ONTOLOGY FOR EUROPE'S SPACE SITUATIONAL AWARENESS PROGRAM

Robert J. Rovetto[(1)(2)]

[(1)] *Research Affiliate, Center for Orbital Debris Education and Research, University of Maryland*
[(2)] *National Aeronautics and Space Administration 2017 Datanauts*
Email: rrovetto@terpalum.umd.edu

ABSTRACT

This paper[1] presents an ontology architecture concept for the European Space Agency's (ESA) Space Situational Awareness (SSA) Program. It incorporates the author's domain ontology, The Space Situational Awareness Ontology and related ontology work. I summarize computational ontology, discuss the segments of ESA SSA, and introduce an option for a modular ontology framework reflecting the divisions of the SSA program. Among other things, ontologies are used for data sharing and integration. By applying ontology to ESA data, the ESA may better achieve its integration and innovation goals, while simultaneously improving the state of peaceful SSA.

1 INTRODUCTION

This paper presents an ontology architecture concept for the European Space Agency's (ESA) Space Situational Awareness (SSA) program [1][2], incorporating the author's domain reference ontology, The Space Situational Awareness Ontology [5] and related ontology work[2]. The ESA SSA program divides SSA into three segments: Space Surveillance and Tracking (SST), Near-Earth Objects (NEO), and Space Weather (SWE). One goal of the program is to "Integrate national data and sensor contributions while developing new applications and services" [3]. Toward this, I propose a framework composed of modular computational ontologies to facilitate ESA SSA data integration, and introduce the potential for novel ontology-based applications.

A computational ontology [26-29] has a structured vocabulary with a formally specified semantics as a proper part. It defines a set of category and relational terms and asserts rules and axioms to formally represent a given domain, a conceptualization thereof, or for a specific application. These terms must be sufficient in quantity and description for an intelligent agent to manipulate, and perform inferences [45]. Ontologies encode the *meaning* of data, rather than the structure of databases. They model the actual and possible relationships, processes, events, objects, properties, and patterns in a domain of interest. Thus, ontologies express general knowledge via a system of abstract classes, properties, and their interrelations. They can also represent individuals (or particular objects) in the world that instantiate classes.

Ontologies are used in software engineering, artificial intelligence, database management, computational linguistics, natural language processing, semantic web efforts, and big data. They have been applied to astronomy and other data-intensive disciplines [18-21]. XML-based efforts for space surveillance [22], and ontology-based methods for remote-sensing [41] have also been developed. The ESA has explored ontological applications in [46][47][49-51].

Applied ontologies are used to afford semantic and syntactic interoperability across platforms and applications; data- sharing, integration, extraction; decision support, and knowledge discovery. Logic-based implementation languages, used to formalize knowledge in the ontology, permit automated reasoning. The ontology development process may apply concepts from *philosophical* and *formal ontology* [37-41]—the general study and characterization of the world.

Maintaining and improving SSA is vital for the safety of persons in orbit and on terra firma; the security of our space-borne and ground-based space assets; and the future of spaceflight. It is simultaneously a scientific endeavour to understand our orbital neighbourhood. The *space debris* hazard, alone, calls for more complete observational coverage of the orbital space environment. This requires leveraging SSA data from various sources (sensors, databases, etc.). Ontology engineering provides a means to do so, and formal ontological analysis will refine our knowledge of orbital space by explicating its fundamental concepts [4].

In what follows I summarize the ESA's SSA program, followed by a discussion of the proposed ontological architecture for the ESA SSA program, and the existing SSA Domain Ontology. I draw upon my previous astronautical ontology work in [4-7]. Some space ontology architectures are summarized in [8].

[1] This work was conducted independent of author affiliations.
[2] See https://purl.org/space-ontology or contact the author for ontology files.

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2 METHODOLOGY

Developing ontologies is an iterative process from the identification of goals, applications, subject-matter, datasets and scope to terminology development, knowledge representation, and evaluation. The ontology engineering literature discusses different methods, tasks and perspectives [26][27][29], some of which may adopt software development methodologies. Below I list some generic ontology development tasks.

