Semantic Aspects of EarthCube

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Purpose

In this document, we give a high-level overview of selected Semantic (Web) technologies, methods, and other important considerations, that are relevant for the success of EarthCube. The goal of this initial document is to provide entry points and references for discussions between the Semantic Technologies experts and the domain experts within EarthCube. The selected topics are intended to ground the EarthCube roadmap in the state of the art in semantics research and ontology engineering.

We anticipate that this document will evolve as EarthCube progresses. Indeed, all EarthCube parties are asked to provide topics of importance that should be treated in future versions of this document.

Deep Versus Shallow Semantics

Ontology languages—and knowledge representation languages in general—differ in terms of expressivity, i.e., they differ with respect to the language primitives that they provide for modeling, and in the extent to which these language primitives are endowed with a formal semantics. Knowledge representation in this respect can be traced back to a history that is over two thousand years old (see, e.g., [HKR10, Chapter 1]), and the state of the art in ontology engineering and Semantic Web is reaping the rewards of this long-standing tradition.

It is in exactly this tradition that ontology languages, such as the W3C standards OWL [HKP+09] and RDF [MM04], are endowed with a so-called *formal semantics*, which is essentially based on the model-theoretic semantics of mathematical logic. In an ontology engineering context, this semantics can be understood as an *inferential* semantics, which, intuitively, determines how the joining of different pieces of knowledge *entails* new knowledge, in the sense of logical, deductive, inference.

OWL and RDF differ, e.g., in terms of language constructs, the meaning of which is captured by the respective formal semantics. For example, OWL provides the *owl:sameAs* language construct. The formal semantics of OWL essentially declares that it is used for identifying two resources (i.e., URLs), which refer to the same entity. Hence, whatever is said about the first, can be inferred to also hold for the second. While RDF does not forbid the use of owl:sameAs, its formal semantics does not capture this meaning, i.e., from an RDF perspective, owl:sameAs can only be used informally, and its meaning is up to the user or to the system that happens to encounter it.

OWL, in fact, provides a stronger (or deeper) semantics than RDF, in the sense that it has more language constructs with a formally defined semantics. OWL and RDF can thus be understood as being part of a spectrum of knowledge representation languages, which range from very shallow (or even formal semantics-free) languages, to languages with very strong formal semantics that significantly surpass OWL in terms of language constructs and engineering capabilities [Obr03]. For example, on the very shallow end of the spectrum is tagging with natural language terms (for which the semantics is not formally defined, but determined by our use of natural language and domain-specific scientific terms, i.e., informal or controlled, but relatively unstructured vocabularies), or the use of microdata (as, e.g., in schema.org). Taxonomies, thesauri, and class hierarchies also range at the shallower end. The OWL 2 tractable profiles [HKP+09] range between RDF and OWL 2 DL. At the deeper end, beyond OWL, are e.g., full first-order logic languages such as ISO Common Logic [CL], extensions of first- (or even higher-) order predicate logic by expressive means of the likes of uncertainty handling, commonsense reasoning, temporal modalities, to name just a few.

Both shallow and deep semantics approaches respective benefits and drawbacks. Shallow approaches, for example, are easier to get started with, but miss rigor as they suffer from a lack of power to restrict possible multiple interpretations, and thus make it more difficult to realize subsequent knowledge integration and interoperability. Deep approaches are harder to understand, and engineering is a serious effort, though with the advantage of making it easier to bridge heterogeneity gaps. In general, deeper approaches enable greater precision and accuracy in the applications which use them. It could perhaps be claimed that the recent success of ontology engineering and Semantic Web Technologies rests at least partially on the fact that RDF and OWL map out a *sweet spot*, a reasonable compromise between deep and shallow semantics.

For EarthCube, it is important to understand this issue, and to carefully navigate this spectrum while being aware of the trade-offs involved. In particular, it would be naive to expect that knowledge engineering could start on the shallow end of the spectrum, and then subsequently be refined or deepened as EarthCube progresses. A recent and rather prominent example for the fallacies in this approach is the use of the aforementioned owl:sameAs language construct in RDF-based Linked Data [BHB09]: While it is occurs in very substantial quantities, its usage is mostly informal and in particular is not aligned with the formal semantics that it should inherit from OWL [HHM+10]—a problem with, at hindsight, could have been avoided by taking deep semantics into consideration in the first place. With respect to EarthCube, a shallow semantics approach seems sufficient for tasks such as improved retrieval but is likely to fail for data integration.

Semantic Interoperability and Semantic Heterogeneity

While we still lack a formal definition of semantic interoperability, it is usually defined as the ability of services and systems to exchange data in a meaningful way [HKPBR99, GEFK99]. For example, from a systems perspective, semantic interoperability can be 'defined as the enablement of software systems to interoperate at a level in which the exchange of information is at the enterprise level. This means each system (or object of a system) can map from its own conceptual model to the conceptual model of other systems, thereby ensuring that the meaning of their information is transmitted, accepted, understood, and used across the enterprise.' [OWM99] In contrast, syntactic interoperability only focuses on the technical ability of systems to exchange data. To give a concrete example, a service may request data about wind speed and direction to compute the dispersion of a gas plume and request both values as floating point numbers. A service that can deliver such weather data is called syntactically interoperable. If, however, the first service expects a 'wind blows from' semantics while the second service offers data in a 'wind blows to' semantics, the results of the dispersion model will be wrong and potentially dangerous [PL04, K05]. While, strictly speaking, data cannot interoperate, the term is often used in a broader context. Semantic Interoperability is key to EarthCube and all other infrastructures in which data has to be published, reused, and integrated. The risk associated with a lack of semantic interoperability is that incompatible data is unwittingly combined or that unsuitable methods and models are applied to datasets. Many spectacular cases have been reported over the last years, the crash of the Mars Climate Orbiter due to a confusion between English and metric units being one of the most prominent examples [B06]. Geospatial ontologies [K05,E02], semantic annotation of geospatial data [FS02], matching/alignment of multiple, local ontologies, ontology-driven Web portals [MSSSS03, LRGJ12], query processing for heterogeneous geospatial sources [CX08], and geospatial ontology-driven analysis [ASRUAK06] have been proposed as one way to capture the body of knowledge of a specific domain and assist scientists in understanding methods and datasets.

