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PRELIMINARIES OF A SPACE SITUATIONAL AWARENESS ONTOLOGY

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Space situational awareness (SSA) is vital for international safety and security, and the future of space travel. By improving SSA data-sharing we improve global SSA. Computational ontology should provide one means toward that goal. This paper develops the ontology of the SSA domain and takes steps in the creation of a Space Situational Awareness Ontology. It outlines objectives, requirements and desiderata; and describes the SSA domain and discipline of ontology. The purposes of the SSA ontology are to explore the potential for ontology development and engineering to (i) represent SSA data, general knowledge, and domain objects, (ii) clearly annotate and express the meaning of that orbital, near-earth and deep-space data, and (iii) foster SSA data sharing among SSA actors and space object catalogs. By improving global SSA via actionable data- and knowledge-exchange, we can achieve the broader goals (and motivations) of (iv) advancing our capacity for planetary defense from near- or deep-space objects, and (v) improving spaceflight safety for future generations.

INTRODUCTION

Space situational awareness (SSA) is vital for international safety and security. Of paramount importance is the early detection of potential hazards to astronauts, space-borne assets, and our terrestrial home. Improving the state of SSA is a global necessity, one that requires international cooperation, ever-advancing sensor networks, and analyzing and sharing SSA data. Achieving an ideal state of SSA is to achieve actionable, real-time, predictive awareness of the space environment. To move toward such a state, we need to improve our space data-sharing capabilities. This paper focuses on one approach to achieving this: ontology development.

Ontology is the general study of reality, of any domain of interest. It is the study of the sorts of objects and their relationships in a given domain. Formal methods and ontological categories in this philosophical discipline are often applied to computer and information science. The products are *computational ontologies*, computable artifacts representing the individuals, kinds and relations of a domain. They are formal theories representing domain objects and expressing domain knowledge in a computable format. These artifacts are used, in part, to annotate data, and foster data-sharing, interoperability, and communicate a shared conceptualization. Computational *on-*

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tology development and engineering, then, is the process by which these ontologies are designed, developed and implemented.

In what follows, preliminaries of a Space Situational Awareness Ontology (SSAO) are presented. The goals of this ontology are twofold. First, to formally represent the SSA domain in a scientifically accurate manner: its objects, the space environment, how they interact, the patterns thereof, and how all these entities can (if at all) be categorized. The second goal is to improve global SSA by fostering data- and knowledge-sharing between SSA communities. An assumption of this paper, then, is that SSA data-sharing will, indeed, improve SSA, i.e., it will improve space safety, and our capacity for planetary defense from natural space-borne hazards. The intended use of the ontological system is for peaceful applications in the space domain, such as preventing and minimizing orbital debris and satellite collisions; and increasing awareness of potentially hazardous asteroids and other natural bodies. It therefore stands to contribute to safe spaceflight navigation.

There is little[*] ontology development efforts in the SSA or broader space environment domain as compared to other disciplines. In this respect, this paper offers novel concepts. This paper broadens the domain of, but follows ideas introduced in Rovetto (2015)[1], which presented a project concept conceived with the discovery that the orbital debris problem may benefit from more data exchange and integration[†]. The overall idea is motivated from a passion and intellectual fascination for astronautics and astrodynamics, and a desire to help ensure safe spaceflight by, in part, solving the orbital debris problem. Ontology development is a research field that may improve SSA, and thereby help prevent and solve space domain problems.

If we are to achieve real-time responses to rapidly changing orbital events and potential space environment threats, SSA data must be *dynamically* updated and available in real-time. I therefore state this caveat with respect to exploring the research topic of ontology engineering for the SSA domain. Given the current state of the art in computing, there is the possibility that ontologies may slow computational processes when reasoning over large data-sets in real time[‡]. Ontologies should, therefore, be used to the extent that they (i) do not hinder space safety and SSA[§], and (ii) contribute to achieving the above goals. In short, the priority—improving space safety and planetary defense via greater global SSA—must guide research tracks. This paper takes steps in one research track: *ontology for SSA*.

The paper is divided thusly: the domain to be ontologically characterized is described; the discipline of ontology is summarized, desiderata for an SSAO ontology is listed, the SSAO is introduced with part of its taxonomy, and an example first-order formalization is presented. Steps/tasks in the SSAO development process is marked with '(S#)' and suggested guidelines by '(R#)'. Italics or bold marks key terms. Bold and camel-cased terms are unary category terms. Italicized and camel-cased terms are relation terms.

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[*] For two early efforts, see [17], and [18]. The former is a schema, not an ontology, but has many essential terms for SSA taxonomies. The latter has terms from different scientific disciplines relevant to SSA.