Ontology Purpose. Identify the purpose, e.g., goals, problems to solve, applications, domain, etc., and requirements. Specify competency questions (e.g. for database queries).

Research. Conduct domain and ontology research. Identify & review data sources. Specify the scope of the ontology.

- Identify fundamental concepts & domain knowledge to be captured by the ontology (e.g., astrodynamics, spacecraft structures)
- Identify & review domain data (e.g., specific space object catalogues)
- Review, assess, select or create ontology development approaches, architectures, tools (editors, reasoners).
- Explore the development of novel methods and systems

Vocabulary & Taxonomy Development

- List essential domain-specific terms
- *Define Terms / Formalize Concepts/Knowledge*: Natural Language Definitions (human readability), and Artificial Language Definitions (computer readability)
  - First-order or Higher-order logic
  - Implementation Languages, e.g., Common Logic Interchange Format (CLIF)[30], KIF[31], Web Ontology Language (OWL)[32], etc.
  - Assert rules, constraints, and axioms to precisely formalize definitions and domain knowledge.
- *Organize Terms ("taxonomize")* where necessary, e.g., using structuring relations such as class-subsumption (is-a), parthood (part-of), etc.

Test, Evaluate, Revise. Check for coherence, consistency, completeness, accuracy, etc.; Use automated reasoners, data sources (instance data) and software applications to perform queries (e.g. SPARQL), answers competency questions, test for reaching goals, etc.

3 THE EUROPEAN SPACE AGENCY SPACE SITUATIONAL AWARENESS PROGRAM

The ESA SSA program is divided into segments (Fig.1): Space weather, Near-Earth Objects, and Surveillance & Tracking. The ESA describes each in the following manner.

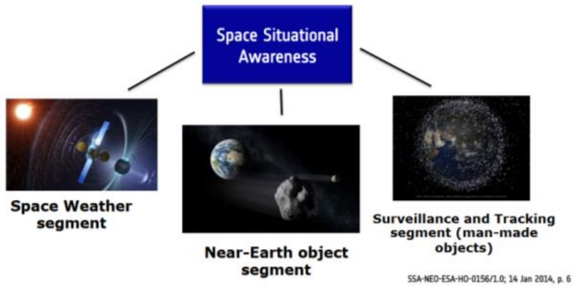

Figure 1. ESA Space Situational Awareness segments [10]

The Space Weather (SWE) segment of ESA SSA involves monitoring space weather "that can affect spaceborne and ground-based infrastructure or endanger human life or health." Space weather is described as "the environmental conditions in Earth's magnetosphere, ionosphere and thermosphere" and "phenomena involving ambient plasma, magnetic fields, radiation, particle flows and other physical happenings in space"[11]. The main activity of SWE, then, is, "monitoring conditions at the Sun and in the solar wind, and in Earth's magnetosphere, ionosphere and thermosphere".

The Near-Earth Object (NEO) segment involves observing the near-Earth space environment for NEOs. The class of NEO comprises "natural objects that can potentially impact Earth and cause damage", and involves "assessing their impact risk and potential mitigation measures". We read: "The SSA-NEO system is based on syndicating and federating observation and tracking data provided by a large number of European and international sources." [12].

The Space Surveillance and Tracking (SST) segment consists of surveying and tracking the artificial space objects in Earth orbit. This includes "active and inactive satellites, discarded launch stages and fragmentation debris that orbit Earth". The Database and Information System Characterising Objects in Space (DISCOS) [13] is one data system used by the SST segment. We read that any SST system is like a production line for observational data: "Sensors, such as telescopes or radars […] produce images of the Earth-orbiting objects" which "are then transformed into plots that describe the path or trajectory of any particular object. Then, the plot must be examined to determine if it is showing a new object, or one already known to the system." [14]

The scope of SSA according to the ESA can be summarized as that which occurs near Earth and the activities by which we gain situational awareness of that environment. This sense of SSA in Europe is thereby consistent with the broadest sense expressed in [5]. The SSA domain, then, encompasses objects and their interactions in orbital, near-Earth and deep-space environments, together with our activities in relation to them. Space objects and phenomena include entities such as asteroids, artificial satellites, orbital debris, and solar wind. SSA ontology, then, captures knowledge of these entities relative to Earth or some other central body.

