Semantic Mediation of Observation Datasets through Sensor Observation Services

Manuel A. Regueiro
Centro Singular de Investigación en Tecnoloxías da Información
manuelantonio.regueiro@usc.es
http://citius.usc.es

José R.R. Viqueira
Centro Singular de Investigación en Tecnoloxías da Información
jrr.viqueira@usc.es
http://citius.usc.es

Christoph Stasch
52° North Initiative for Geospatial Open Source Software GmbH
c.stasch@52north.org

José A. Taboada
Centro Singular de Investigación en Tecnoloxías da Información
joseangel.taboada@usc.es
http://citius.usc.es

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Abstract

The large volume of environmental observation data that is currently being produced by public and private initiatives is highly heterogeneous both in data formats and semantics. A major challenge is to make all these data accessible in a uniform and integrated manner. Sensor Web Enablement specifications of the Open Geospatial Consortium provide standard data encodings and web service interfaces. However, semantic data mediation is still an issue to be solved. This paper describes a first effort for the semantic mediation between heterogeneous environmental observation datasets through Open Geospatial Consortium standard Sensor Observation Services. The solution enables application domain experts to provide semantic data integration knowledge within the scope of two well known top-level ontologies, namely W3C Semantic Sensor Network and NASA Semantic Web for Earth and Environmental Terminology. Such knowledge is combined with data source knowledge during the evaluation of global Sensor Observation Service *GetObservation* requests. Finally, the solution follows a Local As View data integration approach, thus new data sources may be incorporated without having to change the available data integration knowledge.

1 Introduction

Environmental observation data is daily being produced by a wide variety of sensing systems. Various generic architectures have been proposed for the management and processing of such geospatial and environmental data [1, 2, 3]. Besides, there is a clear tendency to make all these mainly public data available through Spatial Data Infrastructures (SDIs) [4]. Directives like INSPIRE[1], which provide a legal framework for the SDI construction, include already meteorological and oceanographic data. However, the characteristics of sensing systems are highly heterogeneous and the same holds for the types of data they produce. For example, static in-situ meteorological stations generate time series that are usually managed within DBMSs. On the other hand, mobile remote satellite sensors generate series of raster images usually recorded and manipulated within files of specific formats. Apart from data models and encodings, semantic heterogeneity is also a key factor to incorporate these data in decision support tasks. Thus for example, many different types of temperatures may be denoted with the term “Temperature” in different data sources, including atmospheric air temperature and sea surface temperature. Besides, sea surface temperature may be measured in-situ by a buoy, sensed remotely from a device on board of a satellite, such as MODIS device on board of Terra and Aqua NASA satellites, or estimated by the execution of some model such as ROMS (Regional Ocean Modeling System).

Providing syntactic integration of environmental observation data sources is achieved by the incorporation of standards for both data encodings and data access interfaces. Various such standards are defined in the scope of the Sensor Web Enablement (SWE) initiative of the Open Geospatial Consortium (OGC). In particular, the Observations and Measurements (O&M) defines both a data model [5] and an XML encoding [6] for environmental observation data. The Sensor Observation Service (SOS) [7] specifies an interface to access

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[1] `http://inspire.ec.europa.eu/`

observation data sources. On the other hand, to achieve semantic integration, mappings have to be defined between the vocabularies used by the different data sources. Usually, top-level vocabularies, terminologies or ontologies are used as frameworks for the specification of such mappings. Two well-known ontologies in the scope of sensor environmental data are the W3C Semantic Sensor Network (SSN) [8] and the NASA Semantic Web for Earth and Environmental Terminology (SWEET) [9].

Data mediation has been studied in the area of *Federated Databases* since almost 30 years ago [10]. Semantic mediation has already been identified as a challenging research topic in various papers [3, 11] and it has been undertaken in some specific disciplines (scientific data sources [12], oceanographic vocabularies [13]).

Various SOS implementations are currently available. Most of them are tailored to in-situ observations recorded in relational DBMSs [14, 15, 16]. Few support raster observation data sources [17]. Recently, a virtual data integration solution was proposed [18] that supports both vector and raster observation data. However, to the best of these authors knowledge, semantic mediation between SOS data sources has not been reported in the literature.

This paper provides an overall description of a framework for the semantic mediation between environmental observation datasets through OGC SOS interfaces. Version 1.0 of the SOS interface is used by the current version of the framework. The system uses both SNN and SWEET as the basis for the specification of data integration knowledge by the domain expert. In particular, the expert may define: i) mappings between data source and global O&M concepts such as *Observed Property*, *Observation Process* and *Feature of Interest* and ii) integrated views of the data in the form of global *Offerings*. The framework uses a well-known mediator/wrapper architecture [19] and it follows a Local As View (LAV) [20] data integration approach in the mediator, which simplifies the incorporation of new data sources.

The remainder of this paper is organized as follows. Section 2 provides some background and a more detailed description of the problem to be solved. Related pieces of work are discussed in Section 3. The data mediation architecture is described in Section 4. Section 5 illustrates the contents of data source ontologies. The definition of data integration knowledge is illustrated in Section 6. Section 7 describes the implementation of the semantic data mediation process. Qualitative and performance evaluation results are discussed in Section 8. Finally, Section 9 concludes the paper and outlines future work plans.

2 Background and Problem

2.1 OGC SOS Standard

SOS services provide standardized interfaces [7] to access data sources of observations that are modeled and encoded according to the O&M specifications [5, 6]. An observation provides a value for a *Property* of a given application domain entity, called *Feature of Interest* (FOI) at a specific time instant. For example, the “sea surface temperature” (*Property*) of the “Gulf of Mexico” (FOI). Geographic properties of the FOI are very important to interpret and analyze the observed values. The *Process* used to obtain the observed value is also referenced by the observation. Such *Process* is typically a combination of a sensing device with some processing. For example, the combination of a temperature sensor with aggregation and spatial interpolation operations. Measured values may also include a Unit of Measure (UOM), for example 17 degrees Celsius.

Observations available through a SOS are organized in possibly overlapping collections called *Offerings*. Version 1.0 of the SOS interface has the following three mandatory operations, together with various other optional ones. Operation *GetCapabilities* obtains metadata of both the service and each of the available *Offerings*. Each *Offering* is described by its spatio-temporal extent and lists of *Properties*, *Processes* and *FOIs* referenced by its observations. Operation *DescribeSensor* obtains the Sensor Model Language (SensorML) [21] description of a given *Process*. Finally, the operations *GetObservation* retrieves the observations of a given *Offering* that matches a set of specified criteria. Such criteria include one or more *Property* URIs, zero or various *Process* URIs, zero or various *FOI* URIs, optional temporal filters, an optional spatial filter and an optional observed value filter.

