source but rather on the consensus scientific understanding of the represented entities. In this way, the result can be used to annotate different bodies of data about these entities in ways which will aid both discovery and integration of heterogeneous data. To be effective, such an ontology should not merely provide a common vocabulary of terms to describe types and properties of objects but also define the formal relationships between the elements of the physical systems involved in a way that can be accessed computationally and allow analytics to be efficiently and effectively executed.

The SOO is built in adherence with established best practices in ontology development, such as those provided by the Open Biomedical Ontologies (OBO) Foundry [8]. As such, the SOO is committed to creating a consensus-based realist representation of the world, reusing existing ontologies such as the BFO and the CCO suite, and promoting interoperability and data integration. There are currently more than 700 classes represented in the SOO. Each term is identified using an International Resource Identifier (IRI) and has a textual definition and label. The majority of the terms also have logical definitions that enhance their representation by connecting them to other entities through the relations. Sources are provided for definitions when appropriate and common alternative term names are listed.

Whenever possible, names of entities in the ontology match the standard terminology used by domain experts. This is not always possible, however, due to either the use of multiple terms for the same entity or the use of ambiguous terminology. For example, 'orbit' is ambiguous between the process of orbiting, the path that an orbiting object traverses, and a single revolution around a central body. When this occurs, terminology is chosen based on the criteria of ontological accuracy, minimal ambiguity, and proximity to common usage. When multiple names are commonly used for the same entity (e.g. NORAD ID, NORAD catalog number, satellite catalog number, SATCAT, catalog number, USSPACECOM object number, NASA catalog number, etc.), one name is selected as the primary and the others are listed as alternative terms for that entity by using annotation properties.

A properly constructed ontology provides many benefits. The ontology provides a hierarchy of clearly defined terms that represent classes, relations, individuals, or data types. Each term is uniquely identified by an IRI that permits unambiguous application and reuse. Whenever possible, terms are reused from existing ontologies to reduce the duplication of efforts and creation of data silos caused by non-conformant representations. In addition to textual definitions, terms are defined using computer-readable logical axioms that relate classes to one another through the use of object properties that provide an added layer of representation. Domain ontologies such as the SOO are built through both a top-down and a bottom-up process. The top-down approach involves examining the domain from a wide perspective and then building down from higher-level ontologies such as BFO and the CCO that represent the most general terms. The bottom-up approach is driven by a detailed examination of the domain and the types of available data.

A well-formulated ontology provides an efficient means to organize information. As such, an ontology readily supports the development of information objects and object-based production (OBP). With OBP, information gain increases because of the inherent benefits associated with correct tagging, sharing, and alignment of multi-intelligence data sources. The SOO has been designed with OBP in mind, and in particular with the goal of supporting SDA.

Once sufficiently developed, ontologies are used to annotate and map data. These mappings are used to generate triples that are combined in a dynamically updated triple store

