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An ontological architecture for orbital debris data

Robert J. Rovetto[1]

Abstract The orbital debris problem presents an opportunity for international cooperation toward the mutually beneficial goals of orbital debris prevention, mitigation, remediation, and improved space situational awareness (SSA). Achieving these goals requires sharing orbital debris and other SSA data. Toward this, I present an ontological architecture for the orbital debris and related domains, taking steps in the creation of an orbital debris ontology. The purpose of the ontology is to capture general scientific domain knowledge; formally represent the entities within the domain; form, structure, and standardize (where needed) orbital and SSA terminology; and foster semantic interoperability and data-exchange. In doing so I hope to offer a scientifically accurate ontological representation of the orbital domain; contribute to research in astroinformatics, space ontology, and space data management; and improve spaceflight safety by providing a means to capture and communicate informaiton associated with space debris.

Keywords Orbital debris · Space debris · Astroinformatics · Informatics · Ontology · Formal ontology · Ontology development · Ontological engineering · Space situational awareness · Semantics · Data sharing

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Introduction

Orbital debris is internationally recognized as a global hazard. It poses a threat to persons and spacecraft in orbit, and is a potential barrier to future spaceflight. The orbital debris problem thereby presents us with an opportunity for international cooperation, and should be understood within the broader context of improving space situational awareness (SSA) for planetary defense, scientific knowledge, and preserving the future of peaceful space travel. SSA is awareness of the space environment and the objects therein. This encompasses knowledge of the natural and artificial objects inhabiting the orbital, near-Earth and deep-space regions. Knowledge of orbital debris is therefore part of SSA. Orbital debris data, then, is SSA data.

This paper focuses on one area for that cooperative potential—data sharing—and the part it plays in resolving the orbital debris problem and improving global SSA. Existing cooperative efforts include the sharing of some spacecraft and orbital data by agencies and satellite operators; growing numbers of international data-sharing agreements; non-profit organizations; and reports on international space data (Keller et al. 2013). Despite these efforts, the degree of data-exchange is still limited.

Originally conceived in 2011, this project involves researching the potential of ontology engineering as a partial approach toward data-sharing, interoperability and knowledge discovery for the orbital debris domain. The idea is to apply formal ontological methods and concepts from philosophy and artificial intelligence in the creation and use of ontologies in order to facilitate data exchange and knowledge sharing among orbital debris and SSA communities. Space debris data-sharing will improve the state of SSA, placing the global community in a more informed position toward debris prevention and resolution. Furthermore, with more complete situational knowledge of the space environment comes greater

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potential for planetary defense. The motivation for this research is therefore to contribute to alleviating the hazards posed by space debris, and ensure spaceflight for future generations.

In what follows I present an ontological architecture for the domain of orbital debris , taking steps in the creation of an orbital debris ontology. The purpose of one or more domain ontologies is to capture general scientific domain knowledge; formally represent the entities within the domain; form, structure, and standardize (where needed) orbital and SSA terminology; and foster semantic interoperability and data-exchange. Specific goals of this ontological system, therefore, include:

I.   Orbital debris and SSA domain representation
II. The specification and formalization of terminologies/vocabularies that are faithful to the respective scientific domain
III. Annotation of debris and SSA data
IV. Orbital debris and SSA data-sharing

And in so doing…

V.   Contribute to: orbital debris remediation, and the improvement of SSA and space safety.

Aside from the potential for computational utility vis-a-vis space informatics and space data management, a broader benefit of this project is the conceptual and philosophical analysis (and clarification) of the relevant orbital and space concepts. It is an interdisciplinary enterprise requiring the expertise and efforts from persons in astrodynamics, astroinformatics, ontology (philosophical, formal, and applied), data modeling, knowledge representation and reasoning, and computer science.

The paper is divided thusly: I summarize the problems in sections 2 and 3. Section 4 discusses ontology, and 5 outlines my orbital debris ontology. Section 6 presents the architecture with closing remarks in 7.

The orbital debris problem and space situational awareness

Orbital debris is human-made, Earth-orbiting objects that are no longer usable. Examples include inoperative spacecraft, their segments; miscellaneous astronautical artifacts; as well as satellite fragments. The primary sources of orbital debris are collisions and explosions. The size and shape of debris vary: there are more than 21,000 objects larger than 10 cm, over 700,000 between 1 and 10 cm, and over 100 million smaller than 1 cm (NASA Orbital Debris Program Office). The orbital lifetime of debris varies as well: debris at 800 km altitude and debris above 1000 km remain in orbit for decades to over a century, respectively.

There are a number of hazards posed by orbital debris (Scientific American). Given their high velocities, lifetimes, and growing numbers (Figs. 1 and 2), there is a risk of damage to operational satellites. The probability of catastrophic events is currently low, but "[a]s the debris population grows, more collisions will occur" (European Space Agency, Space Debris—About). "[T]he continuing growth in space debris

Fig. 1 Growth of debris objects ≥10 cm, by type. (ODQ 2014)
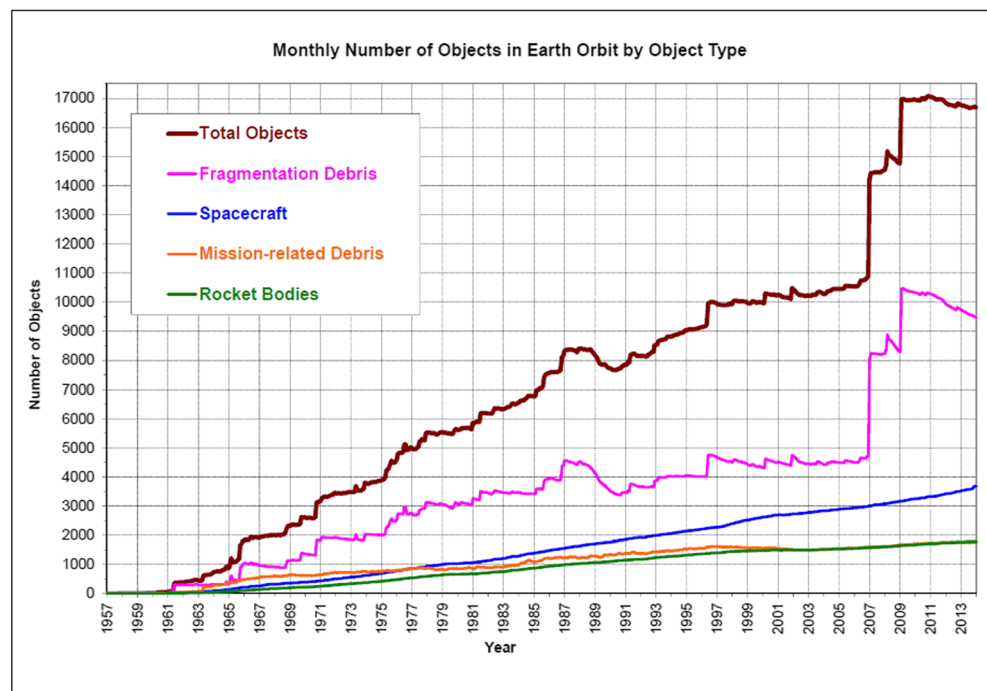
Monthly Number of Cataloged Objects in Earth Orbit by Object Type: This chart displays a summary of all objects in Earth orbit officially cataloged by the U.S. Space Surveillance Network. "Fragmentation debris" includes satellite breakup debris and anomalous event debris, while "mission-related debris" includes all objects dispensed, separated, or released as part of the planned mission.