2.2 Semantic Knowledge Representation and Management

This section provides an informal description of the appropriate background related to the representation and management of ontologies. Informally speaking, an ontology provides a formal description of the knowledge of a specific domain, defining the available concepts and relationships among them. Ontologies are formally encoded using knowledge representation languages. The Web Ontology Language (OWL) [22] is a broadly used one that is defined by the W3C upon the Resource Description Framework (RDF) [23].

RDF is a format to encode data of *Resources* available in the web. Broadly, RDF enables the definition of statements of the form

```
(subject predicate object),
```

where *subject* is a *Resource*, *predicate* is a *Property* of the *subject* and *object* is either another *Resource* or a data literal. Each *Resource* and *Property* is identified by a Internationalized Resource Identifier (IRI). An example of RDF statement is

```
(john hasName "John"),
```

which states that the literal “John” is the value of the property identified by the IRI hasName of the *Resource* identified by the IRI john. An RDF dataset is modelled with a graph, where *Resources* and literals are the nodes and *Predicates* are the edges.

RDF Schema (RDFS) [24] is a semantic extension of RDF that provides a data modelling vocabulary. Such vocabulary is a collection of RDF *Resources* and *Properties* that enable the definition of classes of resources (individuals) and class hierarchies. As an example, the following RDF statements define that resource http://myserver/john as and individual of class http://myserver/employee, which is a subclass of http://myserver/person.

```
(person rdf:type rdfs:Class)
(employee rdf:type rdfs:Class)
(employee rdfs:subClassOf person)
(john rdf:type person).
```

OWL increases the expressive power of RDFS with additional constructors, which include the following knowledge representation capabilities. The definition of *Object Properties*, *Data Properties*, transitive, symmetric and functional *Properties*. The definition of a *Property* as the inverse of another. The definition of new classes by specifying restrictions over properties. The definition of complex classes as unions, intersections and complements of other. The definition of classes by the enumeration of their instances. The definition of mappings between classes and individuals.

Various different syntaxes have been formalized for OWL. RDF/XML [2] is used by the present framework to record OWL files, however Manchester Syntax [3], which is more compact, will be used in the remainder of this paper.

Regarding semantic knowledge management, various technologies are currently available in the semantic web area. SPARQL Protocol and RDF Query Language enables the declarative query of RDF graphs, using graph pattern expressions. This language is used in the present framework to access and extract information from the required OWL ontologies.

2.3 Problem Definition

In most cases, environmental decision support tasks require the generation of knowledge from observation data that is not collected in a single data source of one organization. This is the main motivation of data mediation approaches in general [11] and environmental data mediation approaches in particular [18]. Besides, semantic conflicts use to appear in the terminology used in the various data sources. For example, two distinct names that denote the same concept in different data sources or the same name that denotes two distinct concepts in distinct data sources.

To illustrate this, let us consider the following realistic use case. Assume that we need air temperature observation data from a specific area, including sea and land, of the region of Galicia (north west of Spain). The following data sources are available. The first two of them were already used for the validation of a first prototype of the framework.

- A network of more than 80 automatic meteorological stations equipped with 693 physical sensors[4]. This network is maintained by MeteoGalicia, the regional meteorological agency of Galicia. Around 120 different *Properties* are observed and aggregated every 10 minutes, one day and one month.

- A network of 9 oceanographic stations that measure both meteorological and oceanographic *Properties*[5]. They also aggregate data every 10 minutes, daily and monthly. This network is shared between MeteoGalicia and Intecmar (a regional center for marine environmental control).

- A network of meteorological stations accessible through AEMET[6], the national meteorological agency of Spain. This national network shares some stations with the network of MeteoGalicia.

A *Property* like the daily maximum air temperature has different names in the three data sources. Besides, shared stations between AEMET and MeteoGalicia have also different

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[2] `https://www.w3.org/TR/rdf-syntax-grammar/`

[3] `http://www.w3.org/TR/owl2-manchester-syntax/`

[4] `http://www.meteogalicia.es/observacion/meteovisor/indexVisor.action`

[5] `http://www.intecmar.org/Plataformas/plataformas.aspx`

[6] `http://www.aemet.es/es/eltiempo/observacion/ultimosdatos`

names. Notice that it is quite common that data sources of different public administration levels might share pieces of sensing infrastructure (stations, sensors,etc.), without assuming a common vocabulary for them. To achieve semantic integration, a user has to get semantic information of the data sources, either from some catalog or directly from the experts, and based on it determine which data to request from each data source. However, a Spanish national SDI could provide semantically integrated SOS access to all the observation data based on such expert knowledge. Such an integrated SOS has to support an integrated vocabulary of concepts and enable data access at different levels of detail. For example, it should be possible to request daily air temperature data, but it should also be possible to request just temperature data.

The importance of semantic mediation has already been stated from a general purpose point of view [11] and specifically from the geospatial community [3].

3 Related Work

The OGC SWE specifications are well known standard means to acquire, catalog and integrate environmental observation data from various sources, as it has already been reported [25]. At the core of these standards, are the O&M data model [5] and data encoding [6], the Sensor Model Language (SensorML) [21] and the SOS web service interface [7].

Various well known open source projects provide SOS implementations [14, 15, 16]. They all rely on DBMS technology to record observations generated by in-situ processes. An initial performance evaluation of these implementations has been done in [26]. Raster observation data generated by remote processes are supported by the implementation described in [17]. A recent approach supports virtual integration of both vector and raster observation data sources [18]. However, none of the above implementations deal with the semantic integration of various observation data sources.

Despite of the above, semantic web technologies have already widely been applied in the areas of geographic and environmental data management. Thus, the semantic enablement of Spatial Data Infrastructures (SDIs) is discussed in [27]. State of art and research perspectives related to geospatial semantic data management are provided in [28]. More specifically, [29] proposes an ontology design pattern to model the quantification over types. A new architecture for semantic gazetteers is presented in [30]. Finally, a plug-in that extends the ontology framework Protégé with a semantic similarity measure is described in [31].

A semantically enabled environmental monitoring framework is described in [32], which uses foundational ontologies to support environmental regulation violations and relevant human health effects. A new extensible architecture for the above framework, which is based on the use of semantic technologies and that eases the incorporation new data sources and domains is proposed in [33].

The application of semantic technologies to observation data has also been subject for research. Thus, the construction of ontologies by reification of observation data has been achieved in [34]. The combination of technologies from the OGC SWE initiative and the W3C Semantic Web, called Semantic Sensor Web (SSW), was first discussed in [35]. More recently, the SSW and the Linked Sensor Data were identified as future work topics towards a new generation of SWE standards [36]. In particular, semantic sensor data discovery and integration were identified as major challenges to be overcome.

Data mediation is first proposed in the area of Federated Databases [10]. The aim of these approaches is to provide access to various heterogeneous data sources in a transparent way, i.e., like accessing a single virtual data source. The main key challenges in this area were first identified in [20]. A novel architecture for data mediation in the Grid is proposed in [11], where semantic data mediation is also identified as an important piece of future work.