To maintain awareness of the space environment, optical [9] and radar sensors positioned in various locations gather data on space weather events, on various orbital objects and transient objects throughout our solar system. This serves at least two functions. It provides essential data to predict and prevent dangers to Earth-based and space-based infrastructure; but also to improve our scientific knowledge. However, members of the space community have acknowledged [35][36] the need improve SSA and correct existing limitations.

For example, a 2016 United Nations (UN) Committee on the Peaceful Uses of Outer Space (COPUOS) presentation [33], along with the corresponding working paper [34] by the Russian Federation, outlines limitations of contemporary orbital information management. Among them are the following deficiencies in orbital information exchange

- Low data quality; Many false alarms
- Multiple databases; Varying levels of data quality and completeness; Potentially conflicting information
- Distinct data sources are not integrated
- No unified international mechanism for catalogues and identifying space objects.

The last three limitations are primarily what ontology should aim to address, but it is conceivable that the first be improved as an indirect consequence.

4 ONTOLOGY FOR ESA SSA PROGRAM

Given the data-intensive nature of SSA, ontologies are a means to help remediate the above-mentioned SSA information exchange limitations, and achieve the ESA goals of *data integration*, *systems syndication* and *applications-development*. First, an **ESA SSA Ontology** (Fig.2) will relate federated SSA databases by providing a common, standard, high-level, and formally-defined SSA vocabulary that semantically annotates database elements. Vocabulary terms and definitions can be drawn or adapted from existing ESA [25] and other [24] terminological sources. Second, ontology engineering for SSA represents a research track that can be applied to other data-intensive areas in the ESA space program. Ontology-driven learning tools, web-based apps [16], artificial intelligence and informatics [23] applications, are some possibilities.

The European Space Agency can develop an ontology architecture composed of modular ontologies, one for each SSA segment (Fig.2): an ESA **SWE Ontology (SWEO)**, a **NEO Ontology (NEOO)**, and a **SST Ontology (SSTO)**. These ontologies will provide reusable domain models for all ESA SSA databases. Ontological relations—formally represented as binary or n-ary predicates—provide the semantic link between classes within and between each ontology. These links are intended to express either real-world relationships between the instances/referents of the class terms, or the relationships between the corresponding concepts or conceptualization of the domain.

Each ontology can be used independently or imported into a single **ESA SSA Ontology** (ESA-SSAO) file, expressing a unified knowledge model of the domain. It would include the classes and relations from each ontology module. The semantic interoperability this should afford translates, in part, to an agreed-upon ESA SSA vocabulary for use across ESA databases.

Individual European nations that develop their own ontologies can do so in conjunction with a centralized ESA-SSAO. Nation-specific ontologies can extend and import the SSA segment ontologies or selected classes. For example, an Italian Space Agency (ASI) SSA ontology suite may need their own local ontologies, but reuse any upper-level (more general/abstract) categories asserted in an ESA-SSAO. The development of an ESA-SSAO should presumably be done as a group effort with ontology developers from each European nation state. This will limit redundancy among ontology terms, and ensure a unified ontological theory.