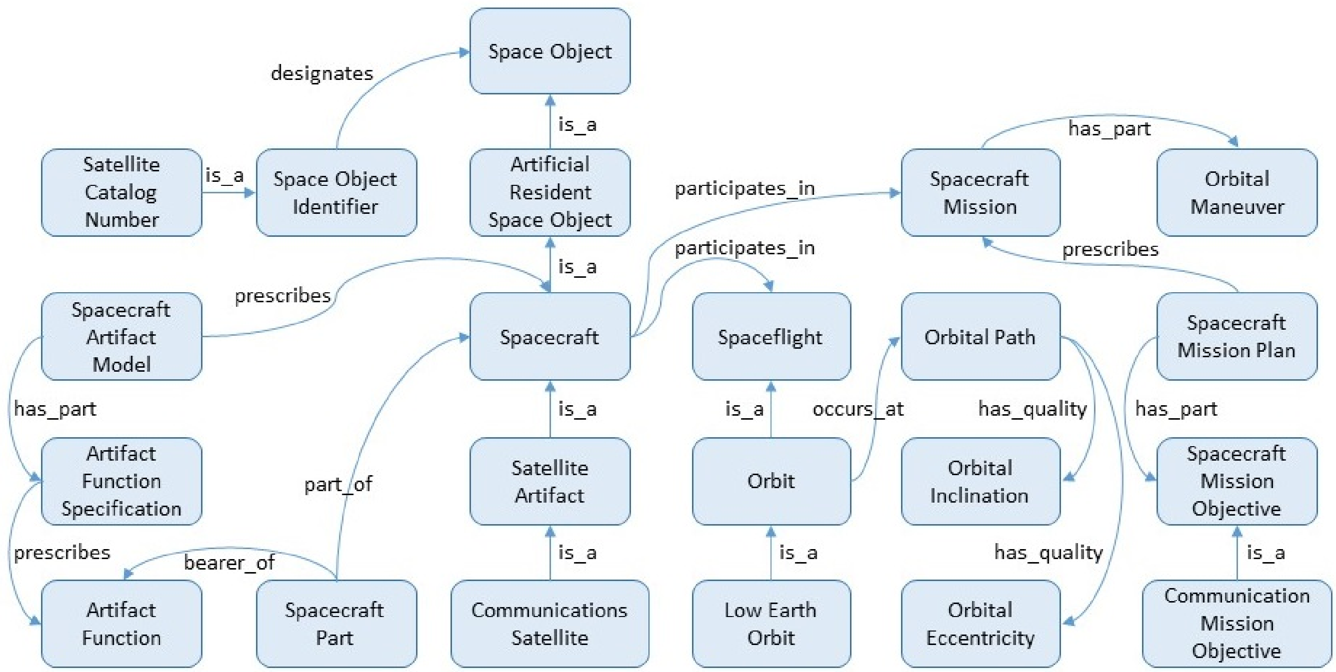

Fig. 1. An overview of selected central classes (blue nodes) in the Space Object Ontology and relations (labeled links) that typically hold between instances of these classes. Note that not every relation holds at the class level (e.g. not every Spacecraft is an Artificial RSO or participates in some Spaceflight), but is included here for illustrative purposes.

using a standardized format such as the Resource Description Framework (RDF) [9]. These triples can be queried using a language such as SPARQL to update and retrieve data at any level of specificity in a flexible and customizable manner [10]. Ontologies are continually enhanced and revised as scientific understanding of the domain advances and new needs are identified. Properly designed ontologies have a significant advantage over a relational database approach in that ontologies can be modified and built upon without breaking the system or requiring complicated specialized mappings to maintain functionality.

III. Core Terminology

Before discussing specific examples that illustrate how the SOO represents complex information about space objects, it is necessary to provide an overview of the ontology's core terminology. The SOO includes subtypes of nearly every basic type of entity represented in the BFO and leverages all of the CCO's mid-level ontologies. Many of the core classes in the SOO are presented in Fig. 1.

A. Space Objects and Spacecraft

Although 'Space Object' is the eponymous class of the Space Object Ontology, it does not represent an ontologically ideal class. Whenever possible, ontology classes should represent fundamental types of entities; classes are not merely names used to group sets of entities. 'Space Object' is an important *classification* of entities for SDA purposes, but it does not pick out a well-formed ontological *type* of entity. This is because a space object is, roughly, an object located in outer space; hence, a spacecraft is only a space object when it is in outer space – it is not a space object before it enters or after it leaves outer space. In other words, 'Space Object' is a phase sortal – a term, such as 'child' or 'adolescent', that only applies to an entity during a temporal period or phase of its existence [11].

Despite these considerations, the term 'Space Object' is too important to the domain to omit from the SOO. The solution is to include it as a defined class, which represents the group of objects that satisfy its logical definition: (object and (located_in some 'Region of Outer Space')). This solution can be applied as needed on a case-by-case basis to capture additional non-class groupings of entities that are especially useful to have a named class for (as opposed to only existing as an anonymous class, which are unnamed groups of entities).

The defined class 'Space Object' has the following subtypes: 'Central Body', 'Resident Space Object', and 'Space Debris Object'. Each of these is also a defined class. 'Central Body' is defined as a space object that bears a central body role. 'Resident Space Object' is defined as a space object that orbits around another space object. According to this representation, RSOs are defined and grouped based on which space object they are residents of. For example, the planets are RSOs of the Sun and most orbital debris objects are RSOs of the Earth. This is useful for classifying orbits and providing a context for their parameters, such as planes of reference and altitude or synchronicity classifications. RSOs are further subtyped into 'Artificial RSO', 'Natural RSO', and 'Near Earth Object', which are respectively defined based on whether the space object is man-made or not and whether its orbital path brings it into proximity to the Earth's orbit.