Various pieces of work have dealt with the problem of semantic mediation among scientific, geospatial and environmental data sources. An approach called *Model Based Mediation* is proposed in [12] for the integration of scientific data sources. Each data source exports raw data and conceptual models with explicit semantics. The mediator combines the data source conceptual models with auxiliary domain knowledge sources, called *glue knowledge*, which includes relationships between concepts and unions and intersections of concepts.

Semantic Mediation between geospatial data sources is a piece of functionality that should be provided by services of the brokering approach introduced by the EuroGEOSS project and adopted by the GEOSS Common Infrastructure [3].

The mediation approach for environmental knowledge representation is discussed in the review reported in [37]. Inputs and outputs of processes in scientific workflows have to be enriched with knowledge representation, i.e., they must be semantically annotated with concepts from relevant ontologies. Reasoning may be next applied to check for compatibility between inputs and outputs. Semantic mediation between various oceanographic vocabularies is discussed in [13].

If we restrict to observation data, in [38], the authors define an extension of standard conceptual modeling approaches with new constructs for the incorporation of observation semantics. The result model can be used to annotate data sets with observation semantics, enabling them to be semantically integrated. Semantic annotation of SensorML [21] documents is performed in [39] to enable the semantic registration of sensing systems in SOS services. The annotation process establishes relationships between concepts in SensorML and O&M. In particular, entities, stimuli and properties are mapped respectively to FOIs, sensor inputs and sensor outputs.

A semantic SOS (SemSOS) has been designed and implemented [40] as an extension of a well known SOS open source tool [14]. Raw sensor data is first semantically annotated and next transformed to RDF to be recorded in a knowledge base. SOS requests are next transformed to SPARQL queries over the stored RDF. SOS responses are encoded in semantically annotated O&M and SensorML documents.

It is finally remarked that despite of all the related pieces of work, none of the reported approaches performs semantic integration of SOS data sources, as it is performed by the present solution.

4 Data Mediation Architecture

The architecture of the present framework is based on the well-known Mediator/Wrapper data integration architecture [19]. Each wrapper is specifically designed for the characteristics of a data source and it adapts its specific data model and data access interface to O&M and SOS. Beyond that, wrappers provide also a means to add the semantic annotation that will later be used during querying and semantic mediation. The mediator will receive inte-

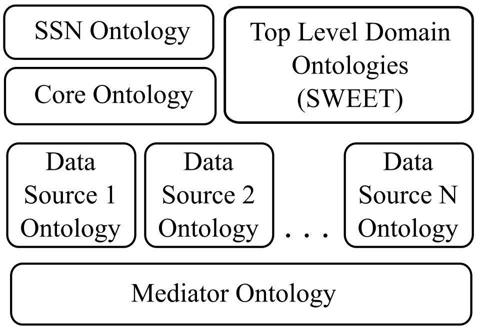


Figure 1: Data Integration Architecture.

grated SOS requests and distribute them among the various *Offerings* of the available data sources. The distribution of the request is guided by data integration knowledge defined by the domain expert in a mediator level ontology.

The data integration architecture that shows the interdependencies between the data source and mediator ontologies is depicted in Figure 1. The *SSN Ontology*, at the top of the figure, provides the basic concepts that are required by the O&M data model (*Observation*, *Process*, *FeatureOfInterest*, *Property*). The *Core Ontology* completes SSN with other required concepts.

Local concepts of data sources are defined in *Data Source Ontologies*. Data source ontology classes may also be related to SWEET classes by the definition of relevant class annotations. A more detailed description of these data source ontologies is given below in Section 5.

The *Mediator Ontology* includes both global classes that may be used to integrate various local ones and semantic relationships between global and local classes and individuals. Beyond the above concept mappings (similar to the *glue knowledge* of [12]), the domain expert may also define global *Offerings*, which might simplify the specification of many typical user queries. A more detailed description of the contents of *Mediator Ontology* and how it is used to achieve semantic integration is given below in Section 6.

The use of the standardized O&M model and SOS interface to communicate mediator and wrappers enables the simplification of the data integration challenges identified in [20].

- The assumption of standardized SOS interfaces and consequently O&M data model at both global and local levels avoid the need to define relationships between global and local data model elements.
- The resolution of syntax conflicts during the integration process is also avoided by the use of SOS interface. On the other hand, semantic conflicts may still arise. Those conflicts must be solved by the specification of appropriate data integration knowledge at the mediator ontology in the form of semantic relationships between global and local classes and individuals.
- Query reformulation algorithms for global queries are also simplified by the use of common SOS interface in all the wrappers, therefore, a Local As View (LAV) approach becomes feasible with a reduced effort.

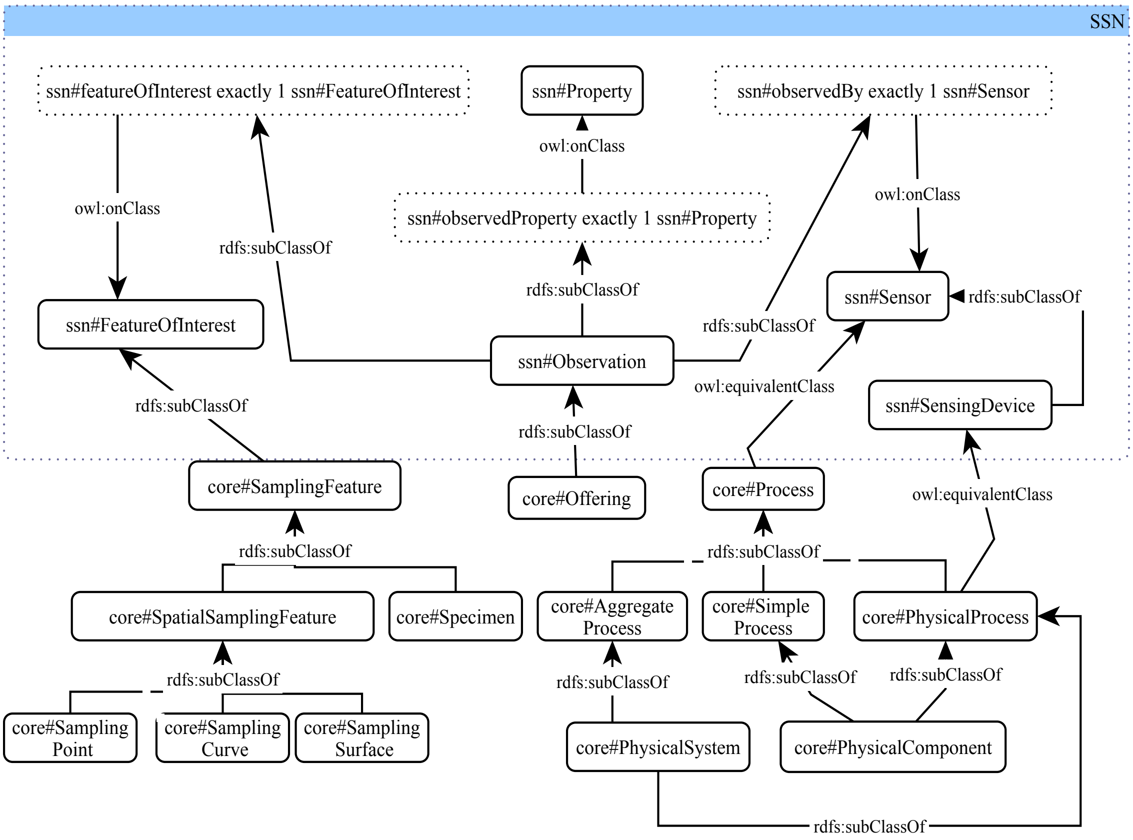


Figure 2: Core Ontology.