[†] Thanks to David Vallado (Analytical Graphics Inc.) for making the need for data exchange/integration known (via a conference presentation in Boulder, CO, 2011) to the corresponding author.

[‡] Personal communication with Lowell Vizenor

[§] E.g. if unable to handle dynamically real-time changing data; or imposing computational restrictions; increasing automated inference times; somehow delaying urgent commands for, say, collision avoidance maneuvers. The utility of dynamic ontologies is therefore a research track.

THE SPACE SITUATIONAL AWARENESS DOMAIN

The universe of discourse to be expressed in an ontological framework is the SSA domain. This paper defines *space situational awareness* as *situational awareness of the orbital, near-Earth and deep-space environments*. It includes the processes by which we achieve that awareness, such as observation, detection, identification, tracking, and prediction/propagation of space objects, and space object orbits and trajectories; as well as the phenomena in the space environment. Elsewhere SSA has been defined as:

- "the ability to view, understand and predict the physical location of natural and manmade objects in orbit around the Earth, with the objective of avoiding collisions"[2]

- "understanding and maintaining awareness of the Earth orbital population, the space environment, and possible threats." [3]

- "[…] the ability to accurately characterize the space environment and activities in space." [4]

The last quotation captures a central conceptual purpose of SSAO. SSA is a broad domain. It will be helpful to either identify or delimit subdomains in order to better manage the subject matter to be formally represented. Partially overlapping divisions of domain content will facilitate SSAO development.

SSA Activities and Goals

Table 1 lists SSA activities and areas from European and United States perspectives. According to [4, p.2] the goals of SSA from the perspective of the latter include "characterising, as completely as possible, the space capabilities operating within the terrestrial and space environments".

Table 1. SSA Sub-divisions according to EU and USA.

European Space Situational Awareness Program [16]	**United States**
• Space surveillance and tracking • Space weather effects • Near-Earth objects	• Intelligence • Surveillance • Reconnaissance • Environmental Monitoring • Command and Contro

These activities involve: observing natural and artificial objects in the space environment, reasoning over accumulated data, predicting future space object motion, and taking actions to avoid hazardous situations. Together they form a SSA whole whose purpose is to ensure safe space and terrestrial activity. To structure the domain, we assert three naturally overlapping benefit- and goal-based categories are as follows.

I Planetary Defense
  - Orbital awareness (orbital debris, active satellites, etc.)
  - Near-Earth awareness (e.g. asteroids, comets)
  - Deep-space awareness (comets, space weather, interstellar phenomena, etc.)
  - Space weather awareness and forecasting (solar activity, etc.)

II Protection of orbital *in situ* persons and space assets (communications satellites, stations)

III Spaceflight safety, Space traffic management

More specific reasons for SSA, drawn largely from [5] and [6], are here organized into additional activity-based (processual) categories:

PRODUCING:	Running catalogs of space objects
PREDICTING:	- Collisions in orbit - Calculating the risk to spacecraft due to environmental threats - Chart the present position of orbital objects and plot their anticipated orbital paths. - Atmospheric re-entry of space objects; When and where a decaying space object will re-enter the Earth's atmosphere.
PREVENTING:	- Collisions on orbit - A returning space object, which to radar looks like a missile, from triggering a false alarm in missile-attack warning sensors
DETECTING:	- Hazards to spacecraft - Malfunctions - New space objects
IDENTIFYING:	Which country owns a re-entering space object
MONITORING:	Behavior of spacecraft, e.g. changes in altitude, position, etc.
DIAGNOSING:	Spacecraft failures and malfunctions

In short, space situational awareness includes at least:

(A) **Observation** of the space environment,
(B) **Identification** and **Tracking** of **space objects** in that environment,
(C) **Accumulation** and **Analysis of Data**, and
(D) **Knowledge discovery** that ideally is **actionable**

Ground- and space-based sensor networks are used to observe the orbital and near-Earth environments. Some SSA networks include the following. For more details on sensors see [7] and [8].

- International Scientific Optical Network [9]
- Canadian Space Surveillance System[10]
- Space Surveillance Network (SSN) [6]
- Russian Space Surveillance System
- Chinese Space Surveillance System
- Space Data Association [11]

To better achieve the above goals and improve global space safety, sensor networks in conjunction with satellite operators around the globe must share SSA data. One potential challenge is that each space actor may use different data formats; have unique database terms referring to the same space object; and their databases (e.g. space object catalogs) may be entirely isolated from one another. Toward resolving these challenges, **ontologies** offer structured, sharable, interoperable and computable taxonomies that have a formal semantics. They formally represent common and tacit domain knowledge shared by all SSA communities as well instance data about the respective domain objects. This allows semantic interoperability among SSA actors.