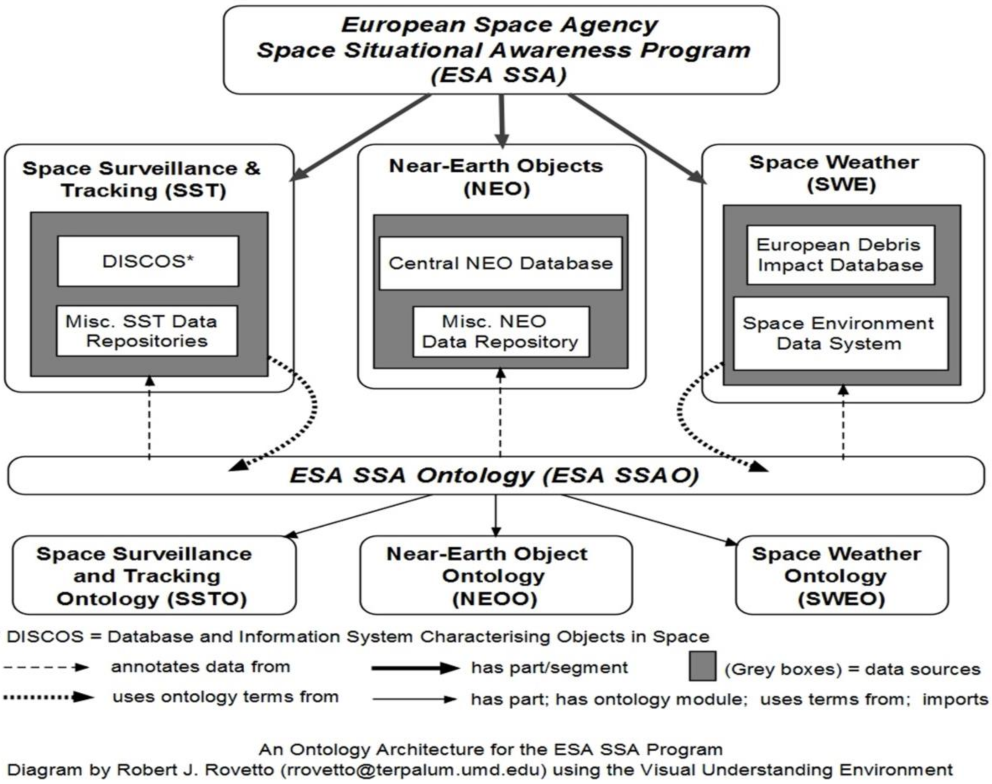

Figure 2. An Ontology Architecture for ESA SSA

As discussed in section 5, this architecture may incorporate the existing ontologies, the Orbital Debris Ontology (ODO) [4][17] and the SSA Ontology (SSAO)[5].

For each ESA SSA segment there are data sources and domain-specific entities of interest. I mention some databases and domain entities for each segment-specific ontology to draw upon and formally represent. This will specify each ontology scope.

4.1 Space Weather Ontology (SWEO)

Based on the description of SWE, but also from an ontological (philosophical) perspective, this sub-domain of SSA is ontologically committed to:

- Monitoring activities
- Earth’s magneto-, iono- and thermo-spheres
- Phenomena within, and causally engaged with, those atmospheric regions, such as…
- Particles, radiation, ambient plasma, magnetic fields,

An SWEO is an ontology of space weather phenomena in our solar environment. This includes ambient plasma; coronal mass ejections; the causal relations and processes between them, etc. There should be classes for all these entities. Space weather science, as well as satellite operators and other stakeholders, are not simply interested in the phenomena itself, but their interactions with Earth. The causal interrelationships with Earth and our space- and ground-based infrastructures (e.g., communications satellites, spacecraft, etc.) should also be captured.

The main activity of the SWE is solar-monitoring. This portion of the ontology may therefore import existing astronomical ontologies [19][20] (or selected classes). Alternatively, a SWEO can assert its own classes but specify equivalences and map terms between ontologies.

The Space Weather Coordination Center [15] has two data systems that may benefit from the proposed ontology architecture: the *European Debris Impact Database*, and the *Space Environment Data System*.

4.2 Near-Earth Object Ontology (NEOO)

The scope of a Near-Earth Object Ontology is that of natural celestial objects located in the near-Earth space environment. NEOO should therefore have terms for “asteroids or comets with sizes ranging from meters to tens of kilometres that orbit the Sun and whose orbits come close to that of Earth's.”[12]. It is an ontology of NEO objects and their properties. How they (and SWE & SST objects) interact with that environment may either be included or developed into a separate ontology.

The database mentioned in the following quotation can utilize a NEOO.