As a consequence of the above, the main contribution of the present data mediation framework is the resolution of semantic conflicts between data sources during the query evaluation. This is achieved by the appropriate processing of the RDF graph of the *Mediator Ontology* with the help of SPARQL.

5 Data Source Ontologies

A more detailed description of the Core and Data Source Ontologies is provided in the following subsections.

5.1 Core Ontology

The *Core Ontology* defines required O&M [5] and SensorML [21] concepts as specializations of relevant SSN concepts. Figure 2 depicts a graphical representation of the classes, restrictions and predicates of this ontology, together with appropriate SSN context.

At the top of the figure, required SSN concepts are depicted, together with representative restrictions and *subClassOf* predicates. Restrictions are depicted inside dotted rectangles using Manchester Syntax, and they represent the fact that each observation must reference exactly one *Sensor*, *Property* and *FOI*.

Based on the above SSN concepts, the following core classes and hierarchies required by the framework are defined.

core#Offering All the *Offerings* provided by data sources and mediator will be subclasses of this core class. Thus, the semantic interpretation of each *Offering* subclass will be the set of individuals (observations) that belong to it.

core#SamplingFeature It represents the concept of *Sampling Feature* defined in the O&M standard data model [5]. As it is argued in [5], the ultimate domain specific *FOI* whose properties are of interest does not match in most cases the proximate FOI linked to each observation. For an example consider a collection of buoys sampling seawater temperature in the Gulf of Mexico. The ultimate *FOI* is the seawater of the Gulf of Mexico, however, it is fundamental to know which buoy is associated to each observation in order to perform required analytics (spatial interpolation for example). Two major types of *Sampling Features* are identified in O&M. *Spatial Sampling Features* arise when the ultimate *FOI* has a geospatial nature and proximate *FOIs* provide samplings at specific locations. Various subclasses are defined based on its underlying geometry (point, curve, surface or solid). A typical example of a *Sampling Spatial Feature* is a sampling station (meteorological station, buoy, etc.). A *Specimen* is used to model physical samples obtained from the ultimate *FOI* and carried out to be observed. An example is a sample of water obtained from a specific location in a river to be analyzed in a laboratory.

core#Process It represents a SensorML *Process* [21], which is equivalent to a SSN *Sensor*. Both physical and non-physical (computing processes for example) and simple and aggregate processes may be represented. A physical process is also represented by the SSN *Sensing Device* class. A *Physical Component* is a simple and physical process whereas a *Physical System* is an aggregate process that has some physical component.

5.2 Representation of Data Source Concepts

Data source *Properties*, *Processes*, *FOIs* and *Offerings* are defined in each *Data Source Ontology* as either specializations of relevant *Core Ontology* classes or as individuals of them. Besides, to broaden the mediator query capabilities, defined classes might be related to classes of some well-known top-level application domain ontology. In the current implementation, SWEET was used as such an environmental domain specific ontology [9]. Figure 3 represents some concepts of the Galician meteorological stations data source.

Each *Property* of a data source is defined as an individual of either *ssn#Property* or some subclass of it specifically defined in the data source (see *MGMS#Temperature* class and relevant individuals in Figure 3). Relationships between data source classes and SWEET are modeled with *relatedTo* annotations.

A similar approach is followed for the representation of *FOIs* and *Processes* in each data source. Notice that a subclass of *core#SamplingPoint* is defined to model automatic meteorological stations in the example. Such a new class is also defined to be related to SWEET *Meteostation* class. An individual of *core#PhysicalSystem* is included to represent

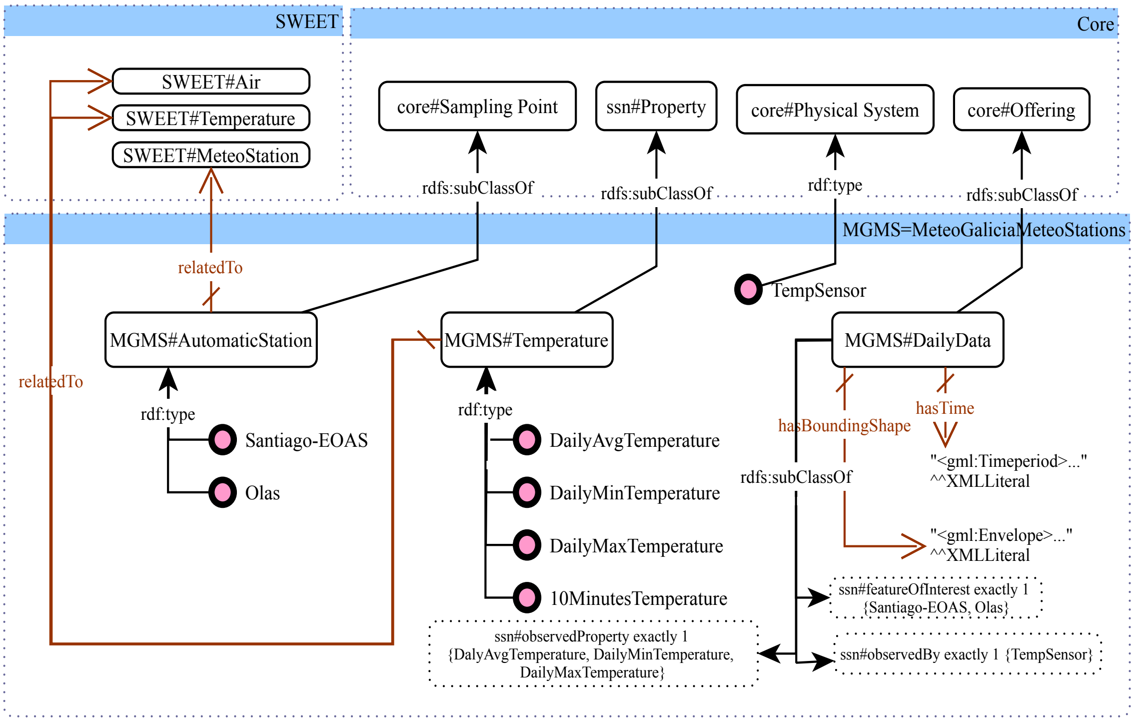


Figure 3: Data Source Ontology.

a temperature sensor. Notice that it is defined as a physical system because it includes a physical sensing device that obtains temperature measures in the station and it also includes algorithms to compute daily aggregates.