Fig. 2 Growth of debris objects ≥10 cm, by nation (European Space Agency Space Object Catalog)
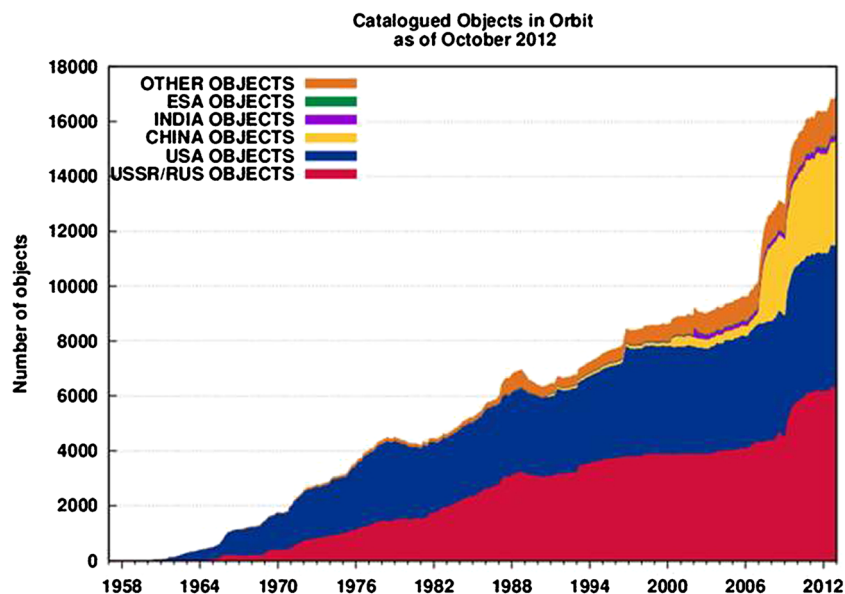
poses an increasing threat to economically and scientifically vital orbital regions" (ESA Global Experts) by increasing the spatial density of debris in otherwise navigable space. This raises the likelihood of collision events making navigation more hazardous. Moreover, as critical orbital regions become more congested debris becomes a greater hindrance to astronomical observations. A task we are faced with is "[...] to prevent a cascade of self-sustaining collisions from setting in over the next few decades." (ESA Global Experts) The hazards of space debris also extend to the surface of the Earth: debris of sufficient size pose a danger (albeit low) to persons and property.

Orbital debris is therefore a risk to satellites, spacecraft, and human life. It has the potential to severely limit, if not prevent, future space travel. To the extent that debris limits access to space, and to the degree that preventative actions are not taken, we are essentially trapping ourselves in. This is the **orbital debris problem**.

Resolving the orbital debris problem entails debris **prevention**, **mitigation** and **remediation** measures, the latter of which involves the development of technologies to physically remove debris. It also includes the enactment of policy that outlines requirements (Johnson and Stansbery 2010; United Nations 2010; U.S. Government Orbital Debris Mitigation Standard Practices), strategies, and methods to minimize the formation of debris, as well as the management of debris.

A necessary part of the solution to the orbital debris problem is accurate and actionable **space situational awareness**. We observe the space environment; detect, locate, identify, track, and predict space objects and their orbital paths. Both ground-based and space-based sensors (radar and optical telescopes, etc.) are used toward these ends. Table 1 presents a

Table 1 Sources SSA data–Potetnial partners for data-exchange

Independent observers (public, amateur, etc.)[a]

United States

- Space Surveillance Network
- Joint Space Operations Command
- Department of Defense Space Object Catalog
- National Aeronautics and Space Administration (NASA)
  - National Space Science Data Center (NSSDC)
  - Goldstone Deep Space Communications Complex
- University of Michigan Orbital Debris Survey Telescope
- Lincoln Space Surveillance Complex, Massachusetts Institute of Technology
  - Millstone Hill Radar
  - Haystack X-Band Radar, & Haystack Auxiliary Radar (primarily ≤10 cm debris observations) (Stansbery 2009)
- Ground-based Electro-Optical Deep Space Surveillance
- Meter Class Autonomous Telescope, Ascension Island
- Maui Space Surveillance Complex, Air Force Maui Optical & Supercomputing Site, Maui High Performance Computing Center
- Space Data Center (SDC) of the Spae Data Association (Private sector)
- Commercial Space Operations Center (CSOC)

United Kingdom Infrared Telescope, Hawaii

Russian Space Surveillance System

- Okno space surveillance stations

European Space Surveillance Sensors (ESA SST)

Chinese Space Surveillance System

International Scientific Optical Network (Geosynchronous catalog)

[a] One or more open-access repositories for amateur observers can be formed. A publicly accessibly system should allow: amateur observers to enter and view their observations of orbital objects. This system could then share data with others.

non-exhaustive list of sensors, tracking stations, sensor networks and observers that gather or process SSA data (including orbital debris), or that maintain space object catalogs (Vallado and Griesbach 2011).

Any given organization tracking space debris acquires large amounts of data, yet "[n]one of the existing networks and SSA initiatives provides complete coverage or a comprehensive catalogue of all objects in orbit. **The sharing of data is also limited**." (Kretzenbacher et al. 2012, emphasis added). The United States, for instance, maintains an extensive system and makes some data available, but "there are gaps in its coverage and catalog" (Weeden 2014). What more, given that it is primarily military-centric, data-sharing is not entirely at a premium (Becker and Chow 2012). There has been an increase in international data-sharing agreements, however (USSTRATCOM 2014, 2015). The above sources of space object observational data, as well those under development and those yet to be constructed, are therefore potential partners in data-sharing initiatives toward more complete SSA. Their particular databases, space object catalogs, and information systems are candidate elements to be made interoperable via the use of ontologies or other data and knowledge management means.

The improvement of SSA for all orbital, near-earth and deep-space objects is critical for national security and **planetary defense**. In pooling data and resources toward better SSA, the individual communities of interest expand their knowledge. Collectively they are in a better position for improving space safety and planetary defense.

> "Improving SSA for all space actors is critical to space activities and the long-term sustainability of space. It provides knowledge about what is happening in space, and in particular Earth orbit. This knowledge provides understanding of potential threats (natural or human-generated)" (Weeden 2014)

Solving the orbital debris problem and increasing SSA are more efficiently addressed via cooperative efforts at the international scale. "The removal of space debris is an environmental problem of global dimensions that must be assessed in an international context, including the UN." (ESA Global Experts) In short, "SSA is inherently international" (Weeden 2013).

The orbital debris data problem

Given the premise that greater data sharing is needed to improve the orbital debris problem, SSA and thus spaceflight safety, technical (and political) obstacles to these objectives constitute what I will call *the orbital debris* (or *SSA*) *data problem*. It involves the state of space object catalogs, databases, or information and knowledge systems that house debris and other SSA data. In what follows, 'information system' (IS) is used as a collective term for these systems. Political obstacles aside, there are at least two specific concerns, both of which apply to other data-intensive disciplines.
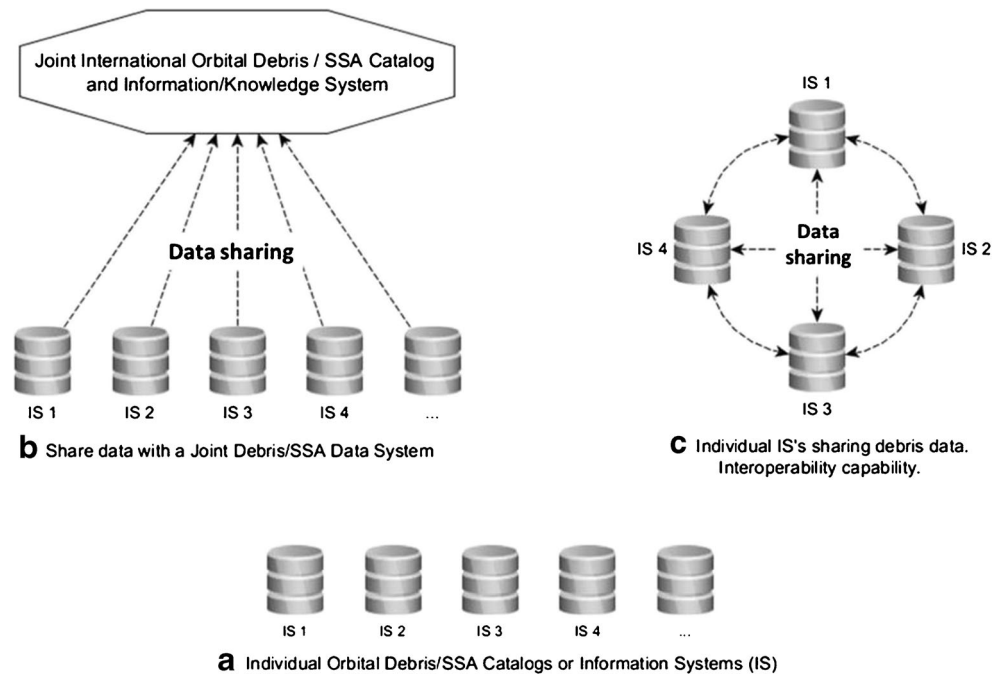
The first concern is a **silo effect**: distinct, essentially isolated, information systems. Individual IS's may (i) share limited, if any, amounts of data, (ii) be inaccessible, and (iii) use different data formats, standards, terminologies, and classification schemes in spite of having a common universe of discourse. (iii) can be described as the problem of heterogeneous data and data formats, an obstacle to data-sharing and interoperability. Consider, for example, this statement expressed vis-à-vis in-orbit collision avoidance: "Unfortunately, the most accurate tracking data for active satellites is often closely held only by the satellite operators." (Kelso and Gorski 2009).