“In collaboration with European scientific and research institutes: develop a new central database for Europe's

NEO information (while maintaining current services)" [12]

4.3 Space Surveillance and Tracking Ontology (SSTO)

An SSTO would be an ontology of:

- space surveillance & tracking sensors, SST activities, methods and processes
- human-made objects in orbit, e.g., operational satellites, space vehicles, orbital debris, etc.

The DISCOS database can utilize an SST Ontology together with analytics software applications to reason over orbital data, and annotate observational data with SSTO terms.

Given the overlapping domain, two alternatives are to use the SSAO [5] in its place (i.e., as an ESA SSTO), or to link a local ESA SSTO with the SSAO. The next section provides a brief description of the SSAO, and explains further.

5 THE SSA DOMAIN REFERENCE ONTOLOGY (SSAO)

The Space Situational Awareness Ontology (SSAO) (Fig.4) is a domain reference ontology for the SSA. It provides a formal representation of high-level SSA concepts and entities (Fig.3 [5]). Along with related ontologies, such as the Orbital Debris Ontology (ODO) [4] (https://purl.org/space-ontology/odo), it is intended to be application-neutral, scalable and reusable by space actors handling SSA data.

The SSA ontology concept was described in [5] and draws on [4]. It is currently implemented in OWL format, is under development, subject to revision, open to collaborative development, and available by contacting the author. A future location of the OWL file will be https://purl.org/space-ontology/ssao.owl. An example user of the SSAO is [16] for ontology-based solar system visualizations, which demonstrates the potential for novel ontology-based applications and services (an ESA goal).

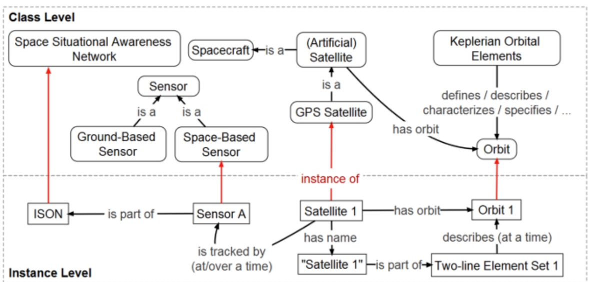

Figure.3. An ontological diagram of SSA entities.

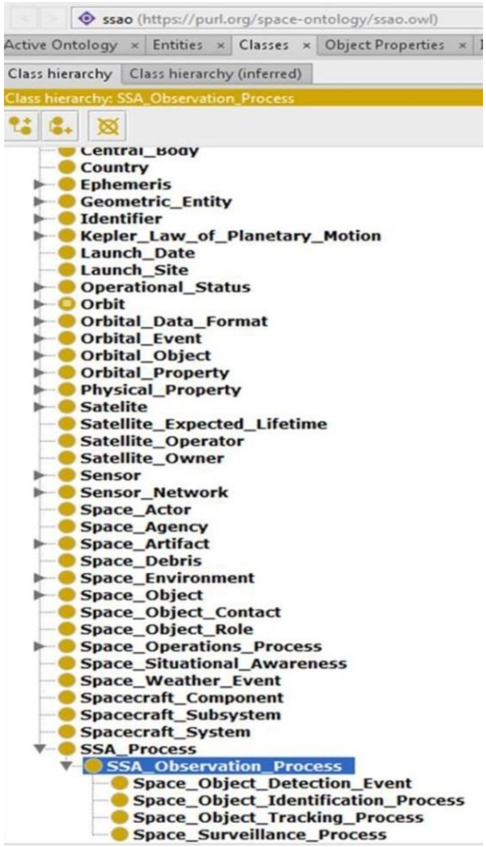

Figure 4. Part of an early version of the Space Situational Awareness Ontology [5] (https://purl.org/space-ontology/ssao), displayed in the Protégé ontology editor.

The SSAO includes defined terms for: observation, detection, and tracking processes; orbital concepts; artificial satellites; sensors, space systems; etc.