Data source *Offerings* are modeled by specific subclasses of *core#Offering*. For an example, see the subclass *MGMS#DailyData* in Figure 3. The temporal and spatial extent of the *Offering* are represented by two annotation properties of RDF type *XMLLiteral* that contain respectively relevant GML *TimePeriod* and *Envelope* elements. Two more optional annotation properties might be included to provide the name and description of the *Offering*. Besides, three class restrictions are used to represent the *Properties*, *Processes* and *FOIs* referenced by the observations of the *Offering*. Thus, as it is shown in the figure, the *DailyData Offering* provides daily average, minimum and maximum temperatures, generated by the *TempSensor* at *Santiago-EOAS* and *Olas* meteorological stations. Notice that all the metadata required to describe the capabilities of each *Offering* are represented in this way in the data source ontology. It is also noticed that *Offerings* are defined as views of the global O&M data model, following a LAV approach [20]. Thus, the above definitions will be used to automatically determine which local *Offerings* have to be accessed to obtain the observations of each global *Offering*.

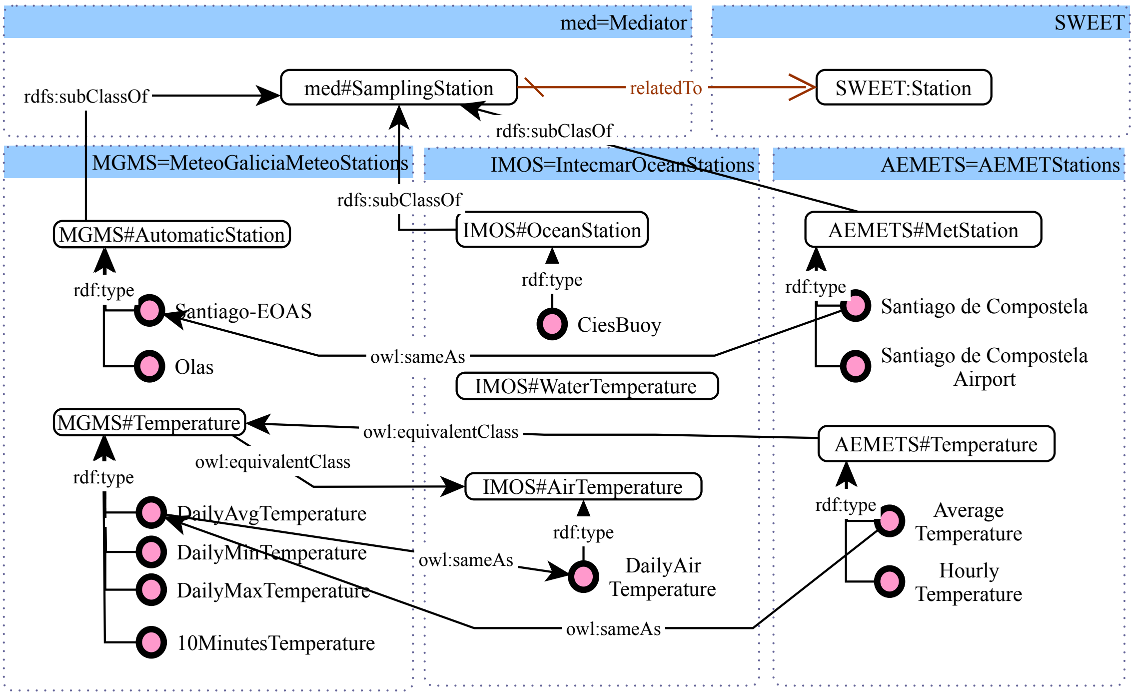


Figure 4: Data Integration Knowledge Representation.

6 Representation of Data Integration Knowledge

Data integration knowledge includes the definition of new classes, the specification of semantic relationships between local and global concepts and the definition of global *Offerings*. Three types of semantic relationships may be specified between classes and individuals defined in data source and mediator ontologies. Figure 4 illustrates the definition of these relationships for the three data sources of the proposed use case.

Subclass relationships They are represented by the property *subClassOf* of RDFS and they enables the integration of various *Property*, *Process* or *FOI* classes into a single one. In the example of Figure 4, class *med#SamplingStation* is used to integrate meteorological and oceanographic stations of the three data sources. Now, this new mediator class can be used in both *GetObservation* requests and the definition of global *Offerings*. Notice also that the global *med#SamplingStation* class is defined to be related to the class *Station* of SWEET, therefore, this SWEET class may be used by semantic clients to find all the stations of the three data sources.

Class equivalence relationships They are represented by the predicate *equivalentClass* of OWL. They enable the representation of the fact that various *Property*, *Process* or *FOI* classes represent actually the same class, despite of having different names in different data sources. Notice that this enables querying the *Offerings* of one data source using URIs of concepts that may be defined in other data sources. As an example, various property

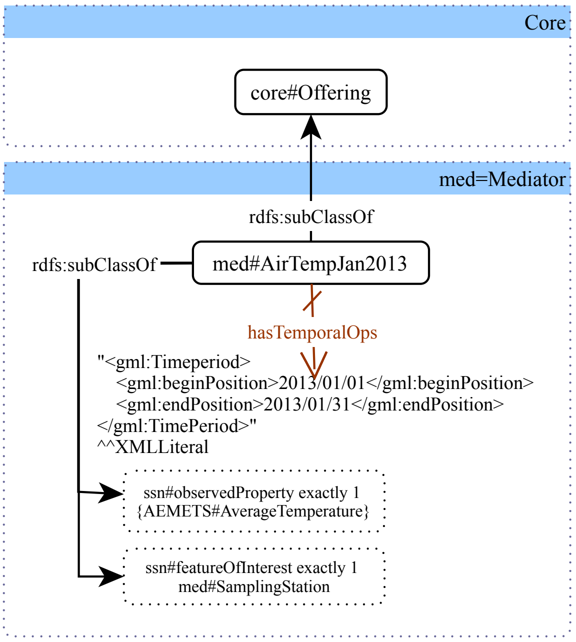


Figure 5: Global *Offering*.

classes representing air temperature are defined to be equivalent in the example provided in Figure 4.