In itself a data silo is not necessarily problematic. Depending on the purpose of the IS, it may be desirable at times. For remediating the orbital debris problem, however, silos are at least potentially problematic because resolving the former entails improving SSA, and "**[f]undamentally, SSA requires data sharing and cooperation between different actors**" (Weeden 2013, emphasis added). The first concern, therefore, reflects a potential hindrance to improving the orbital debris situation. It is an indirect obstacle to ensuring safe and successful space navigation and development. At a more fundamental level, it should be easily accepted that sharing information (i.e. communication) is essential for research and scientific progress. It encourages hypothesis generation, knowledge discovery, collaboration, and division of labor.

As Kretzenbacher et al. (2012) suggest, the idea is to consolidate data for more complete coverage as well as update, if not replace, legacy systems (Weeden 2012). In sharing debris data, organizations with incomplete— and they are all incomplete—debris IS's will *increase their knowledge of existing and potential space hazards*. They will therefore have a more complete picture of the orbital environment and greater awareness toward: debris remediation, planetary defense, and assuring obstacle-free space exploration for generations to come.

We should move from situation A to either situation B or C (Fig. 3), or some combination of the two. It is a move from incommunicative debris/SSA IS's to IS's sharing data with a neutral party (e.g. a consortium) formed for the creation of a joint international and dynamic master orbital debris (or SSA) catalog, and/or to interconnected and interoperable systems. In either

Fig. 3 From incommunicative orbital debris catalogs to debris data-sharing. The idea is to move from **a**, isolated information systems (IS), to either **b** sharing their data with a neutral joint master debris IS, **c** share their data amongst each other in an interconnected fashion (or some combination of the two)

b Share data with a Joint Debris/SSA Data System

c Individual IS's sharing debris data. Interoperability capability.

a Individual Orbital Debris/SSA Catalogs or Information Systems (IS)

situation, ontology may prove useful by explaining, classifying and annotating data, and serving as a partial means to interoperability.[1] The formation of a neutral party has been suggested in (Kretzenbacher et al. 2012), where we read:

> "One possible approach is the creation of a neutral international organization and network that exists solely to facilitate the collection and sharing of SSA data. The proposed network would utilize the capabilities of already existing SSA infrastructure that are not restricted by being part of a defensive network."

Weeden and Kelso (2009) also explore the idea of an international SSA system, where "the primary goal of an international civil SSA system would be to support the safe and sustainable operation of all actors through provision of necessary information" (Space Safety & Sustainability Working Group 2012, p.2). Of course, "any data sharing policy adapted by a comprehensive SSA system will need to balance privacy and security with data dissemination and openness" (Space Safety & Sustainability Working Group 2012, p.23).

The second concern vis-à-vis space object catalogs and other IS's is the sheer quantity of data that is (1) acquired from sensor networks, and (2) generated from astrodynamic conjunction analysis, propagation and prediction models. To take another data-intensive field as a case in point, we read: "The progress of astronomy is about to hit a wall in terms of the processing, mining and interpretation of huge datasets." (Valentijn and Kleijn 2006, p.20) The case for advancing astroinformatics (Borne 2009) is also a case for orbital debris and SSA informatics. The orbital debris (and data) problem is thereby also an opportunity to improve the state of space informatics.

In order to improve SSA via data-sharing, we may adopt one method used by informaticians: ontology development.[2] The next section begins with a brief overview of the field of ontology, followed by a sketch of a modularized ontological architecture for representing the orbital debris and related domains.

Informatics and ontology engineering for orbital debris

Given the data-intensive nature of the orbital debris and space situational awareness domains, analyzing and communicating orbital debris datasets is necessary if we are to alleviate the orbital debris problem. The publication "Future Human Spaceflight: The Need for International Cooperation" (Pace and Reibaldi 2010) acknowledges this when it cites two data-centric areas for international cooperation:

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[1] Interoperability, the problems thereof, and the role of ontologies, have been recently discussed in Thanos (2014).

[2] I am primarily concerned with ameliorating the orbital debris situation and ensuring safe space travel, rather than advocating a particular method toward that goal. If ontological approaches prove to be insufficient or simply unhelpful, then there should be no quarrel with seeking alternatives.

1. "Adoption of open, interoperable communications protocols (e.g., delay-tolerant networks) defined through the Consultative Committee on Space Data Standards."
2. "Adoption of standard orbit data message formats to facilitate exchange of satellite and orbital debris location information to avoid possible collisions in space." (p.28)

"Astrodynamic standards are an important foundation for SSA" (Weeden 2012, p.23). Although the ultimate utility of this research area is still to be determined, *ontologies* provide a formalized knowledge base of a given domain, and may foster semantic interoperability via annotation and classification of data elements housed within siloed information systems.

Ontology for orbital debris

Ontology or **Ontological engineering** (Staab and Studer 2009) in computer science is related to knowledge representation and informatics. The ontology development process involves domain research, concept analysis, a terminology/vocabulary, and the explicit specification of at least an understanding of the given domain of interest. The terms in the taxonomy, their definitions and the interrelationships between them (or that which the terms denote), are intended to express or capture the domain. This results in a logically formalized taxonomical structure that can be computationally reasoned over.

Ontology development is an ongoing iterative process that requires curation, quality-control, revision and updating. This is particularly necessary for ontologies of the sciences, e.g., astronomy, where knowledge is updated and corrected, and where new discoveries are made over time. See Pinto and Martins (2004) for an account of the different stages of ontology building.

A central focus in ontology development is the *intended meaning* of the specified vocabulary. Creating **an ontology** involves the formation of the above-mentioned taxonomical structure. This hierarchical system of category and relation (predicate) terms has a formal semantics, the totality of which expresses some consensual knowledge of the domain. Some ontologies are essentially *reference ontologies*, that is, they present common and general knowledge of the given domain.

For **computer tractability**, a *logical formalization* of terms is employed using an *implementation* or *knowledge representation language*. This allows automated classification and inference, as well as querying. "Ontologies have been developed to provide a machine-processable semantics of information sources that can be communicated between different agents (software and humans)" (Fensel 2004, p.3). An

ontology provides this as a classification scheme of interrelated and axiomatized categories.

In employing the commonly adopted distinction of *classes* (categories, universals, types) and their *instances* (individuals, particulars, tokens), a particular debris fragment is explicitly asserted to be an ***instance of*** the general class of **Debris**. The subclass (subtype, class subsumption) relation structures the class hierarchy. For example, the class **Orbital Debris** is a ***subclass of*** (or simply ***Is a***) **Debris**. The former inherits the properties of the latter. Domain-neutral ontological distinctions adopted from philosophical ontology are used to help make the ontology consistent, coherent and conceptually detailed. In qualitative spatial reasoning, for instance, mereological[3] concepts are employed. Taxonomies, themselves, can be structured along partonomic lines using a ***parthood*** relation, the formal properties of which are to be asserted in the ontology.

Ontologies are intended to **minimize terminological ambiguity**. This is achieved by providing a set of general terms whose intended meanings are clearly and explicitly specified. In other words, terms are given **explicit definitions** that are comprehensible for the human user. If terms are left primitive (undefined within the ontology/system), then intuitions can provide their meaning, but some explicating description is best offered. Ontologies are minimally intended to clearly express what data is about and formally represent a shared understanding or conceptualization of a domain of interest.

Although ontologies can be reused without being composed of modules, when they are modularized, **reusability** is another benefit. "Ontologies were developed in Artificial Intelligence to facilitate knowledge sharing and reuse." (Fensel 2004, p.3) Reusing existing category and relation terms from other ontologies, for instance, is often considered desirable in ontology development.[4] Furthermore, **annotating** data elements (e.g. instance data) with ontological classes is a common task for achieving data interoperability. Axiomatized inference rules in conjunction with the generalized knowledge represented in the ontology are used to reason over that instance data.

Ontology engineering also involves **conceptual** and **philosophical analysis**, which should begin at the outset of the development process. At the most general or abstract levels, ontology development draws on ontological categories from philosophical inquiry. Examples include: Event, Object, Property, Relation, Process, State, and System. Common

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[3] The theory of parts and wholes.
[4] I would, however, argue that this depends not only on the requirements, goals of (and problems solved by) the ontology being developed, but whether the reused (or imported) classes accurately reflect the entities in the domain in question.

distinctions include: Object-Process, Object-Property, Independent-Dependent, and mereotopological concepts such as *Part*, *Whole*, and *Connection*. Formal ontological relations include *Participation*, *Instantiation*, *Dependence*, *Parthood*, *Constitution*, and *Causality*.

Depending on the resources at hand and the desired degree of philosophical rigor, a complete metaphysical account can be given for an ontology at all levels of generality/abstraction. For this communication I remain neutral with respect to how the above-mentioned general categories are philosophically characterized, while relying on our intuitions in the light of the scientific domain under analysis.