Space communities around the globe have overlapping knowledge: the science and engineering of astrodynamics, astronomy, satellite operations, aerospace engineering, etc. SSAO formally represents some of this general scientific knowledge, and the entities it is about, in one or more potentially interconnected and modular ontologies. Given the wide and interdisciplinary scope of SSA, an SSAO is more accurately an SSAO suite that includes specific domain ontologies. These computable terminological systems contain explicitly defined classes that can be mapped to one another, and that can annotate or subsume terms from SSA databases, affording interoperability among SSA information systems. An SSAO ontology thereby has the potential to improved SSA for the respective data-sharing space actors. It also may help glean insights into novel ***astrodynamic standards*** by, in part, putting forth a community SSA vocabulary.

ONTOLOGY AND COMPUTATIONAL ONTOLOGIES

Ontology in computer science circles is distinguished, but related to, philosophical ontology, the latter of which is general study and characterization of actual and potential existence. A philosophical ontology, then, is a theory of the kinds of entities that (are held to) can or do exist and their interrelationships. **Ontology/ontological engineering** [12] has been described as:

> “the set of activities that concern the ontology development process, the ontology life cycle, the methods and methodologies for building ontologies, and the tool suites and languages that support them” [13].

This involves the specification of a computable terminology with a formal semantics: a computational ontology. The meaning of the terms composing the taxonomy is expressed in natural and artificial languages. Good ontology practice calls for one meaning per term to avoid ambiguity and confusion. **Computational ontologies** (also called *information* or *applied ontologies*), then, are computable systems of terms whose intended meanings are represented in an ontology language. As such:

> "[t]he ontology engineer analyzes relevant entities and organizes them into concepts [classes] and relations, being represented, respectively, by unary and binary predicates. The backbone of an ontology consists of a generalization / specialization hierarchy of concepts, i.e., a taxonomy." [12].

Organizing relations, such as ***class subsumption*** (*is a*), are used to organize the terms. The ***is a*** relation can be defined as: some class A is a subclass of class B if and only if A inherits all properties of B. Partonomies are taxonomies describing the partonomic relationship between entities, and uses one or more ***parthood*** relation. For example, *part of* is often defined according to General Extensional Mereology.

In both philosophical and computational ontology, **categories** (types, universals, classes) are often distinguished from their **instances** (tokens, particulars, members, individuals). They are relatable with an ***instantiation*** (*instance_of*) relation.

Each class in the ontology should be given a definition, save primitives[*]. Primitive terms should be given clarifying comments to aid the ontology user in grasping the general sense of the term. Definitions are subject to revision over time as scientific and domain knowledge changes.

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[*] Primitive terms are those that are undefined within the system.

Definitions often take the form of asserting *necessary and sufficient conditions*, which helps automated reasoning, but other sorts of definition are possible. Natural language definitions convey the meaning of terms to human users, including ontology curators and developers. Artificial languages, such as knowledge representation or ontology languages, are used to make the terms computable. Logical formalisms such as first-order predicate calculus are used to help create formal definitions. Thus, two central steps in the ontology development process are forming a vocabulary of terms within the scope of the domain, and defining them. Ontology terms are used to **annotate** instance data (data about individuals in the world, e.g., the Hubble Space Telescope). Types of SSA instance data includes observational data (e.g. infrared, optical data), and data about the orbital parameters of some individual satellite.

First-order, modal and higher-order logics are used, in part, to test for correct inferences in the less expressive computational implementation languages (artificial languages) such as Common Logic (CLIF)[14], and OWL[15]. Any given formalism—from modal logics to implementation languages—has limitations, e.g., limited expressivity. There are also different ways to symbolically represent and computationally implement a given ontological theory. In any case, the implementation language should attempt to capture the full intended meaning (at the conceptual and natural language levels) of terms. Where a mismatch between intended meaning and the implementation exists, it should be explicitly stated in documentation and ontology files to avoid misinterpretations (R1). Table 2 lists some general functions and goals of ontologies.

Table 2. **Goals of computational ontologies**

Computational Goals	Conceptual Goals/Benefits
Annotation	Semantic clarity, Explaining the meaning of domain terms and data
Automated Inference/Reasoning	Conceptual and philosophical explication
Data sharing, Exchange, Integration	Presenting a shared conceptualization
Data representation	Knowledge representation and Reuse
Interoperability	

The applied ontology development process should include the *open world assumption* (R2) and must be *subject to revision and correction* (R3) over time. It is an iterative process involving formal and concept(ual) analysis; development; implementation; validation and testing. Software development methodologies may be adopted. Philosophical ontology informs this process with formal distinctions and tools, just as scientific knowledge inform the philosophical descriptions of the domain.

