

# Sextant: Visualizing Time-Evolving Linked Geospatial Data<sup>☆</sup>

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## Abstract

The linked open data cloud is constantly evolving as datasets are continuously updated with newer versions. As a result, representing, querying, and visualizing the temporal dimension of linked data is crucial. This is especially important for geospatial datasets that form the backbone of large scale open data publication efforts in many sectors of the economy (e.g., the public sector, the Earth observation sector). Although there has been some work on the representation and querying of linked geospatial data that change over time, to the best of our knowledge, there is currently no tool that offers spatio-temporal visualization of such data. This is in contrast with the existence of many tools for the visualization of the temporal evolution of geospatial data in the GIS area. In this article, we present Sextant, a Web-based system for the visualization and exploration of time-evolving linked geospatial data and the creation, sharing, and collaborative editing of “temporally-enriched” thematic maps which are produced by combining different sources of such data. We present the architecture of Sextant, give examples of its use and present applications in which we have deployed it.

**Keywords:** linked geospatial data, linked spatiotemporal data, visualization, browsing, exploration

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## 1. Introduction

Linked geospatial data has recently received attention as researchers and practitioners have started tapping the wealth of geospatial information available on the Web [1]. As a result, in the last few years, the Web of data is being rapidly populated with geospatial information. Ordnance Survey is the first national mapping agency that has made various kinds of geospatial data from Great Britain available as open linked data<sup>1</sup>. Another representative example of such efforts

is LinkedGeoData<sup>2</sup> where OpenStreetMap (OSM) data are made available as RDF and queried using the declarative query language SPARQL [2]. A similar effort is GeoLinkedData<sup>3</sup> where geospatial data from Spain is made public using RDF [3]. Finally, the Greek Linked Open Data portal<sup>4</sup>, that is being developed by our group, has recently published a number of open datasets for the area of Greece as linked open data (LOD).

As the real-world entities represented in the Web of data evolve over time, the datasets themselves get updated and the temporal dimension of data plays a crucial role. For example, in Earth Observation (EO), data is constantly produced by satellite sensors and is associated with metadata containing, among others, temporal attributes, such as the time that an image was transmitted from the satellite to the ground station. In addition, the acquisitions are considered to be valid for specific periods of time, for example until they get up-

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<sup>1</sup><http://www.ordnancesurvey.co.uk/oswebsite/products/os-opendata.html>

<sup>2</sup><http://linkedgeo.org/>

<sup>3</sup><http://geo.linkeddata.es/>

<sup>4</sup><http://linkedopendata.gr/>

dated by new acquisitions. Satellite acquisitions might be utilized in applications such as the CORINE Land Cover programme operated by the European Environment Agency that makes available as a cartographic product the land cover of European areas<sup>5</sup>. Periodically, CORINE publishes the changes in the land cover of these areas in the form of changesets.

Applications for exploiting this abundance of geospatial information have also started to emerge. For example, in project TELEIOS<sup>6</sup>, we have built a service for real-time fire monitoring based on satellite images and open linked geospatial data [4]. In the same project, a burn scar mapping service has been developed which offers maps of burned areas of Greece for the period 1984–2012 based on Landsat images [5].

The core component of these two services is the geospatial RDF store Strabon<sup>7</sup> which stores hotspot products extracted from satellite images, burnt areas, and linked geospatial data offered by the Greek Linked Open Data portal mentioned previously, and queries them to deliver these services. Strabon supports two query languages: stSPARQL, an extension of SPARQL 1.1 for querying linked geospatial data that changes over time [6, 7] and GeoSPARQL [8], a recent standard of the Open Geospatial Consortium (OGC) for static geospatial data.

stSPARQL can be used to query data represented in an extension of RDF called stRDF [6, 7]. stRDF and stSPARQL have been designed for representing and querying linked geospatial data that changes over time, e.g., the growth of a city over the years due to new developments can be represented and queried using the valid time dimension of stRDF and stSPARQL respectively.