I will, however, emphasize that the goals are to solve real-world problems. In this case, the overarching goal is to contribute to spaceflight safety by improving peaceful space situational awareness and alleviating the orbital debris problem. In the more abstract aspects of the ontology development process, we must not get stuck in methodological, philosophical, hyper-logical, or political pitfalls associated with adopting this or that metaphysical or methodological worldview or distinction. At the same time we should not casually accept views we do not agree with in order to accomplish those goals. Ontology developers should invest time to ensure any subsuming ontology to theirs does not misrepresent their domain concepts and entities/phenomena being represented. Consider the view of Semy et al. (2004) who state: "Which upper ontology is best to use as even a conceptual model is situational and may change over time as upper ontologies mature and experience is gained with their use." As a recommended ontology development best practice, I suggest that all domain experts (a) be cognizant of and clear on the metaphysical assumptions, world views and implicit meanings in their domain ontology, and in any subsuming ontology. When philosophical presumptions, distinctions or ontological categories and relations clash with domain expertise or intuitions, and when there are doubts as to the veracity of the ontological definitions and classifications, we should question them. The point is to ensure the ontology faithfully represents the domain: "the first order of business must be to express the structure of the domain at hand without any expressive constraints to help ensure accuracy and completeness" (Menzel 2003, p.8). If not, then at the very least, the ontology should positively supports solving the real-world problems.

Ontology modules for orbital debris

This section summarizes some relevant domain ontologies for an ontology of orbital debris and SSA. Each domain ontology— ontologies of a particular subject matter or universe of discourse—should have: (i) category and relation terms, (ii) natural language definitions as well as a computable semantics, and (iii) a hierarchical structure.

ODO: The Orbital Debris Ontology

The **Orbital Debris Ontology**, or **ODO** for short,[5] is the locus of the idea. It is an ontology of the domain or orbital debris, and as such represents the entities in, and general knowledge about, the orbital debris domain. There is one caveat. Rather than an orbital debris ontology in itself, an SSA ontology with orbital debris-relevant classes and relations may be formed instead. These classes would be portions of the SSA ontological class hierarchy.

Desiderata for ODO, like other ontologies, include at least the following.

(D1)   TERMINOLOGY/VOCABULARY

Include category and relation terms specific to the domain of orbital debris. ODO will/should have terms for at least the following:

- Types of orbital debris
- Properties/features of debris
- Sensors observing the orbital environment
- Sensing and measurement processes
- Relations relating debris to other relevant entities
- Debris processes, including causes of debris formation
- State and Positional information[6]

–   Ephemeris data[7]
–   Orbits and orbital properties

For example, if we follow the National Research Council (1995, p.21) and the United Nations (1999), then debris types (classes) and property classes include the following (Table 2). Terms for some orbital properties include: Eccentricity, Inclination, Right Ascension of the Ascending Node, and the other Keplerian Orbital Elements/Parameters.

Table 3 lists some category and relation terms essential to an ontology of orbital debris, or to a broader orbital environment ontology, or space situational awareness ontology. The domain-neutral object-process distinction reflected in the table can be formulated in various ways depending on the metaphysical accounts, but for the present communication it will be sufficient to rely on our intuitions of objects/things and processes/events. Material objects, such as satellites, are

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[5] Pronounced: *oh-dough*
[6] Mentioned in task 2 from section 4
[7] See: http://ssd.jpl.nasa.gov/?glossary&term=ephemeris

Table 2 Candidate classes for types and properties of orbital debris

Types of debris	Properties of debris
Non-functional spacecraft	Mass
Rocket body	Spatial dimensions
Mission-related debris	Material composition
Fragmentation debris	Radar cross-section
	State vector
	Albedo
	Ballistic coefficient
	Launch characteristics

formally asserted to *participate in* processes, such as orbital plane changes.

(D2) DEFINITIONS FOR TERMS AND A FORMAL SEMANTICS

- *Natural Language* (NL) *Definitions* that easily communicate the intended meaning to human users (comprehensibility).
- *Formal and Computable Definitions*

    First-order predicate logic, high-order or non-classical logics formalize definitions and domain knowledge. Implementation languages such as Common Logic Interchange Format (CLIF) and the Web Ontology Language (OWL) are used for computability and information exchange.

– Care must be taken so as not to engage in "'over-first-orderization', i.e., trying to axiomatize too much" (Menzel 2003, p.5) and not to give inadequate axiomatizations of terms and concepts that are difficult to formalize. We must also be aware of the limitations in expressivity of each logic and ontology implementation language.

- Both sorts of definition should: be consistent (not self-contradictory) and convey necessary and/or sufficient conditions and *identity criteria* for each category of entity. Identity criteria include diachronic (identity across time:

what makes something persist over time) and synchronic (identity at a time).

We naturally begin at the conceptual level, coming to an understanding of ideas, concepts and meanings. We then move to formulate NL definitions that express the intended meaning and conceptualizations. To the extent that we have a good understanding of the domain, our conceptualizations ideally reflect the reality of the domain. Finally, although the logical and computable definition should ideally match the NL definition as closely as possible, any disparity should be explicitly stated (and explained) in documentation. This will help avoid misinterpretations and incorrect or false inferences. Definitional revisions may take place at any point in the ontology development process.

(D3) STRUCTURE THE TERMS, A HIERARCHICAL STRUCUTRE, A BACKBONE TAXONOMY

- Class terms should be formed into a taxonomic structure. The **Is a** class subsumption relation (class-subclass) is often used to structure taxonomies. This, in combination with any other relationships between classes forms a hierarchical classification scheme that affords automated classification and inheritance of properties from parent to child classes.
- Ontology editors with graphical user interfaces, such as Protégé and TopBraid Composer, make this task relatively easy to achieve. Ontology visualization tools and plugins can also improve the ontology development process, and serve as helpful pedagogical tools for users.

Achieving D1-D3 for ODO requires asking the following questions, which are part of the requisite domain research and conceptual development tasks. It is vital to consult domain literature and subject-matter/domain experts, particularly practicing domain experts, when conducting domain research and when checking the accuracy of the ontological representations, assertions, and inferences. This will help ensure high

Table 3 Candidate orbital debris ontology terms

Physical and material object terms	Relation terms	Processual terms
Space debris, orbital debris[a]	Has_debris_source, Caused_by, Has_cause	(Orbital) collision event, explosion event
Spacecraft	Has_ephemerides	Orbital decay process
Satellite	Has_cross_section	Debris tracking process
Ground-based sensor	Has_shape, Has_diameter	Orbital debris mitigation process
Orbit	Has_orbit, Orbits	Orbiting process

[a] Given that the class 'Space debris' can be interpreted as more general than 'orbital debris', I assert the latter as a type of the former. (NASA 2008) does similarly

fidelity and veridicality in definitions and axiomatizations of domain knowledge. Domain experts include national space agencies such as the NASA, the European Space Agency (ESA); specific departments such as the Orbital Debris Program Office at NASA; as well as individual astrodynamicists, satellite operators, and so forth.

Q1 *How are orbital debris currently classified? How can they be classified?*

 • By… size, altitude, etc.

Q2 *What types of debris are currently in orbit?*

 • E.g., Spacecraft fragments, entire rocket body parts, mission-related artifacts (e.g. astronaut gloves, tools), etc.

Q3 *What are the physical, intentional and social properties of orbital debris?*

• Physical properties (relational or otherwise), include size, shape, mass, location, attitude, velocity, orbital characteristics, etc.
• Intentional and social properties include cognitive attributions, and socially constructed or legal properties and relationships, such as ownership. This also includes space policy governing the management of debris.

Q4 *What is an ontological characterization of orbital debris?*

 • Answering this provides a higher-level (broader) classification and definition of 'Debris'.
   It provides one answer to the following question.

Q5 *What type of entity is orbital debris?*
   A Physical Object, Material Artifact, a Role, …?'

Orbital debris may be characterized as types of **Physical Object**, i.e., spatio-temporally localized objects that have some material properties. This is intuitive because the concept (and talk) of debris brings to mind material things. However, deeper ontological analysis yields another possibility. Debris may be modeled as a **Role** we attribute to physical objects in orbit, a role that is played or borne by the object relative to social conventions, processes and systems. One might justify this alternative characterization as follows.