Semantic technologies and ontologies are believed to be core components in establishing semantic interoperability as both help to restrict the interpretation of domain terminology

towards their intended meaning and hence allow for more intelligent metadata. As ontologies are best thought of as constraint networks [K09], semantic interoperability can never be guaranteed in infrastructures that require the on-the-fly combination of data or service chaining. Hence, in addition to ontologies, reasoning services are required that support service matching [GH07] or translate between ontologies. Over the last 10 years, service interoperability has been addressed by several proposals and standards such as OWL-S [OWLS04], WSMO [RKL+05], WSDL-S [A05]/SAWSDL (a W3C recommendation) [VS07], SA-REST [SGL07] or USDL [USDL11]. While these approaches propose service ontologies as an essential part, additional work is required to ensure that different knowledge and service infrastructures can interoperate. For instance, the so-called Geo Web that is largely based on services defined by the Open Geospatial Consortium (OGC) cannot communicate with the Semantic Web which will be a major roadblock for EarthCube. A Semantic Enablement Layer [JSBKMS09] can transparently mediate between both infrastructures and, hence, allow Spatial Data Infrastructures (SDI) to access reasoning services, Linked Data, and ontology repositories from the Semantic Web as well as the other way around, e.g., enable Semantic Web applications to dive into the Geo Web. Such a layer needs to be transparent to ensure that no changes to existing and well standardized infrastructures are required. First implementations for the semantic enablement of several SDI components have recently been published [BMJNM11, SSOR09, JBSSEL11, MMR12, HPST09]. GeoSPARQL has recently been standardized and proposed as a common query language for the Geospatial Semantic Web; see [BKta] for an introduction.

Instead of continuing the millennia old search for the universal ontology, different types of ontologies have been proposed in computer science. The classification of ontologies based on their granularity and thematic scope into top-level, domain, task, and application ontologies was first introduced by Guarino [G98]. An alternative classification into global and local ontologies has been proposed by Uschold [U00], while others distinguish between domain-independent and domain-specific ontologies. Several global, top-level ontologies such as DOLCE, SUMO, BFO, GFO, and Upper Cyc have been proposed as well as domain ontologies for the Earth sciences such as SWEET [RP05]. Initially, it was assumed that each scientific discipline could agree on a domain-level ontology and that these ontologies could all refer back to one common foundational ontology. Lower level ontologies, e.g., application ontologies, were thought of as mere specializations of these ontologies. It turns out, however, that even within very specific domains it is difficult to get scientists to agree on a common definition for their domain vocabulary and especially to align these definitions with the very abstract and loaded classes from top-level ontologies. For instance, lenticular clouds can be classified as events or physical objects at the same time [G04] while these two classes are often defined as core distinctions in top-level ontologies. More recently, Sinha and Mark [SM10] demonstrated that feature types such as Hill can be specified as physical objects, features, or amount of matter, while these three classes are among the core distinctions proposed by the DOLCE foundational ontology for physical endurants. In other terms, many types are multi-aspect phenomena [G04] to a degree where even top-level distinctions cannot be utilized without reference to context. However, there are approaches that attempt to address linkages between these notions via bridge axioms, including BFO notions of SNAP and SPAN, i.e., temporal snapshots vs. temporal

spans [GS04]. Similarly, the theory of granular partitions [BS03, BSM07] does take into consideration context, and tries to resolve problems related to parts of objects. The relation between objects and events and their ontological distinction has been an active area of research for many years, see, e.g., [GM09]. Consequently, taking heterogeneity as reality, the increasingly popular Linked Data approach does not follow the idea of a few authoritative ontologies but proposes to define local and application centric ontologies to suit the needs of specific data sets and repositories.

This paradigm shift is accompanied by a changing focus towards ontology matching, alignment, semantic translation [SE08,JHSVY10], and multi-ontology query processing [MKSI96] that allow to directly interact between different ontologies without the need to agree on one common reference first. Ontology design patterns, a (partial) analogy to the successful software engineering design patterns, have been proposed to support the development of a multitude of ontologies [G05]. Examples of such patterns that have been applied to semantics-based systems in the geosciences include the Semantic Sensor Network ontology [W3CSSN12]. In a highly interdisciplinary setting, semantic heterogeneity should not be misunderstood as a burden but is a consequence of diverse models, methods, and viewpoints brought in by different scientific disciplines and ongoing debates with domains [J10]. Semantic Web technologies and knowledge engineering frameworks should assist domain experts in making their conceptualizations explicit, and hence foster data sharing and reuse by supporting semantic interoperability without giving up on diversity [J12]. Similarly, there is no need to agree on one common representation framework. To support a knowledge infrastructure and community such as EarthCube, ontologies based on description logics (e.g., OWL) have to go hand in hand with numerical and statistical models [SRT05]. Currently, Semantic Web research is investigating how machine learning can assist in extracting knowledge from data and in reducing the burden of ontology engineering [SKW08, TMBS08, LH10, FDF12, RLTDF12, J12]. Such a data-driven perspective is also gaining ground in the area of geospatial semantics [BMT08, SM10b]. Bottom-up approaches, however, cannot replace top-down engineering–both have to work hand in hand. EarthCube will require a lattice of theories that fosters interoperability and at the same time allows for multiple perspectives. Such a lattice of theories will consist of top-level and domain-level ontologies, local and application-centric micro-ontologies, as well as bottom-up learned fragments. Semantic Web reasoning systems will enable integration within this lattice.

Limits of the Ontological Approach

Like every knowledge representation language, the Web Ontology Language OWL [HKP+09] has advantages and disadvantages. The main advantage of using OWL as a basis for EarthCube is, that in doing so, EarthCube is aligning with the current mainstream, which will make it easiest to import new methods, tools and existing ontologies and data.

Concerning some of the known drawbacks of OWL, it is important to notice that state of the art research is actively addressing them, and while newest developments take time before being

incorporated in a standard, some methods are mature enough to be used in conjunction with OWL. Other capabilities may in fact remain out of scope for EarthCube, or should be incorporated only in a very careful manner in cases where they are unavoidable. The following are some of the important "known drawbacks" of OWL.

Use of rules paradigms

The Rule Interchange Format, RIF [KB10], is a W3C standard for expressing rules on the Web. Rules and OWL were for a long time thought to be very complementary, with radically different design rationales. However, it is important to notice that many (monotonic, Datalog-style) rules can already be represented in OWL 2 DL [KMH11] (but were not representable in OWL 1 DL). Furthermore, recent research is significantly closing the gap. For example, a new construct called nominal schemas [KMKH11], which is a very light-weight extension to OWL [CKH12], makes it possible to represent arbitrary Datalog rules, even without restriction on the arity of the predicates. It thus completely captures, for example, DL-safe SWRL [HPB+04] and RIF Core [BHK+10]. Another light extension of OWL, so-called conjunctive roles [CH12], makes it possible to capture most Datalog rules under a first-order logic semantics. Providing tool support for these rules-extensions of OWL could easily be realized within EarthCube by extending existing tools for OWL (e.g., the Protege OWL editor). It can be expected that such "light" extensions, which cover Datalog-style monotonoic rules, would cover many of the rules-modeling requirements within EarthCube.