Computational ontologies may draw upon philosophical ontology by employing highly general **distinctions** and **ontological categories,** such as the following.

Space
Time
Space-Time
Event
System
State
Function

Concrete Particular
Abstract Particular
Entity
Object
Process
Property-bearer
Property

Identity
Persistence
Modality
Continuant / Endurant
Occurrent / Perdurant
Universal vs. Particular

These categories, which are given symbolic definitions in formal ontology, are related to one another with **formal** (**domain-neutral**) **ontological relations** such as the following.

Dependence
Inherence
Instantiation
Causation
Participation
Connection
Parthood
Composition
Constitution

Various sub-relations of Dependence (and other relations) can more specifically characterize the actual physical, material and relational dependencies among the entities in the SSA domain. Parthood and composition are mereological relations, where *mereology* (and mereotopology) is the general study of the relationships between parts and their wholes (and connectedness). Additional tools for ontological analysis include formal theories of **unity**, and **identity**.

Note that there are different accounts of each of the above concepts. There is arguably no universal agreement as to their ontological status, e.g., as to whether causation is indeed a relation. The SSAO, like other domain ontologies, may therefore: (a) assert its own treatment on the respective concept, (b) adopt existing ones, or (c) adopt an ontology methodology that does not commit to such philosophical distinctions.

Finally, ontological inquiry into SSA (specifically astrodynamics) has a large **epistemological** and **modal** component. That is, SSA involves knowledge of the *present* situation (detecting an existing space object), current events and processes (detection of collision events, ongoing spacecraft operations, maneuvers, etc.), physical states and properties (shape, mass, the Keplerian orbital parameters), and very importantly *predictive* (or *future*) knowledge. The latter involves extrapolating possibilities, such as potential collisions, orbital paths, etc. It is therefore critical for a SSAO to capture the prediction, propagation, and modality aspects of the domain (R3).

APPLYING ONTOLOGY TO SPACE SITUATIONAL AWARENESS

There are different ontology development approaches [21], but developing a cogent and working Space Situational Awareness Ontology includes at least steps S1 through S5.

(S1) **Identify**: domain problems to solve, goals, requirements, and questions

(S2) **Domain research**: reference documents, domain-experts, domain data & databases

(S3) **Demarcation** of sub-domains for better content management (context-specific)

(S4) **Vocabulary/Terminology:** List domain-specific terms to be formed into a taxonomy. Concept(ual development

(S5) **Definitions** of terms from S4 using natural and artificial language definitions, including formal rules and logical axioms to capture domain knowledge.

General goals, S1, include SSA data-sharing among civil, federal and military SSA actors. A more specific goal is the **sharing of unmediated data** between interested space actors in order to minimize time between observations. This will lower response time to potential or imminent threats to space assets. If international SSA communities use different data formats, then ontology offers an avenue toward interoperability.

S2 includes consulting domain literature, research groups, individuals, space object catalogs and databases, space agencies, SSA sensor networks, and so on. It is essential for a variety of practicing subject-matter professionals with different viewpoints and ideas to be involved. Domain professionals help explain, verify and correct domain knowledge expressed by the formal ontological representations of ontology developers and curators. They therefore help ensure faithfulness to domain, but also stand to gain insights from formal and philosophical ontologists. Ontology developers and curators will ideally be domain experts (or vice versa). Toward this, educational courses in SSA-related topics for ontologists should be provided (R4). If an ontological approach according to which existing ontologies are reused, both domain-experts and ontologists should evaluate all ontology resources [22].

One function of an SSAO is to symbolically represent and computationally implement SSA knowledge. Toward S4 and S5, we form a SSA **taxonomy**, assert the interrelationships between terms (mirroring real-world relations among their referents), and structure the terms into a hierarchy using the class-subsumption relation (or otherwise). Class terms may be organized along the dimensions of SSA subareas and activities discussed in section 2, or along other dimensions and domain sub-groupings. A SSAO should have domain-specific category terms for the following entities, grouped into categories marked by "(T#)":

(T1) **SPACE OBSERVATIONS** (an observation as distinct from the observed)

(T2) **SPACE OBJECTS & PHENOMENA** being observed

- o *Classify* space objects and phenomena: Satellites, Spacecraft, Orbital Debris, Asteroids, Space weather phenomena, etc.