Common definitions describe debris as being unusable or functionless. The object in question, however, may have been functional in the past, or may have been part of a functional spacecraft. Some space objects in Earth orbit may also be reusable. As such, they cannot be described as orbital debris

at all times. In other words, being orbital debris (or being usable/functional) is not an *essential* or *rigid property* of the object. Essential properties are those that are necessary at all times for being the type in question. In this sense, one may wish to classify Orbital Debris as a role *played by* Physical or Material Objects in specific circumstances. Finally, and alternatively, do away with Roles and assign a socially-relative status or property to the orbiting object: functional, non-functional, usable, etc.

Many, if not most, relevant terms in this domain belong to others. 'Planet' (or 'Planetary Body'), for example, is not unique to the subject matter of orbital debris, but more accurately belongs to the discipline of astronomy. All the same a **Planet** class should be included when formalizing orbital knowledge of debris in orbit. Likewise for the **Physical Properties** of debris objects, i.e., mass, dimension, material composition, etc. Given that ODO will require terms from various disciplines it can be construed as an **application ontology** (but not necessarily so), i.e., an ontology created for a specific use or application. Application ontologies often use concepts from different domains and import terms (classes, relations) from other ontologies, including domain-specific or domain-neutral reference ontologies. The application at hand is to foster data sharing among orbital debris and space object information systems to improve the state of orbital debris SSA toward ensuring spaceflight safety.

ODO can reuse classes from ontologies of these other disciplines, if the latter are accurately formalized. Other relevant domains include: astrodynamics (orbital mechanics/dynamics) and celestial mechanics, astronomy, and satellite operations. If domain-specific ontologies for these fields do not exist, then the appropriate domain-specific classes can be asserted and defined as needed. If terms from existing ontologies are insufficient, then at least two actions can be taken. One, send a suggested curation change (with explanation) to the ontology developers in question. Two, create the desired category terms from scratch and incorporate them in ODO.

I will divide the relevant domain-specific ontologies in two groups and discuss them in the next section: Scientific Domain Ontologies and Data (or Information Object) Ontologies. Although this presupposes a distinction between information objects (e.g., data) and what the data is supposedly about, explaining the distinction is beyond the scope of this paper.

Scientific domain/reference ontologies for ODO

These ontologies capture general scientific knowledge, including physical laws/principles of nature, of the respective discipline. Scientific domain ontologies act as reference ontologies or models expressing knowledge needed to annotate and ontologically describe instance data and

ODO assertions. Given the overlap between, and the interconnectedness of, these disciplines, there will be a certain amount of prescription and arbitrariness regarding the boundaries, scope and content of each ontology. Thorough conceptual and philosophical analysis should be done for those concepts that resist placement, that are inherently vague, or that have multiple equally plausible ontological characterizations. The concept of *Orbit* may be an example.[8]

Astronomy ontologies

One or more Astronomy ontologies should contain general terms for astronomical phenomena studied by astronomers. The most conspicuous astronomical entities relevant to ODO are natural celestial bodies, i.e., planets. A broader Space Situational Awareness Ontology (SSAO) will include classes for more astronomical entities, e.g., space weather phenomena, asteroids and comets, etc.

Existing ontologies include the University of Maryland's (UMD) astronomical ontologies (Astronomy/Science Ontology), and the International Virtual Observatory Alliance (IVOA) Ontology of Astronomical Object Types. Together, this suite of ontology files includes astronomical objects, scientific units, and so forth.

Depending on the domain-neutral distinctions, an astronomy ontology can be divided into at least two interconnected ontologies. For example, if we assume that astronomical phenomena can be classified according to an object-process distinction, then we can form an Astronomical Object Ontology and an Astronomical Process Ontology.

The IVOA astronomical ontology includes both object and process classes in their taxonomy. The former represents what are classified as **astronomical objects**, entities such as planets, moons, stars, and comets. These entities are what are often called celestial bodies (although I use the term 'celestial' to refer to non-human made bodies in space). The latter represents planetary and stellar processes, i.e. **astronomical processes**.

Ultimately whether the object-process distinction is sufficient to capture (truthfully represent) astronomical phenomena will depend on how it is specified, i.e. on the definitions of Object and Process classes. In general, it is not clear that all astronomical phenomena can, in fact, be faithfully categorized as either object or process in the traditional philosophical sense. A hybrid of the two classes, such that objects have processual properties and processes have object-like properties, might be in order for instance. From a philosophical perspective, cases can be made for various metaphysical characterizations, but this is an area for further discussion elsewhere. I

would suggest that employing a richer ontological distinction, such as **object-process-system** may be helpful.

Celestial mechanics & Astrodynamics ontologies

An Astrodynamics Ontology represents knowledge of astrodynamics, i.e., the motion of *human-made* objects in space. This is a primary focus for ODO because we are interested in the current and future orbital states (position, velocity, etc.) of debris. Candidate category terms include those for the **Keplerian Orbital Elements/Parameters**, **spacecraft maneuvers**, and the **types of spacecraft orbits**. Instance data includes data about particular maneuvers, and the particular orbital elements defining the orbits of individual spacecraft, debris objects and other space objects at one or more times.

Given the shared scientific foundations, astrodynamics is closely related to celestial mechanics. A Celestial Mechanics Ontology—to the extent it is distinct from an Astrodynamics Ontology—is of the orbital motion of *natural* bodies in space. Due to the shared fundamentals, these two fields may be expressed in a single ontology.

Although both classical and modern relativistic physics should be taken into account, whether both are in fact expressed in the ontologies may ultimately depend on the purpose of the system and the resources at hand. Classical physics is retained for its wide applicability, but the Relativistic physics must be included not only because it is more precise, but because successful satellite operations require it.

Candidate classes for these ontologies include: **Orbital Velocity**, **Orbital Pertubation**, **Astronomical Coordinate System**, and **Keplerian Orbital Element(s)/Parameter(s)**, which includes **Inclination**, **Eccentricity**, **Right Ascension of the Ascending Node**, and the other elements. Instances of these categories include specific velocities, and particular perturbing forces or processes affecting the motion and orbit of a spacecraft.

Toward a taxonomy of these disciplines, the category **Space Dynamics**, may subsume that of **Astrodynamics** and **Celestial Dynamics**. The latter two preserve the artificial-natural connotations while the former is added to be more general than either of the two.

The development of these scientific domain ontologies involves analyzing and ontologically representing the data formats for encoding the orbital elements, formats such as the Two-line Element Set (TLE) National Aeronautical and Space Administration (NASA). We must determine whether classes for each orbital element are best placed within one of these ontologies, or in an information/data/measurement or geometric object ontology. Given the extensive use of physical-geometric concepts, a combination of terms representing physical phenomena, measurements and geometric constructs

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[8] At the time of this writing I have a philosophical and formal analysis of the category of Orbit in progress.

will be involved. This research topic provides interesting investigations into: the ontology of physical geometry; philosophy of space and time; the relationship between geometric/mathematical entities and physical phenomena; and the philosophy of science.

Data type, Information & Geometric entity ontologies

Data/Information Ontologies and Geometric Ontologies represent the data types, standard units, data formats, information objects (or entity) and geometric objects. Coordinate systems, conceived as a geometric construct, are to be represented in these ontologies. Note that the concept of a **data** or **information entity** is not entirely clear and free of problems, but it will suffice to make the point. It is also unclear whether geometric entities are correctly classified as a type of these entities, types of abstracta, cognitive artifact, or otherwise.

Agencies such as NASA and National Institute of Standards and Technology (NIST) are notable sources for this knowledge. Formal representations of these sorts of entity exist as well. The IVOA and UMD ontologies, for example, have measurement and unit portions, and the NASA Semantic Web for Earth Environmental Terminology (SWEET) ontologies include a number of terms for units. Finally, the Quantities, Units, Dimensions and Data Types Ontologies (QUDT) also offer data type ontologies.

Astrodynamics Standards Ontology

An astrodynamics standards ontology should include standard formats for representing coordinate systems, and ephemeris data among other entities. The NORAD Two-Line Element Set (NASA TLE) is the most prominent standard format for defining an orbit. Orbital State Vectors, by contrast, is another format used to express the position of an object in orbit. The referents (if there are any) of each data element—presumably the Keplerian Orbital Elements—in the TLE should be determined. For example, Orbital Inclination as an angle between a reference plane (a geometric construction) and the orbital plane, is apparently an Angle (an information, mathematical or geometric entity). More generally, it may be characterized as a Relational Property. For SSA organizations with distinct formats for the same orbital elements, an ontology serves to provide common terminology annotating and classifying each common orbital parameter.

Table 4 provides an example domain-specific category terms for the ontologies just discussed. For information on astrodynamic standards see Vallado (2001).