Non-monotonicity, i.e., local world closure and defaults

Capabilities of non-monotonic logics, such as default reasoning or the (local) closed-world assumption are not present in OWL. However, there is a significant body of knowledge on extending OWL with such capabilities (some of which is closely related to the OWL and Rules integration discussed in the previous paragraph). For an overview, see the related work sections in [KMH11, KSH11] and [KHM12]. However, since the research discussion is still very much in flux, it may be advisable to incorporate such capabilities only in a very careful manner, until the foundations have been solidified. *Simple* adaptations for modeling local closure or defaults, may be possible, and the concrete methodological approach will have to be determined based on use case requirements.

Modeling of uncertainty and probabilities

OWL in its current form does not provide for the modeling of uncertainty or probabilistic knowledge. Extensions have been developed, indeed there is a significant body of work on this, but it is still rather unclear which of the proposals would constitute "preferred" paradigms. Since the research discussion is still very much in flux, it may be advisable to incorporate such capabilities only in a very careful manner, until the foundations have been solidified. *Simple* adaptations for modeling uncertainty may be possible, but the concrete methodological approach will have to be determined based on use case requirements.

Spatial Reasoning Ontology Standards

A large amount of Earth Science linked data has an inherent spatial context. Without spatial reasoning, however, the value of this spatial context is limited to Earth Scientists. Over the past decade several vocabularies and query languages with varying levels of support for fundamental geospatial concepts have been attempted to exploit this knowledge and enable spatial reasoning. [ASRUAK06] gives examples of and strategies for computing geospatial relationships such as topological relations, cardinal direction, and proximity relations. Recently OGC sponsored a new standard called GeoSPARQL [OGC11, BKta] that attempts to unify data access for the geospatial Semantic Web. GeoSPARQL promised to be a standard vocabulary for many current data sets. Since the standard started with spatial comparisons, some feature add-ons are possible in the next two to four years. These should be of value to the Earth Science community. An example would be the addition of different coordinates reference systems used in earth sciences to supplement the current geographic coordinate reference systems.

Knowledge Acquisition (including Extraction from text), CMaps (cognitive maps) and Domain Expert Support

Developing domain ontology/knowledge bases remains a major bottleneck and risk since it is a resource intensive and time-consuming task. Quality knowledge acquisition has had a high barrier and requires the cooperation of earth science domain specialists, who provide concepts, and ontologists/knowledge engineers to faithfully structure and represent these in processable forms. It is generally impractical for the average earth science subject-matter expert to learn knowledge engineering and proper structuring of formal ontologies. (Initiatives within the Social Semantic Web recognize this problem, and have begun to identify mechanisms to collective motivate users to volunteer time and resources to participate in the semantic content creation process [SS10].) Due to time constraints it is also generally impractical for a large group of knowledge engineers and ontologists to master the concepts, terminology and principles of one or more earth science domain and/or independently extract domain knowledge from documents. Collaborative methods and the use of ontology patterns are one way the problem is being addressed, but several technologies and complementary tools are also important [Cue05]. These include:

- Conceptual modeling (Cmap) tools that are easy enough to learn and simple enough to use to allow domain experts to capture their background and domain knowledge along with reasoning approaches in intermediate, expressive forms. CMAP tools present a simple graphical representation in which instances and classes are presented as nodes, and relationships between them are shown as arcs. Resulting concept maps can be used to enable discussion and to later generate formal domain ontologies and supporting background knowledge. Tools of this type include various concept map tools such as CMAP, OntoEdit & Mind2Onto, MAP2OWL, and COE.
- Tools and technology that support conversion of conceptual models into a formal representation including if-then rules (COE).

- Tools to extract background and domain knowledge from text including Web documents and represent it formally (e.g., Text2Onto [CV05], TEXCOMON, Text to Knowledge Mapping [OE06], YAGO [SKW08].).
- A class of tools that provides enhanced metadata descriptions to text (e,g, YAGO-NAGA tool and approach).
- Tools to allow domain expertise to express their knowledge in a controlled form of natural language to manage both the syntactic and semantic ambiguities of ordinary language by enforcing a single definition for every term. Controlled forms can then be converted to some formal representation such as OWL (e.g. Attempto Controlled English (ACE), Rabbit & Roo [HJD08], Peng-D [Sch05], ClearTalk [Sku03] and Gino (guided input natural language ontology editor).
- Tools that visualize formal languages in a simple form and allow easy editing. Examples include GrOwl [KWV07].

Semantic Mediators and Intelligent Brokers

Agent Brokering employs central mechanisms to help resolve such things as disparate vocabularies, support data distribution requests, enforce translatable standards and to enable uniformity of search and access in heterogeneous operating environments. Broker architectures have an important role in addressing interoperability and data integration issues in federated data and agent-based systems. Brokering is currently employed widely by Spatial Data Infrastructures (SDIs), current examples of which include the USA National Spatial Data Infrastructure in the USA, and INSPIRE in Europe. Examples in the geosciences include GEON, CUAHSI, OneGeology and the Semantic Mediator of the Marine Metadata Interoperability (MMI) Project. The MMI mediator allows registering a vocabulary or service and issuing a semantic query on these. Projects that have used the MMI semantic mediator include the International Coastal Atlas Network (ICAN), OOSTethys (OGC Ocean Science nteroperability Experiment), Oceans Innovation Demo 2008 and Q2O (QARTOD 2 OGC). Based on such experience they have been proposed as part of the CI approach within the EarthCube Interop group.

This makes sense given that broker approaches and their implementation are rapidly maturing with embedded capabilities that now include new technologies such as terminology and semantic meditation. In the Biomedical realm, for example, standardized terminological services have been developed as an insertable module to refine user queries. They have also been used for mapping the user's terms to appropriate medical vocabularies. Mediating broker have been developed to help with composition of services and information on the Semantic Web. In such efforts compositional knowledge is used to help automate Web service flow generation. This includes operational (syntactic), semantic and pragmatic knowledge. Operational knowledge helps assure that correct output and input types for possible service composition, while the semantic component uses domain-specific expert knowledge to shape the Web service compositionality.