Individual equality relationships They state that two *Property*, *Process* or *FOI* individuals represent actually the same individual. They are represented by the predicate *sameAs* of OWL. This enables the representation of the fact that a given individual might be present in various data sources with different names. Thus, in the example of Figure 4 the automatic station *Santiago-EOAS* of MeteoGalicia is exactly the same station that is accessed through AEMET with the name *Santiago de Compostela*. Therefore, queries referencing *Santiago-EOAS* at the mediator should also retrieve the data of *Santiago de Compostela* recorded by AEMET. As another example, in the figure various daily air temperature properties are defined to be the same one, despite of having different names.

Beyond the definition of relationships between local and global concepts, in order to simplify typical user queries, the application domain expert may also define global *Offerings* that might integrate observations of various data sources. Each such new *Offering* will be defined as a subclass of *core#Offering*. The optional name and description of the *Offering* may be provided with *hasName* and *hasDescription* annotations properties. Temporal, Spatial and value filters may be specified, respectively, with *hasTemporalOps*, *hasSpatialOps* and *hasComparisonOps* annotation properties. A restriction on the possible *Properties* that the *Offering* observations may reference is specified by an expression of the form (using Manchester Syntax)

ssn#observedProperty exactly 1
P_1 OR P_2 OR . . . OR P_n OR
$\{p_1, p_2, \ldots, p_m\}$

where, P_i are direct or indirect subclasses of *ssn#Property* and p_i are individuals of direct or indirect subclasses of *ssn#Property*. Similar restrictions may be defined to filter *Processes* and *FOIs*, using SSN properties *ssn#observedBy* and *ssn#featureOfInterest*, respectively. As an example, Figure 5 provides a graphical representation of the definition of a global *Offering med#AirTempJan2013* that enables the access to daily averages of air temperature from all the stations of the three data sources. Notice that the temporal filter is specified with a *hasTemporalOps* annotation property and *Property* and *FOI* filters are defined by relevant class restrictions. It is finally noticed that although the restriction references just the property *AEMETS#AverageTemperature*, observations of the other two data sources are also accessed, due to specific individual equality relationships defined in the *Mediator Ontology* (see Figure 4).

7 Implementation of Semantic Data Mediation

The three mandatory operations of the SOS interface are implemented by the mediator of the proposed framework. At the current version of the framework, *DescribeSensor* operation does not take advantage of semantic integration capabilities, thus only the other two operations *GetCapabilities* and *GetObservation* are discussed in the following subsections. To ease the description of the algorithms that implement these operations, some preliminary pieces of functionality have to be introduced.

If p is an RDF predicate, then $inv(p)$ denotes the inverse predicate of p. If r is an RDF resource and p is an RDF predicate, then $r.p$ denotes the set of resources $\{r_i\}$ such that the triple $(r\ p\ r_i)$ belongs to the ontology RDF graph.

If R is a set of RDF resources and p is an RDF predicate, then $TClosure(R, p)$ denotes all the resources in the transitive closure of p, i.e., all the resources r_i for which a sequence of triples of the form

$< (r\ p\ s_1), (s_1\ p\ s_2), \ldots (s_{n-1}\ p\ s_n)(s_n\ p\ r_i) >, r \epsilon R$

exists in the ontology RDF graph.

Let R be a set of RDF resources and P be a set of RDF predicates. Then the *Generalized Transitive Closure* of P from R, denoted $GTClosure(R, P)$ is obtained by iteratively adding to R the $TClosure(R, p)$ for each p in P, until the size of R does not change in two consecutive iterations. Informally, $GTClosure(R, P)$ yields all the resources related directly or indirectly with resources of R by some predicate of P.

Let C be a set of OWL classes. Then the operation $Individuals(C)$ yields all the individuals of classes of C.

Let C be a set of OWL classes and let s be another OWL class. The set of all subclasses of s that are related to classes in C is denoted by $RelSubClasses(C, s)$ and it contains all the subclasses of s that also belong to

$$\begin{aligned} GTClosure(C, \{&inv(\text{rdfs:subClassOf}),\\ &\text{owl:equivalentClass},\\ &inv(\text{owl:equivalentClass})\}) \end{aligned}$$

7.1 Operation GetCapabilities

All the data required by the *GetCapabilities* response for each Offering of each wrapper is already contained in its *Data Source Ontology*, as it was shown in Subsection 5.2. However, for mediator *Offerings*, the temporal and spatial extension and the set of *Property*, *Process* and *FOI* individuals are not directly available and they have to be deduced by some reasoning algorithm. The following steps provide an overall description of such an algorithm.

1. Obtain the spatial and temporal filters from relevant annotation properties of the mediator *Offering*.
2. If $PropInds$ and $PropClasses$ are respectively the sets of individuals and classes referenced in the restriction on property *ssn#observedProperty* of the mediator *Offering*, then the set $AllPropInds$ of all *Property* individuals referenced either directly or indirectly by the restriction is obtained as follows.

   $$\begin{aligned} &C \leftarrow RelSubClases(PropClasess, ssn\#Property)\\ &I \leftarrow Individuals(C) \cup PropInds\\ &AllPropInds \leftarrow GTClosure(\text{I}, \{\text{owl:sameAs},\\ &\qquad\qquad\qquad\qquad\qquad \text{inv(owl:sameAs)}\}) \end{aligned}$$

   As an example, for the mediator *Offering* of Figure 5, the obtained set of all *Property* individuals would be

   {MGMS#DailyAvgTemperature,
   IMOS#DailyAirTemperature,
   AEMETS#AverageTemperature}

3. In a similar manner, obtain also the set of all *Process* and *FOI* individuals referenced either directly or indirectly by relevant restrictions of the mediator *Offering*. For the mediator *Offering* of Figure 5, the set of all *Process* individuals would be empty and the set of all *FOI* individuals would be

   {MGMS#Santiago-EOAS,
   MGMS#Olas,
   IMOS#CiesBuoy,
   AEMETS#SantiagoDeCompostela,
   AEMETS#SantiagoDeCompostelaAirport}

4. For each wrapper *Offering*
   (a) Obtain the wrapper *Offering* temporal and spatial extent and filter them using the filters obtained in step 1.
   (b) Obtain the wrapper *Offering* sets of *Property*, *Process* and *FOI* individuals and filter them using the relevant sets of individuals obtained in steps 2 and 3. For example, for the wrapper *Offering* of Figure 3, the filtered *Properties*, *Processes* and FOIS are respectively the following:

       {MGMS#DailyAvgTemperature},
       {MGMS#TempSensor}
       {MGMS#Santiago-EOAS, MGMS#Olas}