An example debris scenario

When identifying and tracking an object in space, data is gathered and extrapolated on a variety of features of the object and its motion, such as size, shape, attitude, velocity, direction, position. This applies to any space object in orbit: from operational satellites to orbital debris. The classical orbital parameters may be treated as properties of object's motion, its orbit, or the object itself, depending on further analysis. These Keplerian parameters describe the object's orbit, are determined at a time (an epoch), and propagated forward in time to yield a predicted orbital path. As such, this research presents a potential case study for investigating the relationship of predictive models/modeling to scientific inquiry and ontology.

Toward ontologically representing orbital scenarios, I will use the February 10, 2009 collision of the Iridium 33 and Cosmos 2251 satellites (Orbital Debris Quarterly 2009)[9] as an example. Figure 4 portrays the event using class and relation terms. Consider this arbitrary natural language expression describing the scenario. Far more is to be said for any orbital situation, but this will suffice to make the point.

Debris fragment 1993-036BLP was formed by the collision of Irridium 33 and Cosmos 2251 satellites at time t. 1993-036BLP has a near circular orbit at an average altitude of 934 km, with Two-line Element set [E1,…,E6][10] for time t (epoch).

The expression refers to a particular Orbital Debris Object (1993-036BLP), a past Event (the collision), Properties of the debris orbit (and/or the debris itself), and Measurements. '1993-036BLP' is the international designator (name, label, etc.) denoting an individual debris fragment formed from the collision, but I do not include particular orbital parameters. Rather, I use '[E1…E6]' as a general placeholder to denote the specific TLE set expressing those six temporally-indexed parameters. The collision of the two satellites is represented by 'Coll-IC'.

Table 5 lists terms for individuals and undefined classes and relations for axiomatizing the scenario. More than one possible predicate are included to express relations between debris and their genesis.

Below is a set of formal assertions, applying the terms from Table 5, and using a common prefix notation to express the

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[9] See also: http://swfound.org/media/6575/swf_iridium_cosmos_collision_fact_sheet_updated_2012.pdf, and http://celestrak.com/events/collision/

[10] Each data element in the TLE can be decomposed into sub-parts as needed.

Table 4 Example general terms (classes) specific to scientific domain ontologies

Domain Ontology	Category Terms
Astronomy Ontologies	Celestial Body, Planetary Body, Planet, Planetary System, Precession, Planetary Orbit, Planetary Orbiting Process
Celestial Mechanics Ontology, Orbital Mechanics Ontology Astrodynamics Ontology	Keplerian Orbital Element, Ephemeris
Astrodynamics Standards/Data Format Ontology	Two-line Element Set

orbital scenario in a computable manner. The assertion '*is_an_instance_of*(Earth, **Planet**)', for example, is read as 'Earth is an instance of **Planet**'. Class terms are in bold, relation terms (predicates) are italicized, and instances are in plain text. Compare these with Table 6, which presents the assertions in a subject-predicate-object form similar to the [Resource Description Framework](#) (RDF). Each row is read from left to right and expresses some specific fact of the orbital scenario. Although the formal assertions have only two arguments, n-ary predicates will be required for increased expressivity, i.e., to better capture the real-world scenarios and general knowledge of the orbital domain. For this reason, more expressive knowledge representation languages, such as CLIF, are preferable.

is_an_instance_of (1993-036BLP, **Orbital Debris Fragment**)
is_an_instance_of (coll-IC, **Satellite Collision Event**)

has_cause (1993-036BLP, coll-IC)
has_formation_event (1993-036BLP, coll-IC)

orbits (1993-036BLP, Earth)

has_altitude (1993-036BLP, 934 km)
has_label (1993-036BLP, "1993-036BLP")
has_international_designator (1993-036BLP, "1993-036BLP")

The term for altitude, like other quantities, can be decomposed into a numerical value and a distance unit. Furthermore, if we wish to explicitly mention the orbit as a particular entity unto itself (albeit a relational one) with orbital properties, we may assert: *has_orbit*(1993-036BLP, O1). We can then describe O1 (the orbit of the debris) and its properties (the Classical Orbital Parameters) by relating it to some TLE set or Orbital State Vector. Each Orbital Parameter—Inclination, Right Ascension of the Ascending Node, Eccentricity, etc.—should have its own corresponding class term, instances of which reflect the orbital properties of some space object in orbit. TLE sets (or otherwise) include terms denoting the measured values of these parameters. If 'TLE-1' is asserted to refer to some specific TLE set of 1993-036BLP, we may then assert the following expressions:

is_an_instance_of (O1, **Orbit**)
is_described_by (O1, TLE-1)

Another possibility to model orbital characteristics is to describe the debris object as participating in an orbiting *process* (or orbital/orbit process) that is described by a TLE set at a time, or that has specific orbital parameters as properties (at a time). However we represent these entities, ODO, an orbital environment ontology, or any space object or space situational awareness ontology, will require capturing general rules and knowledge about orbits. For any orbital object (debris or otherwise), for example, the formal statement

Table 5 Individuals, classes and relations for ontologically characterizing the satellite collision scenario

Individuals/Instances	Classes	Relations
Earth	Planet	Instantiation (*instance_of*)
Irridium 33	Satellite	Subsumption (*Is a*)
Cosmos 2251	Communications Satellite	Causation (*has_cause*) has_formation_event
Coll-IC	Satellite Collision Event	has_orbit
1993-036BLP	Orbital Debris Orbital Debris Fragment	has_altitude
	Orbit, Orbiting Process	orbits

Table 6 Subject-Predicate-Object form of formal assertions (read left to right for each row)

Subject	Predicate	Object
Earth	*is_an_instance_of*	Planet
1993-036BLP	*is_an_instance_of*	Orbital Debris (Fragment)
1993-036BLP	*has_label, has_name, has_international_designator*	"1993-036BLP"
1993-036BLP	*orbits*	Earth
1993-036BLP	*has_formation_event* (or: *was_formed_by, has_cause*)	coll-IC
coll-IC	*is_an_instance_of*	Satellite Collision Event

'*has_orbit* (**Orbital Debris Object**, **Orbit**)', which expresses the idea that all debris objects have or are in some orbit, appears to hold true. In other words, if an object is an orbital debris object, then it is in orbit. Furthermore, all orbits have (or are described by) some orbital parameters (inclination, eccentricity, etc.). More specifically, if x is an instance of **Orbit**, then x *has orbital parameter* **Inclination** (and so on).

The instance data—the particular values—of the TLE for this debris fragment are to be annotated with their corresponding class terms, e.g. **Inclination**, **Eccentricity**, **Right Ascension of the Ascending Node**, etc. Finally, some of the above relations may be ternary, rather than binary, where the third argument is a time instant or interval.

An architecture for an ontological framework for orbital debris

Figure 5 presents a unified ontological framework for the domain of orbital debris (or SSA more broadly). It is also interpretable as portraying the scenarios from Fig. 3. The lower rectangular figure contains cylinders representing individual debris or space object catalogs housing instance data about

particular defunct satellites, spacecraft and other space objects considered as orbital debris. Instance data, which includes sensor data of actual space objects, should be annotated with ODO general categories to provide meaning and a formal semantics to the user and computational system, respectively. ODO (re)uses terms from scientific, engineering and data type (or information entity) ontologies (if they exist). Domain-specific ontologies may be subsumed by more general ontologies and a top-level ontology, the latter of which consists of domain-neutral categories and relations. This framework is offered as one possibility, subject to change, and makes no claims to completeness.

In summation, individual orbital debris (or SSA) object information and systems are to be interconnected or otherwise share debris data toward a more exhaustive coverage of debris SSA. The application of ontologies may foster this by providing a common and formally specified orbital debris and space situational awareness terminology and knowledge base. Category terms from ODO may be a portion or subset of a broader SSA ontology. Terms from more general, yet domain-specific scientific and engineering disciplines, will be incorporated. In creating precise definitions of domain-specific terms and concepts, this research may contribute to the