Knowledge Sifter [KCD+04] is an example of a scalable agent-based system that supports access to heterogeneous information sources such as the Web, open-source repositories, XML-databases and the emerging Semantic Web. The Knowledge Sifter architecture consists of layers of specialized agents reside that perform well-defined functions to supports interactive query specification and refinement, query decomposition, query processing, integration, as well as result ranking and presentation.

EuroGEOSS is an Earth Science Brokering framework (i.e., a family of brokers including semantic mediators) employed to bind various heterogeneous resources and adapt them to different community tools. In collaboration with FP7 GENESIS project (http://www.genesis-fp7.eu/), EuroGEOSS prototyped a Semantic Discovery Broker extending functionality of the existing Discovery Broker capacity. It implements a "third-party discovery augmentation approach": enhancing discovery capabilities of infrastructures by developing new components that leverage on existing systems and resources to automatically enrich available geospatial resource description with semantic meta-information. Currently, the EuroGEOSS DAC is able to use existing discovery (e.g. catalogs and discovery brokers) and semantic services (e.g. controlled vocabularies, ontologies, and gazetteers) in order to provide users with semantics enabled query capabilities, helping to bridge a critical gap that hinders multidisciplinary infrastructures.

Brokering frameworks, such as EurpGEOSS, follow several simplifying principles to help manage risks and enable improved semantic brokers to be added to the architecture:
- Use *Autonomy and Modularity* to keep the existing capacities as independent as possible by interconnecting and mediating standard and non-standard capacities;
- *Enhance and Supplement*, but do not supplant, system mandates and prior governance arrangements;
- Provide *Low Entry Barriers* for both resource users and data producers;
- Support *Flexibility and Extensibility* to accommodate existing and future information systems and information technologies; and
- *Incrementally Build On* existing cyberinfrastructures and incorporate heterogeneous resources by introducing distribution and mediation functionalities to interconnect heterogeneous resources.

Ontology Repositories and Management

Earth Science and affiliated fields like climatology increasingly has a need to assemble, integrate and analyze large datasets. This remains a challenge because archived data reflects heterogeneous data models and independent conceptualizations, which makes meaningful data sharing difficult. Metadata to annotate the meaning of data is a central feature of information sharing infrastructure to provide such capabilities as:
- data and service discovery,
- facilitating interoperability and

- linking.

Large catalogs or repositories of meta-data are now part of several cyberinfrastructures (CIs) engaged in overcoming the challenging of sharing primary data in the Earth Sciences. Examples include the Earth System Grid (ESG) [WAB+08], INSPIRE [NBR+09] and the HydroCatalog & the metadata services used by CUAHSI (http://semanticcommunity.info/@api/deki/files/13844 /=056_Tarboton.pdf). ESG projects can register appropriate data characteristics (e.g., dataset title, variable names, spatial and temporal boundaries, etc.). INSPIRE includes a Discovery Service about web service capabilities but also to discover and get metadata for specific resources based on the resource unique IDs.

Such efforts are a useful first step, however, the establishment of community metadata standards, frames and creation of applications and standard formats to facilitate collection remains a challenge. For one thing there remain many meta-data formats which allow semantic mismatches. Most metadata lacks proper and systematic semantics to handle diverse data bases and schemas. Current metadata standards, including those specified by the FGDC for spatial data, were not designed for automated Web searching. More semantic languages, such as RDF(S) and OWL, along with tools for dealing with ontologies, can be used to provide better common metadata with useful knowledge structures. As part of the EarthCube CI, large repositories of Earth Science data should be converted into RDF and linked to the existing linked data cloud (http://linkeddata.org/).

To help handle semantic heterogeneity for querying and processing, background and local ontologies in proper semantic languages are needed to resolve individual data source terms or parameter identifiers within and between domains. Further, some integrated upper level suite of ontologies, driven by use case requirements combining particular aspects of domain ontologies would help integrate between different domains. These need to be stored in easily accessed repositories to enable wider use.

Ontology repositories are now part of the semantic thrust in other fields such Biomedicine. BioPortal (http://bioportal.bioontology.org/) provides a good example of a well-maintained virtual repository for ontologies and other knowledge sources, along with a number of services to improve reusability of ontologies, annotations and mappings. Other individual and inter-related ontology repositories are now being created, including several members of the EarthCube community, as part of the Open Ontology Repository (OOR, http://openontologyrepository.org/) [BS09]) effort. This is a volunteer effort to promote the global use and sharing of ontologies by:

- establishing a hosted registry-repository
- enabling and facilitating open, federated, collaborative ontology repositories
- federating independent registries to enable sharing of common vocabularies and ontologies
- community based annotation and mapping, along with search and other capabilities to promote sharing and reuse

- establishing best practices for expressing interoperable ontologies and taxonomy work in registry-repositories.

All work is in compliance with open standards and uses:

- open technology (open source)
- open knowledge (open content)
- open collaboration (transparent community process)
- open to integration with "non-open" repositories via an open interface

OORs are currently used to collect such things as geospatial ontologies as part of an NSF INTEROP project (www.socop.org). Another example is the Ontology Registry and Repository (ORR) developed by the Marine Metadata Interoperability program [RBF09]. ORR is a key enabler for the MMI mission to promote the exchange, integration and use of marine data through enhanced data publishing, discovery, documentation and accessibility [GIR12]. ORR leverages and integrates well-known libraries and open source technologies to provide the oceanographic community with easy-to-use tools for creation and maintenance of vocabularies and term mappings, as well as a central location for such artifacts to greatly facilitate discovery and sharing.

Such ontology repositories have capabilities to store, manage and share ontologies, map between ontology terms, and provide browsing and search for ontologies.

Once developed, ontologies for EarthCube could be stored in these existing repositories, to allow search and update. These should be distributed, or a dedicated EarthCube ontology repository. In either case, the EarthCube cyberinfrastructure needs to supplement the existing metadata catalog to access ontologies in repositories modularly designed to work with the CI architecture.