(T3) **OBSERVATION PROCESSES** engaged by space operators, astrodynamicists, astonomers, sensors, etc.

- o Detection (e.g. Detection Event)
- o Identification
- o Tracking
- o Propagation

(T4) **DATA** (from observations) representing or measuring the objects or some property thereof[*]

(T5) **SENSORS** that gather data from observations, and that engage in observations

Each of these potentially constitutes the subject matter of a distinct, and modular, yet interoperable ontology (or a portion thereof) within a global **SSA Ontology Architecture**. For example, an **SSAO suite** can consist of a(n):

- **Ontology of Space Observation Processes and Procedures**
- **Space / Satellite Operations Ontology**
- **Spacecraft or Sensor Ontology** for space assets, sensors, etc.
- **Space Object Ontology**
- **Orbital Event and Process Ontology**
- **SSA Data Ontology** (representing data formats)

… and so on.[†]

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[*] It will help to be clear on distinctions between data, observations, and what data is about or what it refers to (if anything). This will help avoid category mistakes and misrepresentations.

[†] Given the term 'awareness' in 'SSA', the scope of the SSA domain may also be focused to those space awareness processes and objects (e.g. tracking, communications, sensor-networks, etc.), leaving other space entities to be

Any ontology will have one or more ontology files, implemented in a computable language such as Common Logic (CLIF)[19] or OWL[15], the former of which is more expressive and recommended. Ontology class definitions are formalized in an artificial language like CLIF.

To represent the shared general scientific knowledge relevant for SSA activities, **modular scientific domain ontologies** for each discipline are appropriate. **Astrodynamics**, and the physical principles therein, for instance, is a necessary subject matter to capture. Awareness of space debris—and with it **conjunction analysis**[*]—is a major part of SSA. Following [1], an Orbital Debris Ontology serves to enable space debris data-sharing and thereby improve spaceflight safety and SSA. If the astrodynamics and orbital debris domains are not large enough to form individual ontologies unto themselves, then the respective classes shall be part of the class hierarchy of a SSAO.

The international SSA community employs similar concepts and terms, largely in virtue of this common scientific knowledge. The domain is also interdisciplinary, using concepts from astrodynamics, general physics, and astronomy. Some terms will more precisely belong to a specific scientific, operational, or engineering discipline, and thus to the corresponding scientific domain-ontology. In any case, a degree of arbitrariness will go into grouping the terms and demarcating the knowledge to be represented by each ontology module. Existing domain ontology resources such as [18] or [19], where physical and astronomical terms abound, may make this process more efficient if they can be reused.

For example, a class representing a natural near-Earth object, such as an asteroid, may be formally represented and categorized differently by distinct databases or ontologies. Generally speaking, the class Asteroid, for instance, may be part of an Astronomy Ontology (as a type of Astronomical Object similar to [19]), a Space Environment Ontology, a Space Weather Ontology, a Space Object Ontology (as a type of Space Object), etc. To identify where it may be most appropriately placed, use scientific knowledge of the entity (and its causal interaction with its environment) in combination with formal ontological tools. By identifying the intrinsic and essential properties of asteroids, or by simply appealing to the subject matter studied by the respective discipline, we find that Asteroid is correctly placed in an astronomy ontology. The SSAO would then reference or import the class from the existing ontology into its framework, relating it to other classes and relations. This is efficiently accomplished using ontology/taxonomy editor applications.

Table 3 (as well as 4 and 5) presents some class terms for the SSAO. Although the meaning of most terms is straightforward, formal definitions will be necessary. Some terms are commonly found in the space community, others such as the right-most column are offered as novel additions. Those commonly found can be drawn upon the existing space terminology sources, including space object catalog or database terms. Many relevant terms are for different sorts of entity: natural celestial bodies (e.g., asteroids), information/data objects (labels, names, data formats such as the Two-Line Element Set), space artefacts (e.g., spacecraft), and properties (geometric, physical, social).

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represented in either similarly focused domain ontologies, or in a broader space domain ontology, all of which can be interconnected.

[*] Predicting potential collision events, i.e. future possibilities.

Table 3. General terms for a Space Situational Awareness Ontology.