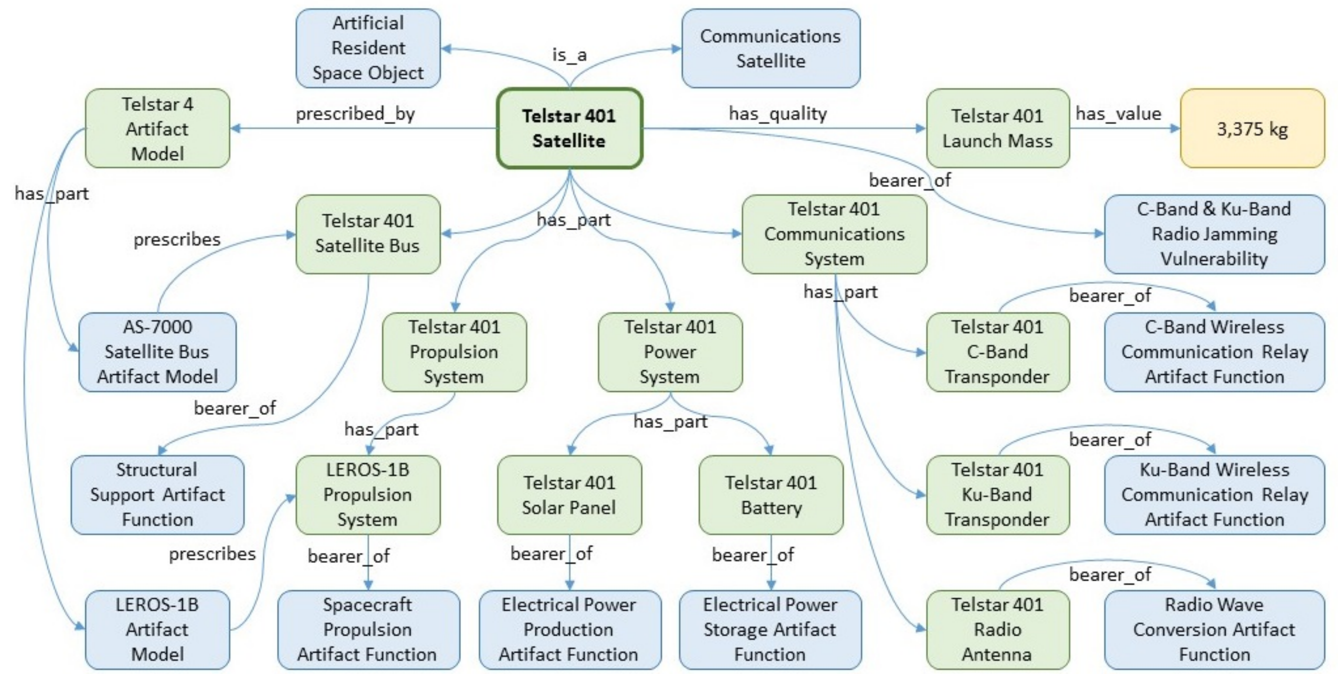

Fig. 2. A partial SOO representation of components of the Telstar 401 satellite along with their design specifications and functions. Blue nodes represent classes in the Space Object Ontology. Green nodes represent instances of SOO classes. Yellow nodes represent values of an instance. Labeled links represent relations that hold between the linked nodes.

'Space Debris Object' includes 'Orbital Debris Object' as an asserted subtype. In making this distinction, we provide both a broader and a narrower definition of space debris. According to the SOO, 'Space Debris Object' includes both natural space objects of a sufficiently small size – such as meteoroids, micrometeoroids, and space dust particles – and man-made space objects that are no longer functional or do not serve a useful purpose. Only man-made space debris objects are included in the set of instances of 'Orbital Debris Object'. While this distinction is not typically made [12-13], we are not alone in doing so [14-15]. Furthermore, this simple distinction is useful for classifying all entities that are either too small to be tracked easily or which may pose unique hazards such as the possibility of an explosion due to unspent fuel or power cells.