Semantically Driven Workflows

Semantics and ontologies can play an important role in scientific workflows composition for distributed scientific data analysis [PDS10, GGK+12]. Furthermore, semantics and ontologies can play an broader role in large scale spatial planning and decision support [LRGJ12], where one encounters different levels of workflows, with information associated with higher level workflows constituting semantic constraints for lower level workflows. Large scale land-based environmental planning and decision making problems typically involve collaborative research across earth science domains as well as social and information science domains. The process for solving such "Grand Challenge" problems (e.g. regional-scale assessment and planning process for reducing conservation conflicts between threatened and endangered species conservation and energy development projects) typically follow a high level workflow consisting of steps such as defining the planning goal/objectives and the decision problem, establishing evaluation criteria for desired state of the system, developing or adopting domain process models, developing data, assessing current states of the system, designing plan alternatives, performing impact analysis on design alternatives, evaluating design alternatives and selecting a plan, etc. Each of the steps could involve a series of sub steps, and some of them involve domain process

modeling – creating conceptual models for domain processes (e.g. cause-effect models among anthropogenic activities, stressors, habitat resources and species), and creating corresponding computational workflows to be used in assessing the current or simulated state of the system. Such computational workflows would in turn include scientific workflows for data processing, modular analytical tasks, visualization, and so on. Just as we have a choice from deep and formal semantics to shallow, lighter weight and implicit semantics, we will have a choice of using enterprise class semantic web services along with semantic search, discovery, composition and orchestration vis-à-vis semantically annotated RESTful services and semantic mashups [SGL07, SBRSS08] .

Ontologies can be used to formalize planning process workflows, domain process workflows, and scientific workflows. Besides coding the various levels of workflow templates, ontologies can be used to semantically annotate the resources needed for instantiating a workflow template (data sets, models and tools), indicating their purpose or classification, for example. Semantic registration of these resources is essential for automatic resource discovery on CyberInfrastructure, which is essential for automatic workflow orchestration. Coupled with semantic reasoning, ontologies can further guide workflow template instantiation, or guide new workflow template composition. There are many ways that the attributes of a specific planning process can semantically inform lower level workflows. For example the type and characteristics of a specific planning problem (e.g. site search or selection) may provide guidance or constraints on the type of algorithms (e.g. optimization) to be used in the computational workflow during the solution alternative design step, or the presence of multiple participant types in the planning process may suggest the use of some specific type of algorithms for deriving a common set of evaluation criteria weights (e.g. the consensus convergence algorithm). When composing a scientific workflow under a domain process computational workflow, the semantic information on the "entity type" being considered and the bounding geographic area for the entity distribution in the domain process workflow can be used to specify the input data requirement for the scientific workflow. Some of these semantic constraints are propagated down from the planning process workflow (e.g. from the planning objectives and planning spatial extent) to the domain process model workflows. All this will furthermore affect the choice of software tools (which implement algorithms) to be used during a scientific workflow.

Effective collaborative research between the Semantics and Ontologies Working Group and the Workflow Working Group can benefit from working on a common Grand Challenge type problem use case. Large-scale environmental planning problems can provide such use cases since they involve applying computational workflows to process massive amounts of heterogeneous spatial data with ever increasing analytic complexity, work that cuts across different earth science domains to social and information sciences, and can provide end-to-end interoperability use cases for EarthCube initiatives.

Conclusions

The Web has been a great boon to scientists by making it easier for them to collaborate, share documents and develop common resources and tools. The Semantic Web technologies will enhance, deepen and accelerate their ability to collaborate by enabling scientists to share their data, scientific models and software services in ways that support automated discovery, interoperability, fusion and reuse. There are tremendous opportunities in the Geosciences for applying this approach to develop a cyber infrastructure that will help to advance the field with both short and long term payoff. This document has outlined several of the immediate steps that can be taken as well as identifying some of the longer term issues and goals. We welcome feedback and contributions from the Geoscience and Computing communities.

References

[A05] Akkiraju, et al. The Web Service Semantics – WSDL-S. W3C member submission, November 2005. http://www.w3.org/Submission/WSDL-S/

[ASRUAK06] Ismailcem Budak Arpinar, Amit P. Sheth, Cartic Ramakrishnan, E. Lynn Usery, Molly Azami, Mei-Po Kwan. Geospatial Ontology Development and Semantic Analytics. T. GIS 10(4): 551-575 (2006).

[B06] Yaser Bishr. Geospatial semantic web. In Sanjay Rana and Jayant Sharma, editors, Frontiers of Geographic Information Technology, pages 139–154. Springer, 2006. ISBN 978-3-540-31305-2.

[BHB09] Christian Bizer, Tom Heath and Tim Berners-Lee, Linked Data - The Story So Far, International Journal on Semantic Web and Information Systems 5(3), 2009.

[BKta] Robert Battle and Dave Kolas, Enabling the Geospatial Semantic Web with Parliament and GeoSPARQL. Semantic Web journal, to appear. Available from http://www.semantic-web-journal.net/

[BMT08] B. Bennett, D. Mallenby, and A. Third. An ontology for grounding vague geographic terms. In Formal Ontology in Information Systems – Proceedings of the Fifth International Conference (FOIS 2008), volume 183, pages 280–293. IOS Press, 2008.

[BHK+10] Harold Boley, Gary Hallmark, Michael Kifer, Adrian Paschke, Axel Polleres, Dave Reynolds, RIF Core Dialect. W3C Recommendation 22 June 2010, http://www.w3.org/TR/rif-core/

[BMJNM11] Bröring, A., Maue, P., Janowicz, K., Nüst, D., and Malewski, C. (2011): Semantically-Enabled Sensor Plug & Play for the Sensor Web. Sensors 2011, 11, 7568-7605.

[BS03] Bittner, Thomas, and Barry Smith. 2003. A Theory of Granular Partitions. In: Foundations of Geographic Information Science, M. Duckham, M. F. Goodchild and M. F. Worboys, eds., London: Taylor & Francis Books, 2003, 117-151.

[BS09] Baclawsk, Kenneth; Todd Schneider. 2009. The Open Ontology Repository Initiative: Requirements and Research Challenges. Workshop on Collaborative Construction, Management and Linking of Structured Knowledge (CK 2009). ISWC 2009, Oct. 25-29, 2009, Chantilly, VA.

[BSM07] Bittner, Thomas; Barry Smith; Maureen Donnelly. 2007. The Logic of Systems of Granular Partitions. http://ontology.buffalo.edu/smith/articles/BittnerSmithDonnelly.pdf.

[CH12] David Carral Martinez, Pascal Hitzler, Extending Description Logic Rules. In: E. Simperl at al. (eds.), Proceedings ESWC2012, Lecture Notes in Computer Science Vol. 7295, Springer, Heidelberg, to appear.

[CKH12] David Carral Martinez, Adila Alfa Krisnadhi, Pascal Hitzler, Integrating OWL and Rules: A Syntax Proposal for Nominal Schemas. In: Proceedings OWLED 2012. To appear.