GeoSPARQL is a recent OGC standard for a SPARQL-based query language for geospatial data expressed in RDF [8]. GeoSPARQL defines much of what is required for such a query language by providing vocabulary (classes, properties, and functions) that can be used in RDF graphs and SPARQL queries to represent and query geospatial data. This vocabulary is organized in an hierarchical and modular fashion and is provided by a core component and various extensions that add specialized vocabulary and/or functionality.

stSPARQL and GeoSPARQL are very similar languages. GeoSPARQL goes beyond stSPARQL with the functionality offered by its RDFS entailment extension, and its topological extension and the related

query rewrite extension. This opens up the possibility of useful forms of topological reasoning not covered by stSPARQL. On the other hand, stSPARQL goes beyond GeoSPARQL in two ways. First, it can model and query the valid time of triples, enabling it to model temporal and spatiotemporal domains, and concepts such as events, facts that change over time, etc. Second, it defines spatial and temporal aggregate functions which are very useful to have in these domains. A more detailed comparison of the two languages may be found in [1].

Strabon is a DBMS for the storage and querying of *linked spatiotemporal data* encoded in the model stRDF and queried by stSPARQL or GeoSPARQL (static data only). It is an open source system and has been developed by extending the well-known RDF store Sesame<sup>8</sup> and using PostGIS<sup>9</sup> and PostgreSQL Temporal<sup>10</sup> for the back-end storage and querying of spatiotemporal data. As we have shown in [6, 7], Strabon is currently the most functional spatiotemporal RDF store available, while at the same time it offers equal or better performance when compared with other RDF stores such as Parliament [9], uSeekM [10], and well-known commercial systems [11].

While developing applications such as those presented above [4, 5], we were faced with the tasks of browsing and exploration of multiple linked spatiotemporal datasets together with other heterogeneous geospatial data available on the web (e.g., geospatial data available in file formats, such as KML, shapefiles, GeoTIFF). Another important task in these applications was the production of thematic maps, i.e., maps useful to end-users for analyzing or assessing an event or situation, like analysis of environmental damages, fire monitoring and management, etc. This motivated us to ask the following question.

How do we easily browse, explore, visualize, and produce thematic maps using open sources of geospatial information, such as linked geospatial and temporal data, and GIS data available on the web?

This article answers this question by presenting Sextant<sup>11</sup>, an open source, web-based tool<sup>12</sup> for browsing and visualizing time-evolving linked geospatial data together with other geospatial data sources, such as KML

<sup>5</sup><http://www.eea.europa.eu/publications/COR0-landcover>

<sup>6</sup><http://earthobservatory.eu/>

<sup>7</sup><http://www.strabon.di.uoa.gr/>

<sup>8</sup><http://rdf4j.org/>

<sup>9</sup><http://postgis.net/>

<sup>10</sup><http://pgfoundry.org/projects/temporal/>

<sup>11</sup><http://sextant.di.uoa.gr/>

<sup>12</sup>The naming of our system is inspired by the navigation instrument sextant (<http://wikipedia.org/wiki/Sextant>) used to measure the angle between any two visible objects.

files. We demonstrate that apart from `owl:sameAs` links, implicit semantic links based on the temporal and spatial dimension are also inherent in linked data. Similarly to well-known GIS tools (e.g., QGIS, ArcGIS), Sextant can be used to produce thematic maps by layering geospatial information which exists in a number of data sources ranging from standard SPARQL endpoints, to SPARQL endpoints following the standard GeoSPARQL defined by OGC for the modeling and querying of geospatial information, and other well-adopted vector and raster geospatial file formats, such as KML [12], GeoJSON<sup>13</sup>, and GeoTIFF<sup>14</sup>.

The features that distinguish Sextant from other Semantic Web or GIS tools are as follows. First, it enables map creation and sharing, as well as the exploration of linked open data by evaluating stSPARQL or GeoSPARQL queries on SPARQL endpoints. In this way rich thematic maps can be created by layering information coming from the evaluation of SPARQL queries. We stress that this is not possible given the current GIS technology, because this technology cannot deal with emerging open sources of information such as the LOD cloud. Second, it visualizes the temporal dimension of data having a spatial extent simultaneously on a map and a timeline. Finally, Sextant is based on OGC standards for visualizing the spatial and temporal dimension of linked data, thus it is interoperable with other well-known tools such as Google Earth<sup>15</sup>.