Fig. 4 A diagram of an ontological characterization of an actual orbital event in which two communication satellites—Iridium 33 and Cosmos 2251—collided in Earth orbit, forming numerous debris fragments. The *upper portion* represents the class- or type-level, with the *lower portion* representing the instance or individual level (the particular event, and physical objects in question). *Red arrows* signify the instantiation relation. 'Is a' signifies the class-subclass (subsumption) relation. The *grey box* represents an individual orbital debris fragment formed by the collision (Coll-IC)
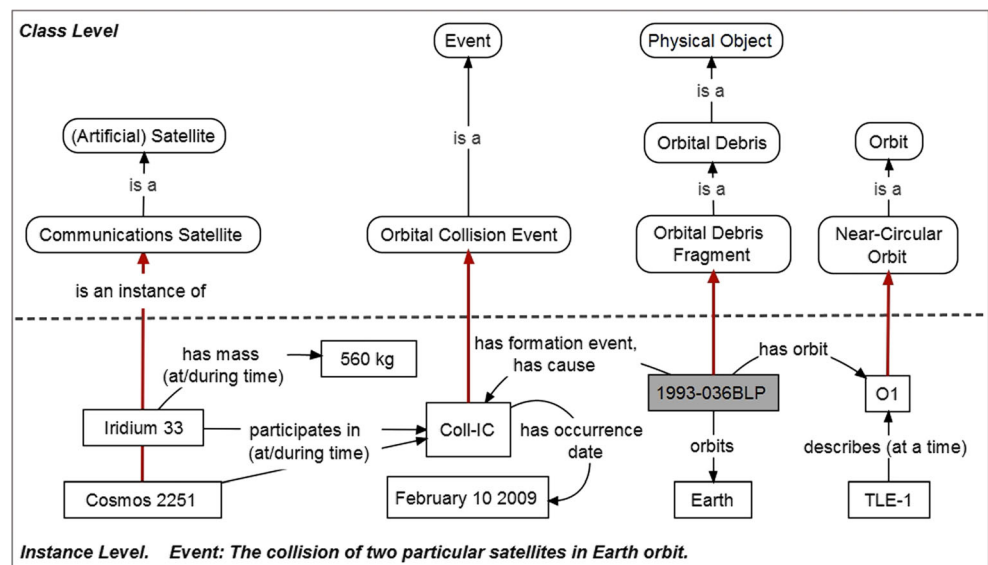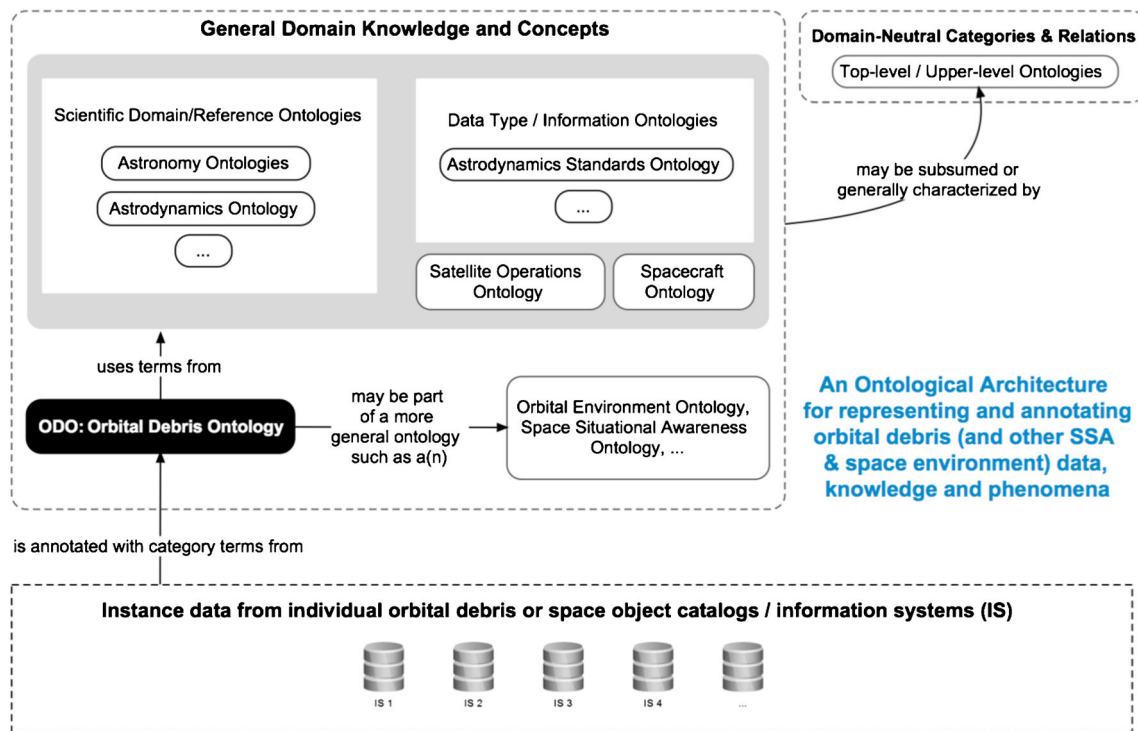
Fig. 5 An ontological architecture for Orbital Debris and other SSA data. The bottom rectangle represents disparate space debris/object information systems (cylinders). information systems. Examples may include those from the organizations from Table 1. Domain data and knowledge is classified, characterized by, and annotated with, terms from ODO (or a broader ontology). ODO, in turn, uses terms from the relevant interconnected domain ontologies, which may use more general (upper-level) ontologies

development of improved astrodynamic and SSA standards toward advancing the state of space development.

Toward the implementation of this ontological architecture, the following suggestions are made. First, ontology development tools such as Protégé, or TopBraid Composer, will be helpful in the process. I have, for instance, created an ODO/ SSA ontology file using Protégé, adding essential orbital classes. Second, I suggest the implementation language be as expressive as possible. For this reason, at least full first-order knowledge representation languages are recommended. Although CLIF is preferable to OWL in terms of expressiveness; the former may not have as many tools and support. Additional research on implementation options is required. Finally, given the global nature of the real-world problem, this project should have national space agencies as partners and participants, agencies such as the European Space Agency (ESA), NASA, and the Russian Federal Space Agency, among other burgeoning space organizations from around the world.

Conclusion

By improving our situational awareness of the orbital environment, we are in a better position to minimize the hazards of space debris, and thereby improve spaceflight safety. Given (i)

the existence of disparate space object catalogs and space situational awareness information systems (ii) heterogeneous data and data formats, (iii) the gaps in orbital coverage, and therefore (iv) our limited knowledge of the orbital debris and broader space object population, orbital debris data sharing is intended to increase peaceful global SSA.

Toward these goals, I have presented an ontological architecture for the orbital debris domain and outlined some requirements for an orbital debris ontology (ODO). The purpose of ODO (or a broader ontology) is to formally represent general scientific knowledge of, and the entities within, the domain; offer a shared lexicon that can be computationally reasoned over; and foster data-exchange among space object catalogs and information systems. Further work includes, but is not limited to: additional domain research; conceptual and philosophical analyses of orbital and astrodynamic concepts; a first- or higher-order formalization of the relevant classes, and a computable specification. The astronautical community should reap the most benefits if this research is conducted by various international space agencies in conjunction with academia. It should include interdisciplinary participation by astrodynamicists, satellite operators, ontologists, philosophers, informaticists, database administrators, computer scientists, and students alike.

I hope this paper has presented ideas for improving the state of orbital debris, and increasing space situational awareness,

via space data exchange, management; and space ontology development.

References

Astronomy/Science Ontology. Department of Astronomy, University of Maryland, USA. URL= http://www.astro.umd.edu/~eshaya/astro-onto/, http://www.astro.umd.edu/~eshaya/astro-onto/ontologies/astronomy.html. Accessed Mar 2015

Becker K, Chow T (2012) Lessons learned from maritime domain awareness for International SSA Data Sharing, 63rd International Astronautical Congress, Naples, Italy. International Astronautical Federation

Borne KD (2009) Astroinformatics: a 21st Century Approach to Astronomy - Astro2010 State of the Profession Position Paper. URL= http://arxiv.org/pdf/0909.3892v1.pdf. Accessed 24 Nov 2014

Commercial Space Operations Center (CSOC), Analytical Graphics, Inc. URL= http://comspoc.com/. Accessed 30 Nov 2014

Common Logic - International Organization for Standards URL= http://www.iso.org/iso/catalogue_detail.htm?csnumber=39175. Accessed Dec 2014

European Space Agency. Global experts agree action needed on space debris. URL=http://www.esa.int/Our_Activities/Operations/Space_Debris/Global_experts_agree_action_needed_on_space_debris. Accessed 24 Nov 2014

European Space Agency. Space debris – About. URL= http://www.esa.int/Our_Activities/Operations/Space_Debris/About_space_debris. Accessed 9 June 2015

European Space Agency. Space object catalog. URL= http://www.esa.int/spaceinimages/Images/2013/04/Object_catalogue. Accessed 24 Nov 2014

European Space Agency. Space surveillance and tracking – SST segment. (ESA SST) URL= http://www.esa.int/Our_Activities/Operations/Space_Situational_Awareness/Space_Surveillance_and_Tracking_-_SST_Segment

Fensel D (2004) Ontologies: silver bullet for knowledge management and electronic commerce, 2nd edn. Springer, Berlin

International Virtual Observatory Alliance (IVOA). Ontology of astronomical object types. URL= http://www.ivoa.net/documents/Notes/AstrObjectOntology/. Accessed Mar 2015

Johnson N,. Stansbery EG. The new NASA orbital debris mitigation procedural requirements and standards, Acta Astronautica 66(2010)362—367.