[CL] Common Logic. ISO/IEC 24707:2007 - Information technology — Common Logic (CL): a framework for a family of logic-based languages. http://iso-commonlogic.org/.

[CV05] Philipp Cimiano, Johanna Völker: Text2Onto. In: Andrés Montoyo, Rafael Muñoz, Elisabeth Métais (Eds.): Natural Language Processing and Information Systems, 10th International Conference on Applications of Natural Language to Information Systems, NLDB 2005, Alicante, Spain, June 15-17, 2005, Proceedings. Lecture Notes in Computer Science 3513 Springer 2005, pp. 227-238.

[GS08] I. Cruz and W. Sunna. Structural alignment methods with applications to geospatial ontologies. Transactions in GIS, special issue on Semantic Similarity Measurement and Geospatial Applications, 12(6):683–711, 2008.

[CX08] I. F. Cruz and H. Xiao, Data Integration for Querying Geospatial Sources. Geospatial Services and Applications for the Internet, eds. John Sample, Kevin Shaw, Shengru Tu, and Mahdi Abdelguerfi, Springer, pp.113-137, 2008.

[Cue05] Cuel R., Cristani M., A Survey on Ontology Creation Methodologies, Int. J. Semantic Web Inf. Syst. (2005), Vol. 1, no. 2, pp. 49-69.

[E02] Egenhofer, M.J. Toward the Semantic Geospatial Web. In *Proceedings of the Tenth ACM International Symposium on Advances in Geographic Information Systems,* McLean, Virginia, 2002.

[FDF12] Nicola Fanizzi, Claudia d'Amato, Floriana Esposito: Induction of robust classifiers for web ontologies through kernel machines. J. Web Sem. 11: 1-13 (2012)

[FS02] F. Fonseca and A. Sheth, The Geospatial Semantic Web, UCGIS White paper, 2002.

[G04] A. Galton. Fields and objects in space, time, and space-time. Spatial Cognition and Computation, 1:39–68, 2004.

[G05] A. Gangemi. Ontology design patterns for semantic web content. In Y. Gil, E. Motta, R. Benjamins, and M. Musen, editors, The Semantic Web – ISWC 2005, 4th International Semantic Web Conference, volume 3729 of Lecture Notes in Computer Science, pages 262–276. Springer, 2005.

[G98] N. Guarino. Formal Ontology and Information Systems. In N. Guarino, editor, International Conference on Formal Ontology in Information Systems (FOIS1998), pages 3–15. IOS Press, Trento, Italy, 1998.

[GEFK99] Goodchild, M.F., Egenhofer, M.J., Fegeas, R., and Kottman, C.A. (eds.) *Interoperating Geographic Information Systems*. New York, Kluwer, 1999.

[GGK+12] Gil, Y.; Gonzalez-Calero, P. A.; Kim, J.; Moody, J.; and Ratnakar, V. (2012) A Semantic Framework for Automatic Generation of Computational Workflows Using Distributed Data and Component Catalogs. *To appear in the Journal of Experimental and Theoretical Artificial Intelligence*.

[GIR12] Graybeal, J., Isenor, A., Rueda, C. (2012): Semantic Mediation of Vocabularies for Ocean Observing Systems. Computers & Geosciences. Volume 40, March 2012, Pages 120-131, ISSN 0098-3004.

[GH07] Stephan Grimm, Pascal Hitzler, Semantic Matchmaking of Web Resources with Local Closed-World Reasoning. International Journal of e-Commerce **12** (2), 89-126, Winter 2007-8.

[GM09] Antony Galton and Riichiro Mizoguchi. 2009. The water falls but the waterfall does not fall: New perspectives on objects, processes and events. *Appl. Ontol.* 4, 2 (April 2009), 71-107.

[GS04] Grenon, P., and B. Smith. 2004. SNAP and SPAN: Towards dynamic geospatial ontology. Spatial Cognition and Computation, 4(1), 2004, pp. 69 -104.

[HHM+10] Harry Halpin, Patrick J. Hayes, James P. McCusker, Deborah L. McGuinness, Henry S. Thompson: When owl: sameAs Isn't the Same: An Analysis of Identity in Linked Data. In: Peter F. Patel-Schneider, Yue Pan, Pascal Hitzler, Peter Mika, Lei Zhang, Jeff Z. Pan, Ian Horrocks, Birte Glimm (Eds.): The Semantic Web - ISWC 2010 - 9th International Semantic Web Conference, ISWC 2010, Shanghai, China, November 7-11, 2010, Revised Selected Papers, Part I. Lecture Notes in Computer Science 6496 Springer 2010, pp. 305-320

[HJD08] Hart, G., Johnson, M., Dolbear, C.: Rabbit: Developing a Control Natural Language for Authoring Ontologies. 5th European Semantic Web Conference (ESWC'08), Tenerife, Spain (2008)

[HKPBR99] F. Harvey, W. Kuhn, H. Pundt, Y. Bisher, C. Riedemann. Semantic Interoperability A Central Issue for Sharing Geographic Information. in The Annals of Regional Science, Vol. 33 (1999), pp. 213-232.

[HKP+09] Pascal Hitzler, Markus Krötzsch, Bijan Parsia, Peter F. Patel-Schneider, Sebastian Rudolph, OWL 2 Web Ontology Language: Primer. W3C Recommendation, 27 October 2009. http://www.w3.org/TR/owl2-primer/

[HKR10] Pascal Hitzler, Markus Krötzsch, Sebastian Rudolph, Foundations of Semantic Web Technologies, CRC Press / Chapman & Hall, 2010.

[HPST09] Cory A. Henson, Josh K. Pschorr, Amit P. Sheth, and Krishnaprasad Thirunarayan. 2009. SemSOS: Semantic sensor Observation Service. In *Proceedings of the 2009 International Symposium on Collaborative Technologies and Systems* (CTS '09). IEEE Computer Society, Washington, DC, USA, 44-53.

[HPB+04] Ian Horrocks, Peter F. Patel-Schneider, Harold Boley, Said Tabet, Benjamin Grosof, Mike Dean, SWRL: A Semantic Web Rule Language Combining OWL and RuleML. W3C Member Submission, 21 May 2004, http://www.w3.org/Submission/SWRL/

[JHSVY10] Prateek Jain, Pascal Hitzler, Amit P. Sheth, Kunal Verma, Peter Z. Yeh: Ontology Alignment for Linked Open Data. International Semantic Web Conference (1) 2010: 402-417

[J10] Krzysztof Janowicz: The Role of Space and Time For Knowledge Organization on the Semantic Web. Semantic Web Journal. Volume 1, Number 1-2, pp. 25-32, IOS Press. 2010

[J12] Janowicz, K. (2012; forthcoming): Observation-Driven Geo-Ontology Engineering. Transactions in GIS.