Space domain experts commonly use the term 'satellite' to refer to space objects and, in particular, to artificial satellites; however, we prefer to use 'Spacecraft' in the SOO because it is more inclusive and does not share the ambiguity that is associated with 'satellite'. 'Spacecraft' is defined as a vehicle that is designed for spaceflight, i.e. to travel into or through outer space. 'Satellite Artifact' is a type of 'Spacecraft' that is specifically designed to remain in orbit around some central body. Note that, contrary to the illustrative liberty taken in Fig. 1, spacecraft is not asserted to be a subtype of space object in the SOO. Despite the best designs and intentions, not every spacecraft will enter outer space, but they are still instances of spacecraft.

Spacecraft are complex artifacts that are composed of a variety of materials, parts, and systems. The SOO includes representations of many types of artifacts that are often part of a spacecraft. These include: spacecraft subsystems, such as communications, power, and propulsion systems; spacecraft parts, such as Whipple shields and multilayer insulation; communications instruments, such as transponders and antennas; sensors, such as accelerometers, spectrometers, and star trackers; as well as spacecraft modules and other important components, such as solar arrays and batteries. As will be discussed in section C below, knowledge of a spacecraft's materials, parts, and systems provides significant advantages in characterizing space objects and assessing their capabilities or vulnerabilities. Some of Telstar 401's parts and subparts are represented in Fig. 2.

B. *Spaceflight, Orbits, and Patterns of Life*

Many processes occur throughout the life-cycle of a space object. Artificial RSOs must be designed, constructed, and launched before being inserted into orbit where they can carry out their mission plan by performing or participating in a number of processes until they either lose functionality or initiate their end-of-life sequences. Natural RSOs and orbital debris participate in many of the same processes that their functional counterparts do during spaceflight. Some of the processes and sub-processes that Telstar 401 participates in are represented in Fig. 3.

'Spaceflight' is defined as a flight process in which an object travels into or through outer space. As mentioned above, 'orbit' is often used ambiguously outside of the SOO and can refer to either the process, the path, or a single revolution. The SOO prefers the processual account and asserts orbit to be a subtype of spaceflight. The associated path is named 'Orbital Path' and is a subtype of three-dimensional spatial region. A