- Astronomical Body
- Spacecraft, Space Vehicle
- (Artificial) Space Satellite
- Communications Satellite
- Orbital Debris
- Sensor
- Space-based Sensor
- Ground-based Sensor
- Optical Telescope
- Space Object

- Orbit
- Orbital Element / Parameter
- Orbital Period
- Inclination
- Eccentricity
- Epoch
- Perigee, Apogee
- Right-Ascension of the Ascending Node

- Satellite Number
- Satellite Catalog Number
- COSPAR ID
- NORAD ID
- Operator
- Owner
- Launch Date
- Two-line Element Set (TLE)

- Astrodynamic Process
- Space Object Tracking Process
- Collision Avoidance Maneuver
- Space Object Detection Event
- Orbital Collision Event
- Space Weather Event
- Space Operations

For each class of entity we should (S6) determine their:

- Properties, features, or attributes
- Identity and unity conditions/criteria
- Dependencies and interrelationships
- Parent categories

Properties of objects are often ontologically characterized as **Dependent Entities**. **Identity** and **unity** condition are often necessary conditions indicating the identity or equality of some entity. Identity conditions are that without which an entity of a given sort would not be of that sort. **Dependencies** are those entities (objects, relations, processes, properties, etc.) that the entity in question relies on, existentially or otherwise. **Parent categories** indicate the minimum properties characterizing a child category. Telecommunications Satellites are types of Artificial Satellites for instance, the former inheriting the properties (e.g. being made by persons) of the latter.

In other words, conduct an ontological analysis to define terms, capture the intended meaning, and give a precise formal semantics. Table 4 lists some specific property and relation terms of interest. Indentation indicates class subsumption. Relations are represented as n-ary (at least binary) predicates.

Table 4: Property and Relation Terms.

Property (unary predicate)	**Relation (n-ary, n≥2)**
Mass	Has Orbit
Material Composition	Has Orbital Element
Shape	Has Inclination, Has Eccentricity, … (through the orbital elements)
Cross-section[*], Radar Cross-section	Has Cross-section
Function Design Function	Has Property, Has Function

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[*] For an ontological analysis of the category of Cross Section see Rovetto(2013)[20].

Albedo	Has Status (e.g., Operational, Inactive, Defunct, Abandoned)

Table 5 presents the domain and range of some predicates. Each row should be read from left to right as a formal statement in the ontology, e.g.: **Satellite *has_orbit* Orbit**.

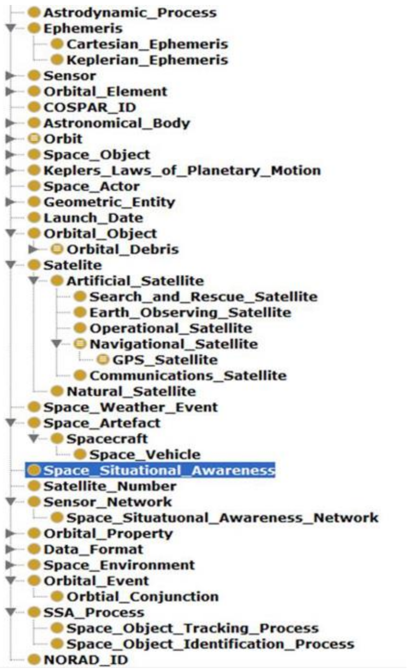
Table 5: Relations with candidate domain and range.

Domain	**Relation**	**Range**
Artificial Satellite	***Has_Status***	Satellite Operational Status (Example values: Operational, Active, Inactive, Defunct, Abandoned, etc.)
Satellite	***Has_Orbit***	Orbit
Orbit	***Has_Orbital_Inclination***	Inclination (Example value: 60°)

Ontology classes will **annotate** instance data housed in SSA databases, and should explicitly and clearly communicate what the data is about. This is a basic goal of ontologies. **Space object catalogs**—data repositories of instance data about actual objects in Earth orbit—are therefore to be annotated with the relevant space object categories: Spacecraft, Space Vehicle, GPS Satellite, Active Satellite, Orbit, Rocket Body, Orbital Debris, Space Telescope, Space-based Sensor, Space Station, etc. For example: **Hubble Space Telescope *is_instance_Of* Space-Borne Telescope**.

An SSAO taxonomy can subsume the class terms of each space actor. Terms from distinct SSA or space object databases are asserted as equivalent to the corresponding (same meaning) terms from a shared SSA ontology. Another ontology methodology is to create an ontology for each space data resource and interconnect them by asserting equivalent or synonymous classes in each. Alternatively, and in turn, each of these SSA-actor-specific ontologies can also be subsumed by yet another more general ontology. Ontologies can serve to map each space actors terminology to one another. One of these, or other methods, stand to foster data-sharing among isolated SSA data systems.

Figure 1 below presents part of the SSAO taxonomy, subject to revision, in its state at the time of this writing. At the time of, and prior to, this paper, steps in the ongoing development of the SSAO ontology file were commenced by the corresponding author. An SSA Vocabulary/Data Dictionary using Microsoft Office Excel was also initiated.