[JBSSEL11] Janowicz, K., Bröring, A., Stasch, C., Schade, S., Everding, T., and Llaves, A. (2011): A RESTful Proxy and Data Model for Linked Sensor Data. International Journal of Digital Earth. DOI:10.1080/17538947.2011.614698, pp. 1-22.

[JSBKMS09] Janowicz, K., Schade, S., Bröring, A., Keßler, C., Maue, P. and Stasch, C. (2010): Semantic Enablement for Spatial Data Infrastructures. Transactions in GIS 14(2), Blackwell Publishing, pp. 111-129.

[K05] W Kuhn - Journal on data semantics III. Geospatial semantics: why, of what, and how?. Lecture Notes in Computer Science, Volume 3534/2005, pp 1-24. 2005. URL http://www.opengeospatial.org/standards/requests/80. Document 11-052r3.

[K09] W. Kuhn. Semantic Engineering. In G. Navratil, editor, Research Trends in Geographic Information Science, pages 63–76. Springer, 2009.

[KCD+04] L. Kerschberg, M. Chowdhury, A. Damiano, et al, "Knowledge Sifter: Ontology-Driven Search over Heterogeneous Databases," *In Proc. 16th Int. Conf. Scientific and Statistical DB Management*, 2004.

[KHM12] Matthias Knorr, Pascal Hitzler, Frederick Maier, Reconciling OWL and Non-monotonic Rules for the Semantic Web. In: Proceedings ECAI2012. To appear.

[KR10] Michael Kifer, Harold Boley, RIF Overview. W3C Working Group Note, 22 June 2010. http://www.w3.org/TR/rif-overview/

[KMH11] Adila Alfa Krisnadhi, Frederick Maier, Pascal Hitzler, OWL and Rules. In: A. Polleres, C. d'Amato, M. Arenas, S. Handschuh, P. Kroner, S. Ossowski, P.F. Patel-Schneider (eds.), Reasoning Web. Semantic Technologies for the Web of Data. 7th International Summer School 2011, Galway, Ireland, August 23-27, 2011, Tutorial Lectures. Lecture Notes in Computer Science Vol. 6848, Springer, Heidelberg, 2011, pp. 382-415.

[KWV07] Krivov S, Williams R, Villa F: GrOWL: A tool for visualization and editing of OWL ontologies. *Web Semantics: Science, Services and Agents on the World Wide Web* 2007, 5(2):54-57.

[KMKH11] Markus Krötzsch, Frederick Maier, Adila Alfa Krisnadhi, Pascal Hitzler, A Better Uncle For OWL - Nominal Schemas for Integrating Rules and Ontologies. In: S. Sadagopan, Krithi Ramamritham, Arun Kumar, M.P. Ravindra, Elisa Bertino, Ravi Kumar (eds.), WWW '11 20th International World Wide Web Conference, Hyderabad, India, March/April 2011. ACM, New York, 2011, pp. 645-654.

[KSH11] Adila Krisnadhi, Kunal Sengupta, Pascal Hitzler, Local Closed World Semantics: Keep it simple, stupid! In: Riccardo Rosati, Sebastian Rudolph, Michael Zakharzaschev, Proceedings of the 2011 International Workshop on Description Logics (DL2011), Barcelona, Spain, July 2011. CEUR Workshop Proceedings, Vol. 745, pp. 532-542.

[LH10] Jens Lehmann, Pascal Hitzler, Concept Learning in Description Logics Using Refinement Operators. Machine Learning 78(1-2), 203-250, 2010.

[LRGJ12] Li, N., Raskin, R., Goodchild, M. and Janowicz, K. (2012; in print) An Ontology-Driven Framework and Web Portal for Spatial Decision Support. To appear in Transactions in GIS vol. 16 (s1).

[MKSI96] E. Mena and V. Kashyap and A. Sheth and A. Illarramendi. OBSERVER: An Approach for Query Processing in Global Information Systems based on Interoperation across Pre-existing Ontologies}, 1996, 14--25, IEEE Computer Society Press.

[MM04] Frank Manola, Eric Miller, RDF Primer, W3C Recommendation 10 February 2004. http://www.w3.org/TR/rdf-primer/

[MMR12] Patrick Maué, Henry Michels and Marcell Roth. Injecting Semantic Annotations into (Geospatial) Web service descriptions. Semantic Web jorunal. DOI   10.3233/SW-2012-0061, 2012.

[MSSSS03] Maedche A, Staab S, Stojanovic N, Studer R and Sure Y 2003 SEmantic portAL: The SEAL Approach. In Fensel D, Hendler J A, Lieberman H, and Wahlster W (eds) Spinning the Semantic Web, MIT Press: 317-359

[NBR+09] Nogueras-Iso, J., Barrera, J., Rodriguez, A. F., Recio, R., Laborda, C., and Zarazaga-Soria, F. J. (2009). Development and deployment of a services catalog in compliance with the inspire metadata implementing rules. In van Loenen, B., Zevenbergen, J., and Besemer, J., editors, Spatial Data Infrastructure Convergence: Research, Emerging Trends, and Critical Assessment, volume 48 of Groene series, pages 21-34. The Netherlands Geodetic Commission (NGC), The Netherlands.

[Obr03] Obrst, L. 2003. Ontologies for Semantically Interoperable Systems. Proceedings of the Twelfth ACM International Conference on Information and Knowledge Management (CIKM 2003), Ophir Frieder, Joachim Hammer, Sajda Quershi, and Len Seligman, eds. New Orleans, LA, November 3-8, New York: ACM, pp. 366-369.

[Obr11] Obrst, Leo; Pat Cassidy. 2011. *The Need for Ontologies: Bridging the Barriers of Terminology and Data Structures.* Chapter in: GSA Memoir on Societal Challenges and Geoinformatics, Sinha, Krishna; Linda Gundersen; Ian Jackson; David Arctur, eds. Publication of a Memoir Volume. Geological Society of America (GSA). November 1, 2011.

[Obr10] Obrst, Leo. 2010. Ontological Architectures. Chapter 2, pp. 27-66 in the book: TAO – Theory and Applications of Ontology: Computer Applications, Roberto Poli, Johanna Seibt, Achilles Kameas, eds. September, 2010, Springer.