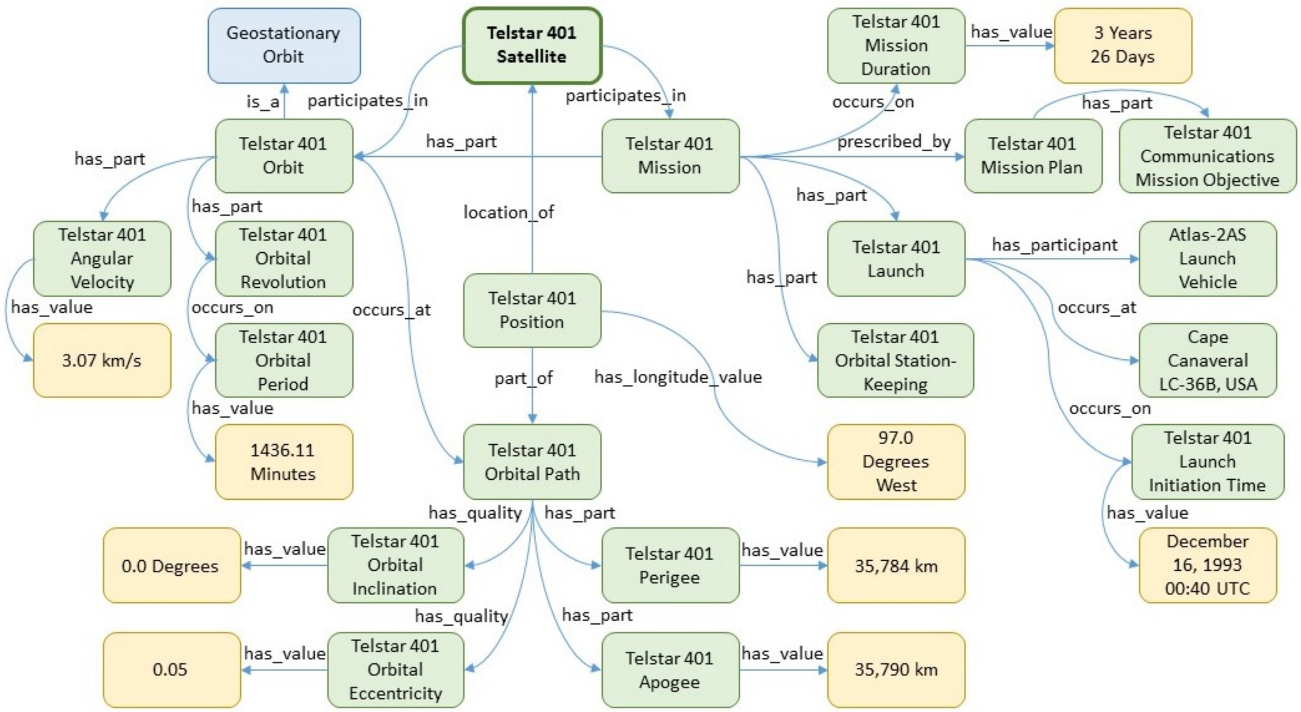

Fig. 3. A SOO representation of some processes the Telstar 401 satellite participated in along with their times and locations.

single revolution around a central body is named 'Orbital Revolution' and is a subtype of fiat process part.

Representing subtypes of Orbit requires further discretion since multiple parameters can be used to drive classification including: central body, altitude, inclination, eccentricity, synchronicity, and relative direction of travel. None of these parameters is entirely independent of all of the others, nor do their dependencies lend themselves to a single neatly-ordered classification hierarchy. Hence, no single representation of orbits is *a priori* superior to all other representations. Rather, the needs of a given application will dictate which representation of orbits is preferred. Since artificial RSOs are almost exclusively in orbit around the Earth, SDA is concerned primarily with space objects located near the Earth; therefore, the SOO focuses on a centric and, in particular, a geocentric classification of orbits. This approach lends itself well to the further classification of orbits based on altitude (e.g. low, medium, geosynchronous, and high Earth orbits), but becomes more complex as parameters are added that cut across the altitude-based boundaries of LEO, MEO, GSO, and HEO.

Despite the necessity of choosing a particular hierarchical representation of orbits, the SOO is not intended to support a single application and is therefore designed to provide the means of representing orbits according to multiple orbital parameters. Defined classes, such as 'Eccentricity Closed Orbit', 'Inclination Closed Orbit', and 'Synchronicity Closed Orbit', are used to provide groupings based on specific orbital parameters. While it is poor practice to build an ontology with asserted multiple parentage (i.e. when an entity is asserted to be an immediate subtype of more than one entity), it is acceptable to employ limited use of defined classes that support an inferred multiple parentage hierarchy. An inferred hierarchy is generated through the use of a reasoner that uses the logical axioms of an ontology to identify errors and to group entities based on their logical definitions. For example, the class 'Geostationary Orbit' or 'GEO' for short is asserted to be a subtype of 'Geosynchronous Orbit', but a reasoner will infer that it is also a subtype of 'Circular Orbit' and of 'Synchronous Orbit'. In this way, the SOO provides a multifaceted representation that is able to integrate and support applications that classify orbits based on different parameters. Most applications will only make use of a portion of the SOO. A significant advantage of the SOO is its ability to bring together otherwise disparate efforts and perspectives using a common vocabulary that makes the combination of data easier and more accurate.

Orbital maneuvers and other processes that space objects participate in comprise another important area represented in the SOO. For example, all space objects experience acceleration, angular momentum, rotational motion, translational motion, and radiation processes. Active artificial RSOs also engage in one or more missions that typically involve telemetry, spacecraft stabilization, observations, radio communications, or orbital maneuvers. The SOO represents these and many other processes in order to support detailed characterizations of the history of each space object's behavior.

Given a sufficiently comprehensive representation of the processes space objects participate in, it is possible to develop representations of more complex space object behavior. In addition to enabling the representation of a particular space object's entire processual history, general patterns of life – also called patterns of behavior – can be developed. Patterns of life can be leveraged to assist in the identification, or at least classification, of a space object whose behavior fits a specific pattern. More commonly, however, patterns of life will be used to identify when an anomaly occurs in a known space object's behavior.

For example, if a spacecraft does not perform a regular orbital maneuver at the expected time, its operators can be alerted to investigate whether the spacecraft is functioning properly. Alternatively, if a space object performs a maneuver that does not match its pattern of life, an alert can be generated to investigate whether the space object was properly classified and whether this aberrant behavior is indicative of a threat to other space assets. A simple case is when a space object that is classified as orbital debris performs a maneuver. This is a clear deviation from even the most general orbital debris pattern of life, and it warrants immediate investigation to reclassify the space object. Hence, the richness of the representations of space objects in the SOO facilitates enhanced SDA by providing more detailed classifications of space objects and their behavior, which can be used for purposes such as automated threat and anomaly detection.