Keller KM, Yeung D, Baiocchi D, Welser IV W (2013) Facilitating information sharing across the international space community: lessons from behavioral sciences. RAND corporation, Santa Monica, CA. ISBN=978-0-8330-7694-6. URL= http://www.rand.org/content/dam/rand/pubs/technical_reports/TR1200/TR1255/RAND_TR1255.pdf

Kelso TS, Gorski A (2009) Space surveillance: lessons learned from the iridium-cosmos collision. Analytical Graphics Inc. Korea: International Astronautical Congress, 2009. URL= http://www.agi.com/resources/user-resources/downloads/white-paper.aspx?id=136. Accessed 24 Nov 2014

Kretzenbacher M, Rathnasabapathy M, Chow T, Kamaletdinova G (2012) Novel approaches to international cooperation and data sharing for SSA. IAC-12-A6. 63rd International Astronautical Congress,

Naples, Italy. URL= http://swfound.org/media/93089/iac-12_b5_1_10_x15145_tc.pdf. Accessed 24 Nov 2014

Menzel C (2003) Reference ontologies —application ontologies: either/or or both/and? In: Proceedings of the KI2003 Workshop on Reference Ontologies and Application Ontologies

National Aeronautical and Space Administration (NASA) (2008) Handbook for limiting orbital debris, NASA-Handbook 8719.14. URL= http://www.hq.nasa.gov/office/codeq/doctree/NHBK871914.pdf. Accessed 30 Nov 2014

National Aeronautical and Space Administration (NASA) (2009) Orbital debris quarterly news (ODQ), Vol 13, Issue 2. URL= http://orbitaldebris.jsc.nasa.gov/newsletter/pdfs/ODQNv13i2.pdf. Accessed 9 Mar 2015

National Aeronautical and Space Administration (NASA) (2014) Orbital Debris Quarterly News, Vol 18, Issue 1. NASA URL= http://orbitaldebris.jsc.nasa.gov/newsletter/pdfs/ODQNv18i1.pdf Accessed 24 Nov 2014

National Aeronautical and Space Administration (NASA). Orbital Debris Program Office. URL= http://orbitaldebris.jsc.nasa.gov/faqs.html. Accessed 24 Nov 2014

National Aeronautical and Space Administration (NASA). Definition of two-line element set coordinate system. URL= http://spaceflight.nasa.gov/realdata/sightings/SSapplications/Post/JavaSSOP/SSOP_Help/tle_def.html. Accessed 24 Nov 2014

National Aeronautical and Space Administration (NASA). National Space Science Data Center (NSSDC) URL= http://nssdc.gsfc.nasa.gov. Accessed 30 Nov 2014

National Aeronautical and Space Administration Semantic Web for Earth and Environmental Terminology (SWEET) Ontologies, Jet Propulsion Laboratory, California Institute of Technology. URL= http://sweet.jpl.nasa.gov/. Accessed March 2015

National Aeronautical and Space Administration (NASA) Two-line element set. URL= http://spaceflight.nasa.gov/realdata/sightings/SSapplications/Post/JavaSSOP/SSOP_Help/tle_def.html. Accessed 24 Nov 2014

National Institute of Standards and Technology (NIST) URL= http://www.nist.gov/. Accessed 24 Nov 2014

National Research Council (1995) Orbital debris: a technical assessment. The National Academies Press, Washington, DC

Pace S, Reibaldi G (eds) (2010) Future human spaceflight: the need for International Cooperation International Academy of Astronautics

Pinto HS, Martins JP (2004) Ontologies: how can they be built? Knowl Inf Syst 6:441–464 Springer-Verlag London Ltd. doi:10.1007/s10115-003-0138-1

Protégé Ontology Editor, Stanford University. URL= http://protege.stanford.edu/. Accessed Dec 2014

Quantities, Units, Dimensions and Data Types Ontologies (QUDT) URL= http://www.qudt.org/. Accessed 24 Nov 2014

Resource Description Framework (RDF) World Wide Web Consortium. URL= http://www.w3.org/RDF/. Accessed 6 June 2015

Scientific American. Space junk. URL= http://www.scientificamerican.com/media/multimedia/0212-spacejunk/space-junk.html#page-six-reasons. Accessed 27 Mar 2015

Semy SK, Pulvermacher MK, Obrst LJ (2004) Toward the use of an upper ontology for U.S. Government and U.S. Military domains: an evaluation. MITRE Technical Report. In: Workshop on Information Integration on the Web

Space Data Center (SDC) of the Space Data Association URL= www.space-data.org. Accessed 30 Nov 2014

Space Safety & Sustainability Working Group (2012) Space Situational Awareness, Space Generation Advisory Council, Schwarzenbergplatz 6 Vienna A-1030 Austria. URL= http://www.agi.com/resources/educational-alliance-program/curriculum_exercises_labs/SGAC_Space%20Generation%20Advisory%20Council/space_situational_awareness.pdf. Accessed 30 Nov 2014

Staab S, Studer R (eds) (2009) Handbook on ontologies, International Handbooks on Information Systems, Springer 2nd ed

Stansbery G (2009) Orbital debris research in the United States. NASA Orbital Debris Program Office, Lyndon B. Johnson Space Center

Thanos C (2014) Mediation: the technological foundation of modern science. Data Sci J 13:14

U.S. Government Orbital Debris Mitigation Standard Practices URL= http://orbitaldebris.jsc.nasa.gov/library/USG_OD_Standard_ Practices.pdf. Accessed 30 Nov 2014

U.S. Strategic Command (USSTRATCOM). USSTRATCOM signs space-data sharing agreement with ESA, U.S. Strategic Command Public Affairs, October 31, 2014. URL= http://www.stratcom.mil/ news/2014/524/USSTRATCOM_signs_Space-Data_Sharing_ Agreement_with_ESA/. Accessed 6 June 2015

USSTRATCOM (2015) Germany make arrangement to share space services, data. URL= http://www.afspc.af.mil/news/story.asp?id= 123437744. Accessed 9 June 2015

United Nations (1999) Technical Report on Space Debris, New York, A/AC.105/720, ISBN 92-1-100813-1

United Nations Office for Outer Space Affairs (2010) Space debris mitigation guidelines of the Committee on the Peaceful Uses of Outer Space URL= http://orbitaldebris.jsc.nasa.gov/library/Space% 20Debris%20Mitigation%20Guidelines_COPUOS.pdf. Accessed 30 Nov 2014

Valentijn EA, Kleijn GV (2006) The Astro-Wise System: a federated information accumulator for astronomy. In: European Research Consortium for Informatics and Mathematics, Number 65, Special: Space Exploration

Vallado DA (2001) A summary of astrodynamic standards. In: AAS/ AIAA Astrodynamics Specialists Conference, Quebec City, Quebec, Canada July 30-August 2, 2001, AAS Publications Office, P.O. Box 28130, San Diego, CA 92198

Vallado DA, Griesbach JD (2011) Simulating space surveillance networks. Paper AAS 11-580 presented at the AAS/AIAA Astrodynamics Specialist Conference. July 31–August 4, Girdwood, AK. URL= http://www.agi.com/resources/user- resources/downloads/white-paper.aspx?id=144. Accessed 30 Nov 2014

Web Ontology Language (OWL) World Wide Web Consortium URL= http://www.w3.org/TR/owl-features/, http://www.w3.org/TR/owl2- overview/. Accessed 30 Nov 2014

Weeden B (2012) Going blind: why America is on the verge of losing its situational awareness in space and what can be done about it. Secure World Foundation. URL= http://swfound.org/media/90775/going_ blind_final.pdf. Accessed 30 Nov 2014

Weeden B (2013) The importance of Space Situational Awareness (SSA) for ADR and OOS. Secure World Foundation. Presentation at Singapore Conference on ADR and OOS 20, Singapore URL= http://swfound.org/media/101966/Weeden-SSA_for_ADROOS. pdf. Accessed 24 Nov 2014

Weeden B (2014) Space situational awareness fact sheet Sept. Secure World Foundation. URL= http://swfound.org/media/1800/swf_ ssa_fact_sheet_sept2014.pdf. Accessed 30 Nov 2014

Weeden B, Kelso TS (2009) Analysis of the technical feasibility of building an International Civil Space Situational Awareness System. IAC in Daejeong, South Korea, October 12–16. URL= http://swfound. org/media/1719/iac-09_bw.pdf. Accessed 30 Nov 2014