- Astrodynamic_Process
- Ephemeris
  - Cartesian_Ephemeris
  - Keplerian_Ephemeris
- Sensor
- Orbital_Element
- COSPAR_ID
- Astronomical_Body
- Orbit
- Space_Object
- Keplers_Laws_of_Planetary_Motion
- Space_Actor
- Geometric_Entity
- Launch_Date
- Orbital_Object
  - Orbital_Debris
- Satelite
  - Artificial_Satellite
    - Search_and_Rescue_Satellite
    - Earth_Observing_Satellite
    - Operational_Satellite
    - Navigational_Satellite
      - GPS_Satellite
    - Communications_Satellite
  - Natural_Satellite
- Space_Weather_Event
- Space_Artefact
  - Spacecraft
    - Space_Vehicle
- Space_Situational_Awareness
- Satellite_Number
- Sensor_Network
  - Space_Situatuonal_Awareness_Network
- Orbital_Property
- Data_Format
- Space_Environment
- Orbital_Event
  - Orbtial_Conjunction
- SSA_Process
  - Space_Object_Tracking_Process
  - Space_Object_Identification_Process
- NORAD_ID

Figure 1: A preliminary taxonomy for the SSAO, displayed in Protégé.

A FORMALIZED SSA SCENARIO

To visually express the idea of a space situational awareness ontology, Figure 2 is a diagram of SSA categories and relations. It depicts a fictional scenario in which a particular satellite is tracked by a sensor that is part of a specific SSA network. The top half above the dotted line represents class-level terms (expressing general knowledge). The lower half represents instances of those classes. Red arrows represent the instantiation relation between the general (class) and the particular (individual). A generic *Part Of* relation is used, but undefined.

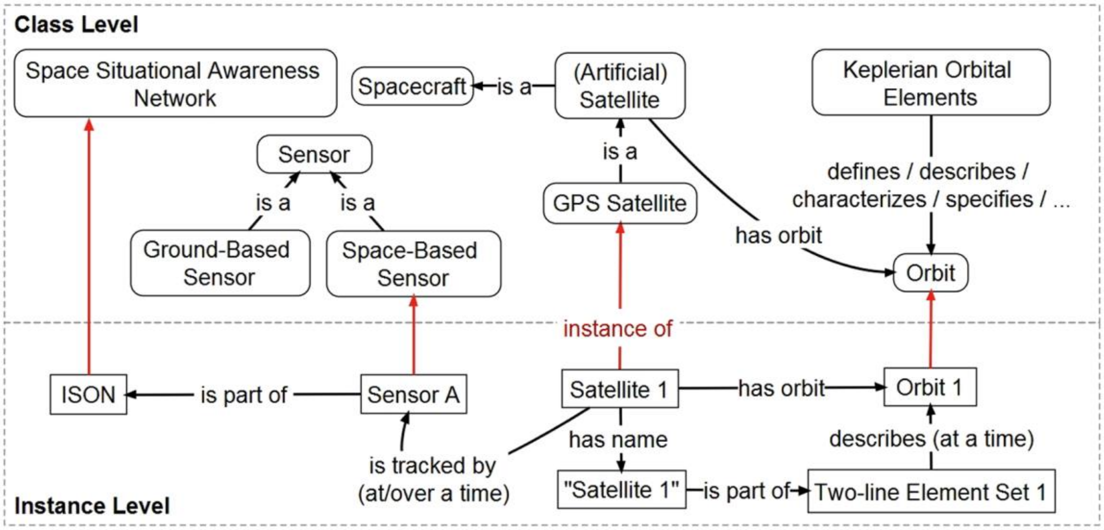


Figure 2: An ontological diagram of some SSA-relevant categories. Rounded rectangles signify classes, rectangles instances, and arrows with italicized text represent relations. Red arrows crossing the dotted line mark the instantiation relation between individuals and their general category or class.

To understand the level of detail that goes into the requisite ontological analysis, note some limitations of Figure 2. The classes and relations are not defined here, but when doing so we must *reference times or temporal intervals*. For example, an instance-level ***Tracked By*** relation may be represented by a ternary predicate relating **Satellite**, **Sensor** and time classes. The scenario assumes the Global Positioning Satellites are, in fact, in orbital motion, an assumption consistent with an intuitive conception of artificial satellites as an artifact in orbital motion about another body. Given Figure 2, being in orbital motion is a property (or state) that needs to be explicitly formalized. By contrast, if we define **Artificial Satellite** as an artifact whose **Function** is to orbit the Earth, then the class-level ***Has_Orbit*** relation should be omitted since it would not hold atemporally. The reason is that prior to orbit-insertion, any given artificial satellite may be resting on the surface of Earth. Finally, some space-based sensors such as the Hubble Telescope are satellites in the sense of being orbiting artifacts. These and other considerations must be taken into account to refine SSAO and ensure coherence and clarity.