C. Models, Mission Plans, Capabilities, and Vulnerabilities

It is important to distinguish between what something is supposed to be like and how it actually is. The representation of plans and artifact models, which are both subtypes of 'Directive Information Content Entity' in the CCO, enable this distinction. A plan prescribes or specifies a set of actions that should be performed in order to achieve the plan's objective(s). Hence 'Spacecraft Mission Plan' is a subtype of plan and consists of at least one 'Spacecraft Mission Objective' plus the recommended means of achieving that objective. Of course, in practice, things rarely go as planned. Nonetheless, it is valuable to be able to identify when a specific spacecraft diverges from its prescribed mission as well as when a spacecraft achieves its objective. The SOO enables comparison of the representation of a spacecraft's mission plan with that of its actual processes. A partial representation of Telstar 401's mission plan is shown in Fig. 3.

The class 'Artifact Model' does the same thing for spacecraft and other artifacts as 'Plan' does for spacecraft missions. An artifact model prescribes a common set of functions and qualities that should inhere in the set of instances of the specified artifact type. Artifact models typically include specifications of which entities should be a part of the artifact, what materials the parts should be made of, how the parts should be arranged, as well as what qualities and functions the resulting artifact should have. Specified qualities may include the total mass and spatial dimensions of the artifact once constructed. Specification of artifact functions is particularly interesting for the purposes of the SOO. By specifying which functions a spacecraft or one of its parts is supposed to have, it is possible to identify the capabilities of a particular spacecraft based on knowledge of either the type of spacecraft or its parts. Spacecraft capabilities include: communications via specified frequencies, attitude control, power production and storage, heating or cooling, imaging or observation, and propulsion. Fig. 2 shows representations of some of the functions that inhere in parts of Telstar 401.

In addition to capabilities, the SOO represents spacecraft vulnerabilities. Since an object's vulnerabilities are typically dependent on its capabilities and general construction, it is possible to identify a spacecraft's vulnerabilities based on knowledge of its capabilities and components. For example, a spacecraft that communicates on the Ku band is probably vulnerable to Ku band jamming or spoofing (see Fig. 2); however, a spacecraft with no solar panels or optical sensors is not vulnerable to either dazzling or eclipsing. In this way, the SOO supports SDA by providing enhanced characterization of space object capabilities and vulnerabilities, which is useful for the identification and assessment of threats from negative events or potential aggressors in space.

D. Spatial and Temporal Regions

Knowing what a particular space object is, what it is doing or is supposed to do, and what it can or cannot do are all critical to SDA; however, this information has little value unless it is understood in the context of precise times and locations. For example, even though spacecraft A has the capacity to render spacecraft B inoperable, A is not a threat to B unless A is on or could maneuver to be on an orbital path that would bring it sufficiently near to B to cause B harm. Following the BFO, the SOO includes representations of spatial and temporal regions that can be mapped to data about space objects, which can then be used to track where a space object is at what time.

Temporal regions can be either zero- or one-dimensional. Zero-dimensional temporal regions have no duration and are more commonly called "temporal instants". An example is an astronomical epoch, which is a temporal instant used as a reference point for a time-varying astronomical quantity such as an orbital element. One-dimensional temporal regions have a beginning and an end and are measured using standard temporal units. Examples include orbital period, sidereal day, and spacecraft mission duration.

Spatial regions can be either zero-, one-, two-, or three-dimensional. These regions correspond to geometric points, lines, planes, and volumes, respectively. Examples of zero-dimensional spatial regions include orbital nodes, apses, barycenters, and Lagrange points. One-dimensional spatial regions include axes, ground tracks, and great circles. Two-dimensional spatial regions include planes of reference such as an orbital plane or an equatorial plane. Finally, three-dimensional spatial regions include orbital paths, three-dimensional positions, hill spheres, and magnetospheres.