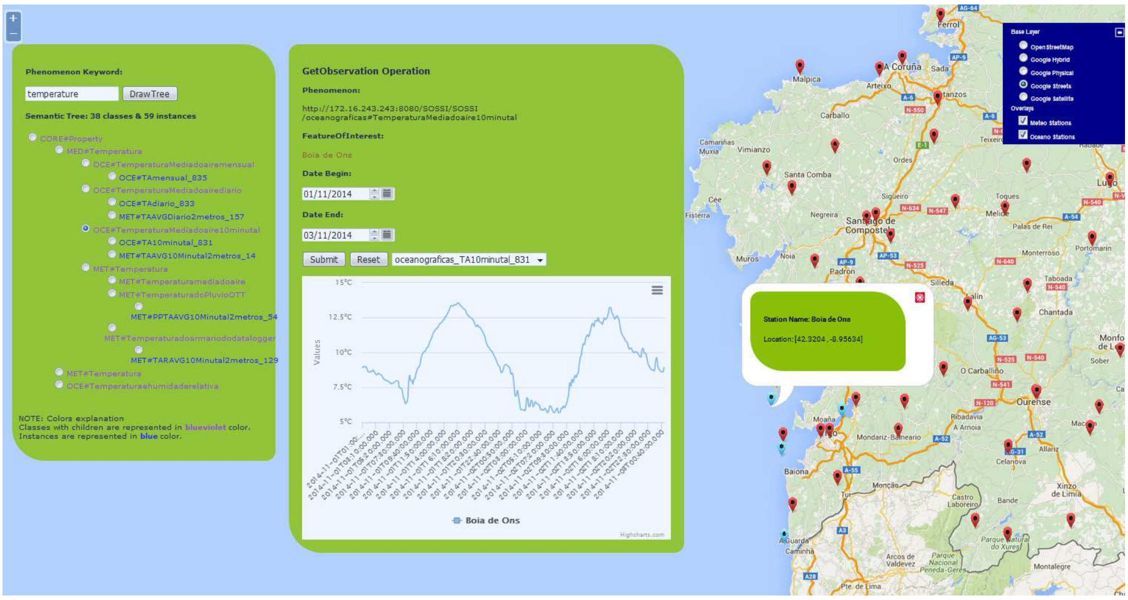
   (c) If none of the above filtered elements is empty then the wrapper *Offering* will contribute to the observations of the mediator *Offering*. Therefore, the filtered temporal and spatial extensions and the filtered sets of *Properties*, *Processes* and *FOIs* have to be merged with the mediator *Offering* relevant extensions and sets.

It is noticed that the above algorithm determines automatically, which data source *Offerings* have to be accessed for each global *Offering*. Therefore, either changes in local *Offerings* or the incorporation of new data sources will not require the redefinition of global *Offerings*. This is a clear advantage of the LAV approach followed. Finally, it is remarked that the *Mediator Ontology* is referenced in a specific XML element inside the contents section of the *GetCapabilities* response. This way, advanced clients may take advantage of the whole ontology maintaining at the same time backward compatibility with standard SOS clients.

7.2 Operation GetObservation

A request to this operation references just one *Offering* and at least one *Property*. Additionally, it may contain temporal, spatial and value filters and lists of *Processes* and *FOIs*. Now, URIs of individuals and classes of the *Mediator Ontology* may be used to reference *Properties*, *Processes* and *FOIs* in a request. Therefore, another reasoning algorithm hast to be used to determine the *GetObservation* request that has to be sent to each wrapper. The following steps provide an overall description of such an algorithm.

1. Obtain the sets of all the *Property*, *Process* and *FOI* individuals referenced either directly or indirectly by classes and individuals included in the request (see steps 2 and 3 in subsection 7.1)
2. If the requested *Offering* is a wrapper *Offering*, then
   (a) Obtain the *Offering* temporal and spatial extents and filter them using the relevant request filters.
   (b) Obtain the *Offering* sets of *Property*, *Process* and *FOI* individuals and filter them using the relevant sets obtained in step 1 above.
   (c) If none of the above filtered elements is empty, then the *Offering* has to be queried, therefore a *GetObservation* request is sent to the relevant wrapper. Filtered temporal and spatial extensions and filtered sets of *Properties*, *Processes* and *FOIs* obtained in the previous two sub-steps will be included in the request.
3. If the requested *Offering* is a mediator *Offering*, then
   (a) Obtain the spatial and temporal filters of the request and combine them with the spatial and temporal filters of the *Offering*.
   (b) Obtain the set of all the *Property*, *Process* and *FOI* individuals referenced directly or indirectly by classes and individuals in the *Offering* relevant restrictions (see steps 2 and 3 in subsection 7.1). Combine the above sets with the sets obtained in step 1.



Phenomenon Keyword: temperature

Semantic Tree: 38 classes & 59 instances

- ○ CORE#Property
  - ○ MED#Temperatura
    - ○ OCE#TemperaturaMediadoairemensual
      - ○ OCE#TAmensual_835
    - ○ OCE#TemperaturaMediadoairediario
      - ○ OCE#TAdiario_833
      - ○ MET#TAAVGDiario2metros_157
    - ● OCE#TemperaturaMediadoaire10minutal
      - ○ OCE#TA10minutal_831
      - ○ MET#TAAVG10Minutal2metros_14
    - ○ MET#Temperatura
      - ○ MET#Temperaturamediadoaire
      - ○ MET#TemperaturadoPluvioOTT
        - ○ MET#PPTAAVG10Minutal2metros_54
      - ○ MET#Temperaturadoarmariododatalogger
        - ○ MET#TARAVG10Minutal2metros_129
  - ○ MET#Temperatura
  - ○ OCE#Temperaturaehumidaderelativa

NOTE: Colors explanation
Classes with children are represented in blueviolet color.
Instances are represented in blue color.

GetObservation Operation

Phenomenon:

http://172.16.243.243:8080/SOSSI/SOSSI
/oceanograficas#TemperaturaMediadoaire10minutal

FeatureOfInterest:

Boia de Ons

Date Begin: 01/11/2014

Date End: 03/11/2014

oceanograficas_TA10minutal_831

Station Name: Boia de Ons

Location: [42.3204 , -8.95634]

Figure 6: Use case semantic web application.

(c) Using the temporal and spatial filters and the sets of all the set of all the *Property*, *Process* and *FOI* individuals obtained above apply steps 2(a-c) for each wrapper Offering. The responses of all the generated *GetObservation* requests are merged by the mediator to generate the result integrated response.

8 System Evaluation

A first prototype of the framework was already implemented, using the real datasets of MeteoGalicia and Intecmar described in Subsection 2.3. The Apache Jena SPARQL engine ARQ was used to query the *Mediator* and *Data Source Ontologies* during *GetCapabilities* and *GetObservation* processing. The results of a first evaluation of the system, which include both a use case application and performance analysis are described in the following subsections. Beyond that, the functionality of the prototype was already evaluated by the experts of MeteoGalicia and Intecmar and was chosen as a start point for the development of their data access point for environmental time series, including both observation and model data. Such development has already started in the scope of a technology transfer project funded by these two entities.