An example definition of, say, ‘GPS Satellite’ that is computable when part of a coherent ontology is the following.

GPS Satellite =def. An **Artificial Satellite** that is ***part_of*** the **Global Positioning System**

In other words, the definiendum is a subclass of **Artificial Satellite** with differentiating properties or relationships of being part of the GPS.

First-order predicate logic (FOL) axioms for Figure 1, along with their natural language (NL) reading, are as follows. Standard FOL constants and connectives are used. ‘t’ denotes temporal instants.

∀ (“For all” Universal quantifier) ⟶ (“if then”’/ implication)

∃ (“There exists”/Existential quantifier) ∧ (“and”/conjunction)

Is_a(Space-Based Sensor, Sensor) (A1a)
∀x[instance_of(x, Space-Based Sensor) ⟶ instance_of(x, Sensor)] (A1b)
All space-based sensors are sensors.

Is_a(GPS Satellite, Artificial Satellite) (A2a)
∀x[instance_of (x, GPS Satellite) ⟶ instance_of (x, Artificial Satellite)] (A2b)
All GPS satellites are artificial satellites.

instance_of(Sensor A, Space-Based Sensor) (A3)
Sensor A is an instance of Space-Based Sensor.

From A1 and A3, Sensor A is also a(n indirect) *instance_of* Sensor. An automated reasoner will make this inference if the classes and axioms are defined and specified properly. If multiple inheritance is desired, then assert an ***is a*** relation between Space-Based Sensor and Spacecraft as well. This and other considerations depend on how we define the classes and what distinctions we adopt, e.g. Artificial-Natural, etc. A more complicated expression is (A4) and (A5).

All satellites tracked by Sensor A have some (A4)
Two-Line Element set (that describes the orbit of the satellite).

∀x [instance_of(x, Satellite, t) ∧ is_tracked_by(x, SensorA, t) ⟶
∃y,z,t [instance_of(y, Two-LineElementSet)

$$\begin{aligned}&\wedge\ \text{instance\_of}(z, \text{Orbit})\\ &\wedge\ \text{describes}(y, z, t)]]\end{aligned}$$

The alternative formalization, A5, removes Orbit classes, and asserts a relation such as ***Describes_orbit_of***.

$$\begin{aligned}&\forall x\ [\ \text{instance\_of}(x, \text{Satellite}, t) \wedge \text{is\_tracked\_by}(x, \text{Sensor A}, t) \longrightarrow\\ &\quad \exists y,z,t[\text{instance\_of}(y, \text{Two-Line Element Set}) \wedge \text{describes\_orbit\_of}(y, x, t)]]\end{aligned}\tag{A5}$$

To formally express the orbital parameters expressed in a TLE, relate the orbit with each parameter, e.g.: has_inclination(Orbit1, 60°).

* * *

This example concludes the paper by demonstrating a sample of the formalization required. Further work is necessary but this is part and parcel of what goes into the formal and applied ontology process for the space situational awareness domain.

CONCLUSION

This paper has presented the foundations of space situational awareness ontology, outlining requirements and desiderata for formal ontologies and space taxonomies for the SSA domain. The discipline of ontology (philosophical and computational) was described; the SSA domain to be ontologically represented was summarized and demarcated, and key class terms identified The computational ontology, the Space Situational Awareness Ontology (SSAO) was introduced with part of its taxonomy, and a sample first-order formalization presented.

The goals of the SSA Ontology are to: provide formal and computable representations of general scientific knowledge (astrodynamics, astronautics, SSA processes, etc.), the objects (spacecraft, orbital debris, sensors, etc.) and inter-relations in the domain; annotate instance data; and foster space data-sharing. Space object catalogs containing satellite observational data can be annotated with the appropriate ontology classes to afford space data-exchange and interoperability. The overarching purpose of these goals is to improve peaceful global space awareness and spaceflight safety for all space actors.

SSA is a global necessity that offers us an opportunity for international cooperation among space actors and academia. Research into and application of the various ontology development approaches and methodologies will hopefully serve to help solve space domain problems such as orbital debris, and improve space safety, by offering a means to facilitate sharing SSA data and knowledge.

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