[OGC11] Open Geospatial Consortium. OGC GeoSPARQL - A Geographic Query Language for RDF Data. Open Geospatial Consortium, 2011.

[OE06] Ou, W. & Elsayed, A. (2006). A knowledge-based approach for semantic extraction. International Conferenceon Business Knowledge Management, Macao, 2006.

[OWLS04] http://www.w3.org/Submission/OWL-S/

[OWM99] Obrst, L., G. Whittaker, A. Meng. 1999. Semantic Context for Object Exchange, AAAI Workshop on Context in AI Applications, Orlando, FL, July 19, 1999.

[PDS10] C. Pedrinaci, . Domingue and A. Sheth, 'Semantic Web Services,' In Handbook: Semantic Web Technologies, Volume 2: Semantic Web Applications. J. Domingue;D. Fensel;J. Hendler, (Eds.). Springer, 2010.

[PL04] Probst, F. and M. Lutz. Giving Meaning to GI Web Service Descriptions. in 2nd International Workshop on Web Services: Modeling, Architecture and Infrastructure (WSMAI-2004). 2004. Porto, Portugal.

[RLTDF12] Achim Rettinger, Uta Lösch, Volker Tresp, Claudia d'Amato, Nicola Fanizzi: Mining the Semantic Web - Statistical learning for next generation knowledge bases. Data Min. Knowl. Discov. 24(3): 613-662 (2012)

[RKL+05] Dumitru Roman, Uwe Keller, Holger Lausen, Jos de Bruijn, Rubén Lara, Michael Stollberg, Axel Polleres, Cristina Feier, Christoph Bussler, and Dieter Fensel: Web Service Modeling Ontology, *Applied Ontology*, 1(1): 77 - 106, 2005.

[RP05] R. Raskin, M. Pan, Knowledge representation in the Semantic Web for Earth and environmental terminology (SWEET), Computers & Geosciences 31 (9), 1119-1125, 2005.

[RBF09] Rueda, C., Bermudez, L., Fredericks, J. (2009). The MMI Ontology Registry and Repository: A Portal for Marine Metadata Interoperability. OCEANS 2009, MTS/IEEE Biloxi - Marine Technology for Our Future: Global and Local Challenges. Oct. 2009.

[SBRSS08] S. Sahoo, O. Bodenreider, J. Rutter, K. Skinner, A. Sheth. An ontology-driven semantic mashup of gene and biological pathway information: Application to the domain of nicotine dependence. Journal of Biomedical Informatics 41 (5), 2008, 752-765

[Sch05] Schwitter, R.: A Controlled Natural Language Layer for the Semantic Web. In: Zhang, S., Jarvis, R. (eds.) AI 2005. LNCS (LNAI), vol. 3809, pp. 425–434. Springer, Heidelberg (2005)

[SE08] P. Shvaiko and J. Euzenat. Ten Challenges for Ontology Matching. In R. Meersman and Z. Tari, editors, On the Move to Meaningful Internet Systems: OTM 2008, volume 5332 of LNCS, pages 1164–1182. Springer, 2008.

[SGL07] Amit P. Sheth, Karthik Gomadam, Jonathan Lathem. 'SA-REST: Semantically Interoperable and Easier-to-Use Services and Mashups,' IEEE Internet Computing, November - December 2007, 84-87. Also W3C submission: http://www.w3.org/Submission/SA-REST/

[Sku03] D. Skuce. 2003. A Controlled Language for Knowledge Formulation on the Semantic Web. http://www.site.uottawa.ca:4321/factguru2.pdf.

[SKW08] F.M. Suchanek, G. Kasneci, G. Weikum, YAGO: A large ontology from Wikipedia and WordNet. Journal of Web Semantics, 2008.

[SM10] G. Sinha and D. Mark. Toward a foundational ontology of the landscape. In Extended Abstracts of GIScience 2010, 2010.

[SM10b] G. Sinha and D. Mark. Cognition-based extraction and modelling of topographic eminences. Cartographica, 45(2):105–112, 2010

[SRT05] A. Sheth, C. Ramakrishnan, and C. Thomas. Semantics for the semantic web: the implicit, the formal and the powerful. International Journal on Semantic Web and Information Systems, 1:1–18, 2005.

[SS10] Katharina Siorpaes and Elena Simperl. Human intelligence in the process of semantic content creation. World Wide Web (WWW) Journal, 13(1), 2010.

[SSOR09] K. Stock, M. Small, Y. Ou, and F. Reitsma. OGC Discussion Paper 09-010 – OWL Application Profile of CSW. Technical report, Open Geospatial Consortium, 2009.

[TMBS08] Christopher Thomas, Pankaj Mehra, Roger Brooks, Amit P. Sheth: Growing Fields of Interest - Using an Expand and Reduce Strategy for Domain Model Extraction. Web Intelligence 2008: 496-502.

[USDL11] Kay Kadner and Daniel Oberle (editors) Unified Service Description Language XG Final Report. W3C Incubator Group Report 27 October 2011.

[U00] M. Uschold. Creating, integrating and maintaining local and global ontologies. In 14th European Conference on Artificial Intelligence (ECAI 2000), Berlin, Germany, August 2000.

[VS07] Kunal Verma, Amit P. Sheth, Semantically Annotating a Web Service, IEEE Internet Computing, March/April 2007, 11(2), 83-85. Also W3C recommendation: http://www.w3.org/TR/sawsdl/

[WAB+08] D N Williams, R Ananthakrishnan, D E Bernholdt, S Bharathi, D Brown, M Chen, A L Chervenak, L Cinquini, R Drach, I T Foster, P Fox, D Fraser, S Hankin, P Jones, C Kesselman, D E Middleton, J Schwidder, R Schweitzer, R Schuler, A Shoshani, F Siebenlist, A Sim, W G Strand, N. Wilhelmi, "The Earth System Grid: Enabling Access to Multi-Model Climate Simulation Data" Bulletin of the sAmerican Meteorological Society (BAMS), 2008

[W3CSSN12] Compton, M., Barnaghi, P., Bermudez, L., Garcia-Castro, R., Corcho, O., Cox, S., Graybeal, J., Hauswirth, M., Henson, C., Herzog, A., Huang, V., Janowicz, K., Kelsey, W. D., Le Phuoc, D., Lefort, L., Leggieri, M., Neuhaus, H., Nikolov, A., Page, K., Passant, A., Sheth, A., and Taylor, K. (accepted): The SSN Ontology of the W3C Semantic Sensor Network Incubator Group. Journal of Web Semantics.