When combined with the relevant coordinate system, which is a subtype of 'Descriptive Information Content Entity', these temporal and spatial entities enable the representation of data according to the times and locations of the entities they describe. More generally, space objects and their functions, qualities, and measurements are time-stamped by their connection with processes. Every process occurs at a given spatial region and occurs on a given temporal region. This approach permits a rich representation of what occurs, when it occurs, and where it occurs. For example, Fig. 3 shows the measured values of Telstar 401's mission duration and average orbital period. Fig. 4 shows when Telstar 401's mission began

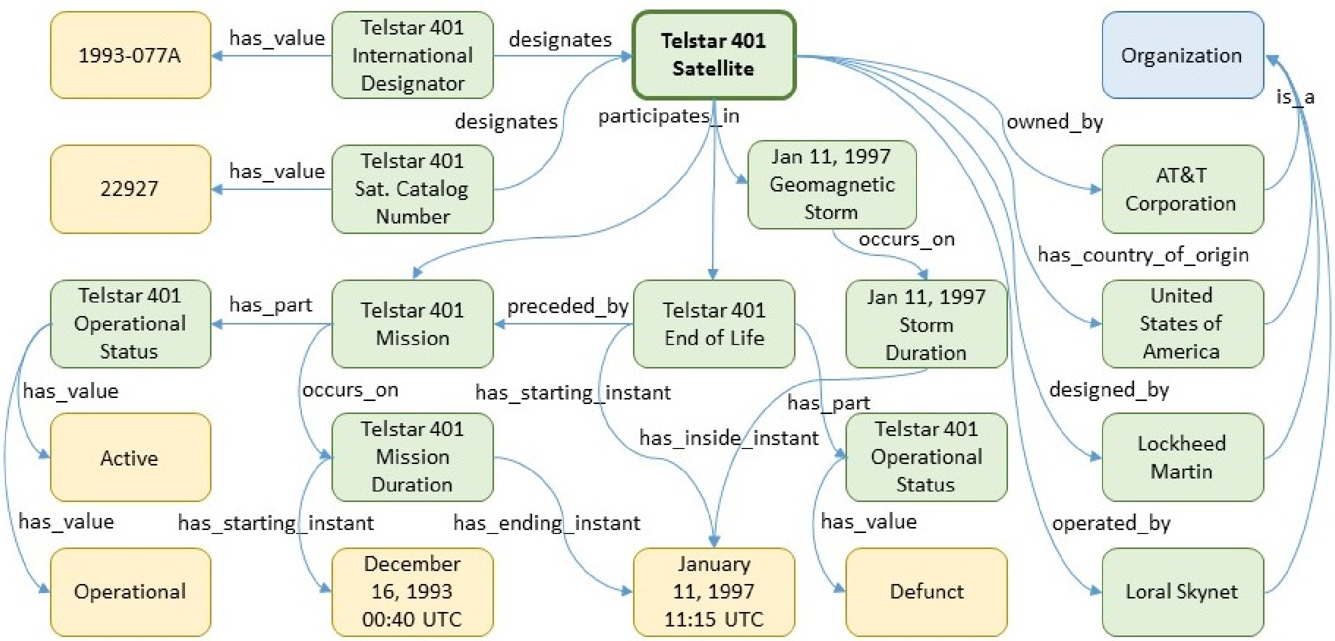

Fig. 4. A SOO representation of identifiers for Telstar 401, organizations involved with it, and the change in the satellite's operational status after encountering a geomagnetic storm.

and ended. These values can be used to time-stamp when Telstar 401's operational status changed from active and operational to defunct.

E. Orbital Elements and Other Space Object Data

In addition to representing where a space object is and what it is doing at a specific time, it is critical to SDA to be able to accurately predict where space objects will be at future times. This is accomplished through the calculation and publication of orbital elements, which are most commonly shared in the form of two-line element sets (TLEs). Orbital elements are parameters – such as orbital eccentricity, orbital inclination, semi-major axis, argument of periapsis, mean anomaly, and longitude of the ascending node – that can be jointly used to uniquely identify the orbit of a space object. With the exception of semi-major axis, which is a one-dimensional spatial region, these orbital elements are represented in the SOO as qualities that relate two entities together. For example, orbital inclination is a relational quality that consists of the angle between a space object's orbital plane and the designated plane of reference – typically either the equatorial plane or the ecliptic plane. Fig. 3 includes values for the orbital inclination and eccentricity of Telstar 401, which are qualities of Telstar 401's orbital path within its orbital plane.