As it pertains to ESA SSA, the current scope of the SSAO includes that of the ESA SST segment. General SSA terms that an ESA SSTO would need are currently found in the SSAO. Therefore, the ESA can reuse the SSAO, import selected classes therein, and collaborate for further development as needed. Alternatively, an in-house ESA SSTO can map its own terms to the SSAO, or extend the SSAO. NEOO and SWEO terms should be related to SSAO terms via the appropriate relational predicates. Similarly, given that space debris is a primary concern of SSA, ODO may also be reused and extended. The alternative is the ESA develop a local Space Debris Ontology.

The SSAO and ODO are part of The Orbital Space Ontology project (https://purl.org/space-ontology), presently an independent effort whose products are offered as domain-specific but upper-level (generic) ontological representations and common terminologies for the space community. Its space vocabulary is growing and used in the respective modular ontologies.

6 POTENTIAL APPLICATION

The web interface of the ESA NEO segment serves as an example source of data and concepts for "ontologizing" the domain. Fig.4 is a screen capture of the search page (http://neo.ssa.esa.int/search-for-asteroids), displaying results for Asteroid 2015NK13. I add red boxes to mark domain-specific class terms, values for physical properties, and the asteroid name.

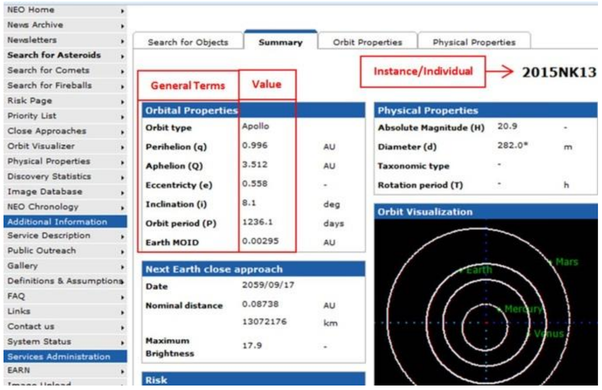

Figure 5. ESA NEO Web Search screen capture with selected class and value terms in red boxes.

From this (and other) resources we find fundamental domain concepts and essential terms for the ontology vocabulary. Orbital properties, for example, are key properties to model. Classes include Perihelion, Aphehelion, and Eccentricity. Values include the particular numerical quantity and unit for the class, e.g. 0.99 Astronomical Units.

In addition to space debris objects and artificial satellites, themselves, ontologies can represent images (or other graphical representations) of them and their orbits. Imagery data can be annotated with ontology terms, to express another level of abstraction and add another layer of semantics to SSA data. Fig.6 is a screen capture from the interactive ESA NEO Orbit Visualizer (http://neo.ssa.esa.int/orbit-visualizer) for asteroid 2015NK13. I have added red annotations ontologically describing some of the graphical elements.

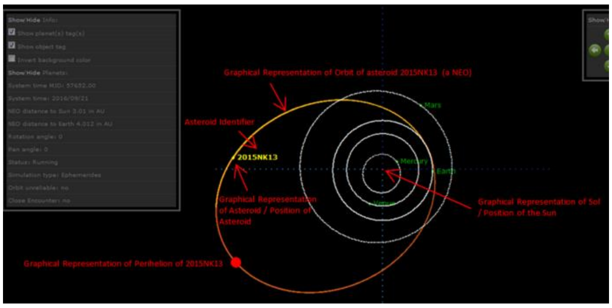

Figure 6. Screen capture of ESA Orbit Visualizer with my added annotations in red

Classes (and definitions) should represent (and describe) graphical elements, e.g., circular shapes for orbits. From the information in these sources, I manually produced a diagram (Fig.7) to visualize a high-level ontological conceptualization. Fig.6 depicts one option for an ontological characterization of the asteroid, it properties, and graphical representations (images) thereof. Rounded rectangles, their heavier-bordered counterparts, and rectangles represent Classes, Instances, and Values. Arrows represent relations between them.