8.1 Use Case: Meteorological and Oceanographic Station Data Mediation

A semantic web application was developed to test the functionality of the framework for the mediation between the datasets produced by the meteorological and oceanographic station networks described in Subsection 2.3. The application exploits the contents of the *Mediator Ontology* provided by the semantic SOS to construct the enhanced end-user interface depicted in Figure 6.

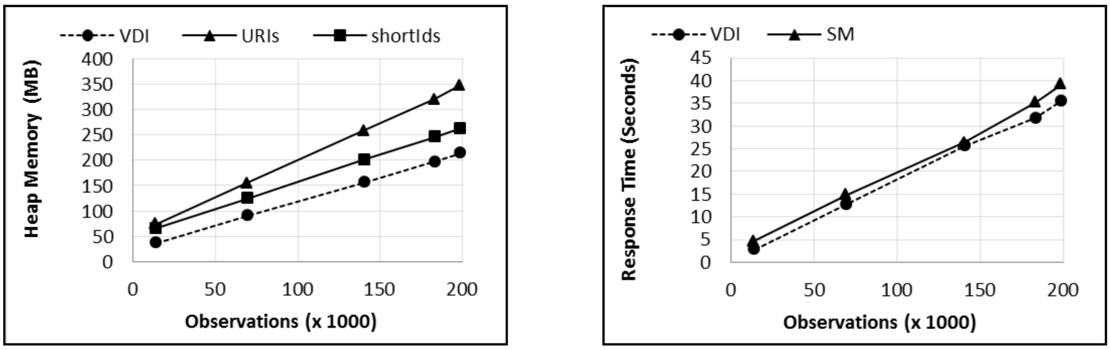
The panel located at the left side of the interface contains a search box where the user may type keywords. Those keywords are used to query the *Mediator Ontology* referenced in the *GetCapabilities* response to get the following *Property Classes* and *Property Instances*.

- Subclasses of *Core#Property* that are directly or indirectly subclasses of some class whose URI contains the query terms. Thus, *Property Classes* defined in *Mediator* and *Data Source Ontologies* will be queried.
- Subclasses of *Core#Property* that are *relatedTo* some class that is directly or indirectly subclass of some class whose URI contains the query terms. Thus, if the user enters the keyword "Temperature", which is contained in the URI SWEET#Temperature, all the *Properties* of the ontology defined as *relatedTo* some subclass of SWEET#Temperature will also be retrieved.
- Classes declared directly or indirectly as equivalent (*owl:equivalentClass*) to some of the above classes.
- Instances of any of the above classes.
- Instances of some direct of indirect subclass of the class *Core#Property* whose URI contains the query terms.
- Instances declared directly or indirectly as *owl:sameAs* some of the above instances.

The result hierarchy of *Core#Property* subclasses and instances is presented to the user as a tree immediately below the search box. The user may choose any element of the tree to construct a *GetObservation* SOS request. At the right side of the interface, a map is used to represent the *CORE#SamplingPoint* instances (meteorological and oceanographic stations) obtained with a SOS *GetFeatureOfInsterest* request. The panel at the center of the interface is used to create the *GetObservation* request, using the Property element selected in the tree, the station selected in the map and a couple of dates. One or various time series may be obtained and graphically depicted in the center panel, as it is shown in the Figure.

8.2 Performance Evaluation

The impact of the use of semantic web technologies in the performance of the framework has also been analyzed. To achieve this, the semantic mediation approach of the present framework (denoted here SM) has been compared with a previous non-semantic virtual data Integration solution [18] (denoted here VDI) in terms of both memory usage and response time. Notice that the VDI solution has already been evaluated with respect to data warehouse oriented solutions in [18]. Both the VDI and SM implementation were deployed in an Apache Tomcat web server configured with 2GB of Java Virtual Machine memory and installed in a computer with CPU Intel Core i3(2.8GHz) and 8GB of RAM. Around 1.2 million observations of meteorological stations and 1.1 million observations of oceanographic stations were loaded in the two data sources of MeteoGalicia and Intecmar described in Subsection 2.3. Microsoft SQL Server was used as the underlying DBMS for both datasets. Five different *GetObservation* request that combine results of both datasets,



(a) Memory Usage

(b) Response Time

Figure 7: Performance evaluation.

with an increasing number of result observations (ranging from around 14 thousand to around 200 thousand) were executed in both implementations.

The use of both permanent and heap Java memory is increased in SM with respect to VDI. Java permanent memory is increased by a constant amount of around 10 MB due to the greater number of classes used in SM implementation, mainly to support ontology management. The use of Java heap memory is also increased for two reasons. First, the representation of SOS and O&M metadata (*Properties*, *FOIs*, *Processes* and *Offerings*) within the Apache Jena objects in SM requires more memory than the simple hash tables of Java objects used by VDI. Second, URIs used by SM are larger than the non-universal identifiers generated by VDI. Figure 7(a) shows the amount of heap memory used by VDI and SM during the evaluation of the requests. SM was tested both using the required URIs and using short identifiers as those used by VDI. It is noticed that the difference between SM with short identifiers and VDI is an almost constant amount of around 40 MB, therefore it is claimed that the use of semantic technology does not have an important impact in terms of memory usage. On the other hand, the impact of large URIs in memory usage clearly increases with the number of observations retrieved. However, this is a payload that has to be assumed to enable universal identifiers within the web of data.

The comparison of VDI and SM solutions with respect to response time is shown in Figure 7(b). It is noticed that the difference between them is of around 2 seconds and does not increases with the number of observations. This is the time payload of the reasoning algorithm described in Subsection 7.2, which enables automatic semantic mediation. Such a payload is clearly dependent on the size of the base ontology (SWEET in this case) and may have an important impact in small request retrieving few result observations.

9 Conclusions

A framework for the semantic mediation between environmental observation datasets through OGC SOS interfaces has been described. The main characteristics of the proposed solution may be resumed as follows: First, it is remarked that, to the best of the authors knowledge, this is the first attempt for the support of semantic integration in an SOS implementation. The framework enables domain experts to define semantic data integration knowledge that might simplify data access tasks of many users. Advanced semantic clients may take advantage of *Property*, *Process* and *FOI* classifications provided in the *Mediator Ontology*, to provide powerful user interfaces. New applications may arise that perform semantic mediation between SOS and other semantic and linked data sources. Backward compatibility with the SOS interface is maintained, thus even standard clients will benefit from the new semantic integration capabilities. A LAV data integration approach was enabled in the mediator, which simplifies the incorporation of new data sources. Regarding performance, the use of semantic technologies and representations (large URIs) has the expected impact in both memory usage and response time. Response time impact may be important if the SOS is used to reply to many requests of few observations each. Future work is related to the integration of the service with semantically enabled catalogs and the development of general purpose wrappers for widely used data source technologies such as relational DBMSs and NetCDF files.

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