Many other types of information are useful in the pursuit of SDA and are therefore represented in the SOO. Identifiers for space objects, including international designator and satellite catalog number (see Fig. 4), uniquely designate space objects. There are many measurements of features of space objects or their orbits represented in the SOO. For example, size, shape, and mass are qualities of a space object (see Fig. 2). Mean motion, delta-v, and angular velocity are measurements of process profiles, which are parts of processes (see Fig. 3). Spatial regions, such as the altitude of an orbit's perigee and apogee as well as a space object's position in geostationary orbit relative to the surface of the Earth in terms of longitude can also be measured (see Fig. 3).

Finally, many non-space objects are relevant to SDA. With the exception of space-based launches such as the release of microsatellites from the International Space Station, launch sites and launch vehicles are currently the only means for putting spacecraft into orbit. Given that each launch has the potential to introduce new capabilities or threats to the space environment and that international agreements place responsibility for damages caused by space objects on the nation or nations involved in their launch, it is important to know what was launched from where and by whom (see Fig. 3). Ground-based sensors – including radar arrays, optical telescopes, and communications relays – play an important part in identifying, tracking, characterizing, and communicating with space objects. As such, they are an essential component in attaining SDA and are therefore represented in the SOO. Building, launching, and operating spacecraft is a complex endeavor that typically involves many organizations or nations. The SOO includes relations to represent the nature of these entities' involvement with a given spacecraft. For example, the Telstar 401 was designed and built by Lockheed Martin along with its subcontractors, owned by AT&T Corporation, operated by Loral Skynet, and launched from the United States of America (see Fig. 4).

IV. Data Integration

The Space Object Ontology offers many benefits over existing efforts, but perhaps its biggest advantage is its ability to align and integrate data from multiple databases or other sources. Ontologies help to mitigate and break down boundaries that typically lead to the creation of data silos that impose significant limitations on data sharing and fusion. New data can be directly annotated using the SOO while existing data can be aligned to classes and relations in the SOO using mappings. This effectively translates all of the space object data into a common language. Data can then be stored in a dynamically updated Resource Description Framework (RDF) triple store, which can be queried to support SDA and the needs of spacecraft operators.

The SOO has proven capable of integrating data from multiple sources that describe a variety of space object features. For example, TLE data, ephemeris data, maneuvers data, the Union of Concerned Scientists (UCS) satellite database [16], as well as data about the components of particular spacecraft have been successfully mapped and integrated into a single RDF triple store. The resulting triple store can be queried using SPARQL to return interesting cross-sections of the digested information. Example queries include: return all spacecraft in LEO with an orbital inclination greater than 60 and the capability to communicate on either Ku or C bands; return all spacecraft with an Earth observation mission that were launched from France or are owned, operated, or built by an organization whose headquarters are located in France; and identify all vulnerabilities for a given spacecraft then return all spacecraft with similar orbital parameters that are capable of exploiting these vulnerabilities.

V. Conclusion

Achieving space domain awareness requires a combination of sufficient information about space objects, space events, and related entities along with the means to efficiently process, understand, and leverage this data. The Space Object Ontology has been designed to provide a better structure for satisfying the second requirement. Although the SOO requires further development to reach its full potential and, even once completed, will only provide a partial solution to the second requirement, this paper has demonstrated some of its many benefits.

In particular, the SOO provides the means to characterize space objects, space events, and related entities in much greater detail than other existing efforts. This enhanced characterization enables better identification, classification, and analysis of space objects. Patterns of life are useful in identifying anomalies in space object behavior, which can support automated alerts to investigate potential threats, spacecraft failures, or the need for space object reclassification. The representation of spacecraft capabilities and vulnerabilities based on spacecraft artifact models and parts is a novel contribution of the SOO that enables semi-automated threat assessments for individual spacecraft. Well-designed ontologies in general, and the SOO in particular, have already proven to provide effective means of combining and leveraging data from disparate sources while avoiding or resolving data silo issues even when a variety of data storage formats are used. Finally, the comprehensive domain coverage provided by the SOO along with its flexibility to represent data at multiple levels of detail and ability to be continually expanded with minimal disruption to the existing structure make the Space Object Ontology a valuable asset in the pursuit of improved space domain awareness.

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