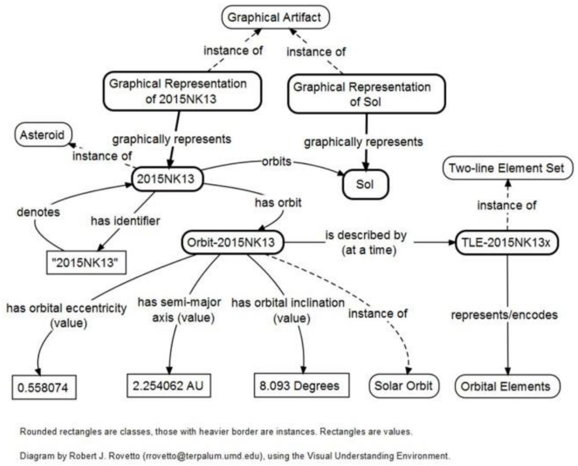

Figure 7. Diagram portraying an ontological characterization of the interelations between a particular asteroid, some orbital properties and graphical representations (e.g. imagery) thereof. Rectangles, rounded rectangles, and heavy-bordered rounded rectangles represent numerical values, classes and instances, respectively. Arrows represents various relations.

Fig.6 portrays classes such as Asteroid, Two-line_Element_Set; formal ontological relations such as instance_of, and domain-specific relations such as has_orbital_inclination. Such high-level modelling can be extended with lower-level (more specific) satellite imagery characteristics, such as those represented in [43], where we find ontology-based remote sensing imagery methods. The SSAO [4-7] has corresponding classes for the aforementioned orbital space entities.

7 CONSIDERATIONS & POTENTIAL FOR GROWTH

The ESA SSA segments (or sub-domain) naturally overlap in some respect. Each expresses a certain delineation of an area of study or task, but they are in fact related. All require observational activities, for instance. Moreover, the relationship between solar activity (SWE) and its effect on atmospheric density may have some causal influence on the trajectories, orbits and behaviour of active artificial satellites and space debris (SST)[52][53]. The actual and potential relationships between these entities and our activities in relation to them should be captured in an ontology to provide a holistic scientific picture.

Given the overlapping domain and scope, the ESA may use the SSAO[5] and ODO[4] instead of, or in concert with, developing an SST ontology. This will stimulate partnerships, and help improve these existing ontology products. Similarly other potential partnerships are with [22] and [21], given the shared domain of interest.

An ESA SSA ontology project is an opportunity to (re)establish partnerships with space actors such as NASA on projects of mutual interest (perhaps via the SSAO and [16]). Moreover, in a 2006 paper, we read mention of an "[…] effort to provide interoperability with the European Space Agency (ESA)/Planetary Science Archive (PSA) which is critically dependent on a common data model." [48] The space ontology architectures concepts in [8] include the ESA, NASA, academia and industry in an interoperable system.

With this comes the potential for innovative applications, such as augmented and virtual reality [49][50] based on ESA data, which can be in turn have a thorough semantics provided by ontologies. An ESA SSA Ontology can also draw on Earth-observing imagery ontologies for ontological representations of sensors and imagery data.

Finally, in the knowledge engineering ULISSE project's [49-51] 'Result in Brief' we read: "[…]the project team proved that building an e-infrastructure for scientific data preservation and exploitation is feasible, and can become a valuable tool for research. This will pave the way for a more sophisticated research mechanism that will support space research and strengthen the European knowledge economy, with direct benefits for scientific productivity and education."

Thus, ontology for ESA SSA has the potential for improving ESA data fusion, developing novel applications, and engagement in partnerships.

8 CONCLUSION

The European Space Agency can improve its goal of integration across its space situational awareness data systems by developing an ESA SSA Ontology framework. This paper presented a concept for a modular ontology architecture that mirrors the structure of the ESA SSA program. It would consist of a Space Surveillance and Tracking Ontology, a Space Weather Ontology, and a Near-Earth Object Ontology. Given the overlap in domain and scope the ESA may reuse the Space Situational Awareness Ontology (SSAO) [5], the Orbital Debris Ontology (ODO), and related ontology work by the author [4][6][7]. By applying ontology to ESA SSA data, the ESA can demonstrate ontology-based proof of concept for its SSA data integration and interoperability goals, as well as spur innovation, partner with prior ESA (and other) ontology efforts, and improve the state of peaceful SSA.

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