The above features of Sextant make it a powerful tool for browsing and visualizing time-evolving linked geospatial data. In addition to this article, the reader can find ample evidence confirming the usefulness of Sextant in the deliverables [13, 14] of EU project TELEIOS written by the two user partners of the project, the German Aerospace Center (DLR) and the National Observatory of Athens (NOA). In this paper, inspired by the use cases of these two organizations in the context of TELEIOS, we showcase the usefulness of Sextant in the domains of Earth Observation and Environment by presenting its browsing and visualization capabilities using a number of link geospatial datasets and other geospatial data sources publicly available on the Web, such as KML files.

The work presented in this article extends the demo papers [15, 16] presented respectively at the Extended Semantic Web Conference 2013 [17] and the International Semantic Web Conference 2013 [18, 19]. The first of these papers, namely [15], shared the best

demonstration award with the demo paper [20].

Tools for visualizing linked geospatial data have started to emerge (e.g., LinkedGeoData browser<sup>16</sup>, Map4RDF [21], LODVisualization [22], Facete browser<sup>17</sup>), but the temporal dimension of such data has not been captured due to the lack of an implementation of a data model and a query language with temporal features covering the various semantics associated with the representation of time (e.g., valid and user-defined), and the lack of a standard temporal extension of RDF that practitioners could utilize when publishing RDF data. According to a recent study [23], the temporal information contained in linked data mostly captures user-defined time, while the valid time dimension is rarely captured. With the development of the temporal dimension of stRDF and its implementation in Strabon [7], linked spatiotemporal data is handled easily by Sextant.

The rest of the article is organized as follows. Section 2 gives an overview of Sextant, presenting its architecture and discussing how semantic web technologies have been employed in it. Then, Section 3 demonstrates the power of Sextant with respect to formulating queries using various vocabularies for the representation of geospatial and temporal information in RDF. Section 4 describes a number of linked geospatial datasets that are used later on when the application scenarios are presented in Section 5. Section 6 discusses related work in visualizing linked geospatial data. Last, Section 7 discusses future extensions of Sextant, while Section 8 concludes the article.

## 2. Overview of Sextant

Sextant is a web-based tool for browsing and visualizing time-evolving linked geospatial data. The main design goals in the development of Sextant have been flexibility, portability, and interoperability. Sextant achieves these goals based on the following technologies. It has been developed using the Google Web Toolkit which is a mature framework that provides rapid cross-platform and cross-browser implementations of web applications. In addition, Sextant builds on the Timemap Javascript library<sup>18</sup> for the visualization of “temporally-enriched” KML files. Finally, to achieve interoperability with other well-known GIS tools (e.g., QGIS, ArcGIS, Google Earth), Sextant is based on the following OGC standards:

<sup>13</sup><http://geojson.org/>

<sup>14</sup><http://trac.osgeo.org/geotiff/>

<sup>15</sup><http://www.google.com/earth/>

<sup>16</sup><http://linkedgedata.org/LGD%20Browser>

<sup>17</sup><https://github.com/GeoKnow/Facete>

<sup>18</sup><https://code.google.com/p/timemap/>

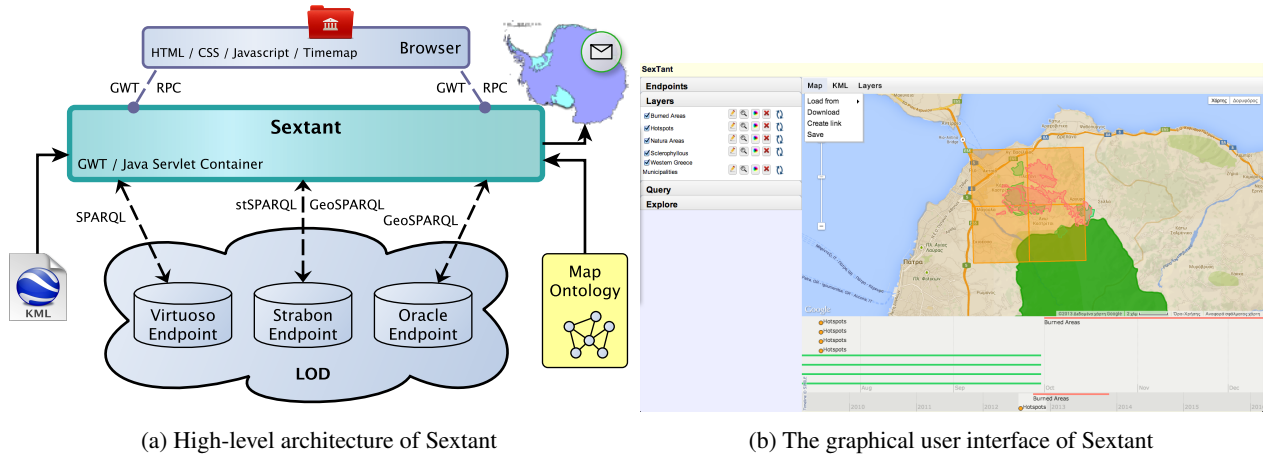


Figure 1: (a) The high-level architecture and (b) the graphical user interface of Sextant

- a) the OpenGIS Simple Features Access (OGC-SFA) standard [24] that defines the Well-Known Text (WKT) format for representing geometries,
- b) the Geography Markup Language (GML) [25] for expressing geographical features,
- c) the KML file format [12] (formerly Keyhole Markup Language) that was designed by Google and later adopted by OGC for expressing geographic annotation and visualization on existing or future web-based online and mobile maps (2-dimensional space), as well as on Earth browsers (3-dimensional space), and
- d) the query language GeoSPARQL for representing and querying RDF data with geospatial information [8].

Figure 1a gives a high-level overview of Sextant, which comprises a front-end and a back-end. In the following, we describe these parts in detail.

### 2.1. The front-end of Sextant

The front-end part (the upper purple rounded rectangle of Figure 1a), which runs on any modern browser (e.g., Opera, Firefox, Chrome, Safari, Internet Explorer), is the graphical user interface depicted in Figure 1b with which a user interacts to accomplish the two main functionalities that are offered by Sextant. These functionalities can be summarized as follows:

- a) Exploration of linked spatiotemporal data spanning multiple SPARQL endpoints and

- b) Creation, sharing, and collaborative editing of thematic maps by combining linked spatiotemporal data and other geospatial information available in vector or raster formats, such as KML, GeoJSON, and GeoTIFF.

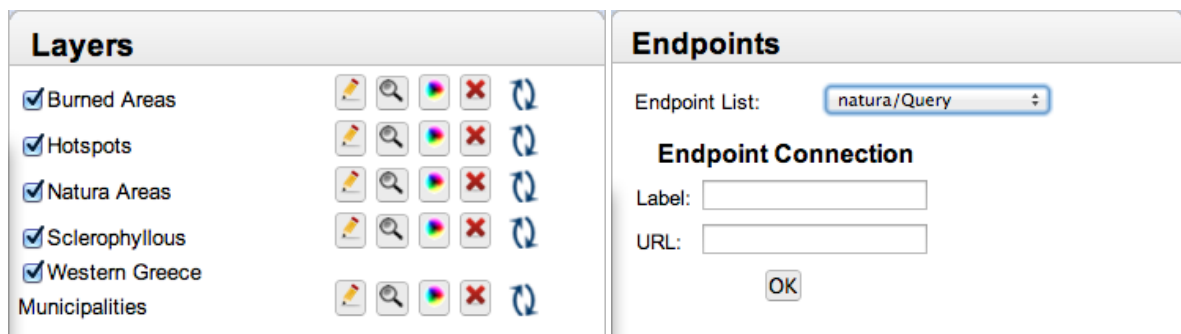
With respect to the above functionalities, the front-end is only responsible for the presentation level. This includes visualization of spatiotemporal information on a map and a timeline (see the right part of Figure 1b), organization of a map into layers and management of them with respect to naming, ordering, and coloring (see Figure 2a), registration of SPARQL endpoints to contact for browsing their content (see Figure 2b), formulation of SPARQL queries and evaluation on a registered SPARQL endpoint (see Figure 2c), harvesting the content of a SPARQL endpoint with the aim of building a class hierarchy, and discovering the spatial extent of available information (see Figure 2d), and managing the valid time span of retrieved data (see Figure 2e).

### 2.2. The back-end of Sextant

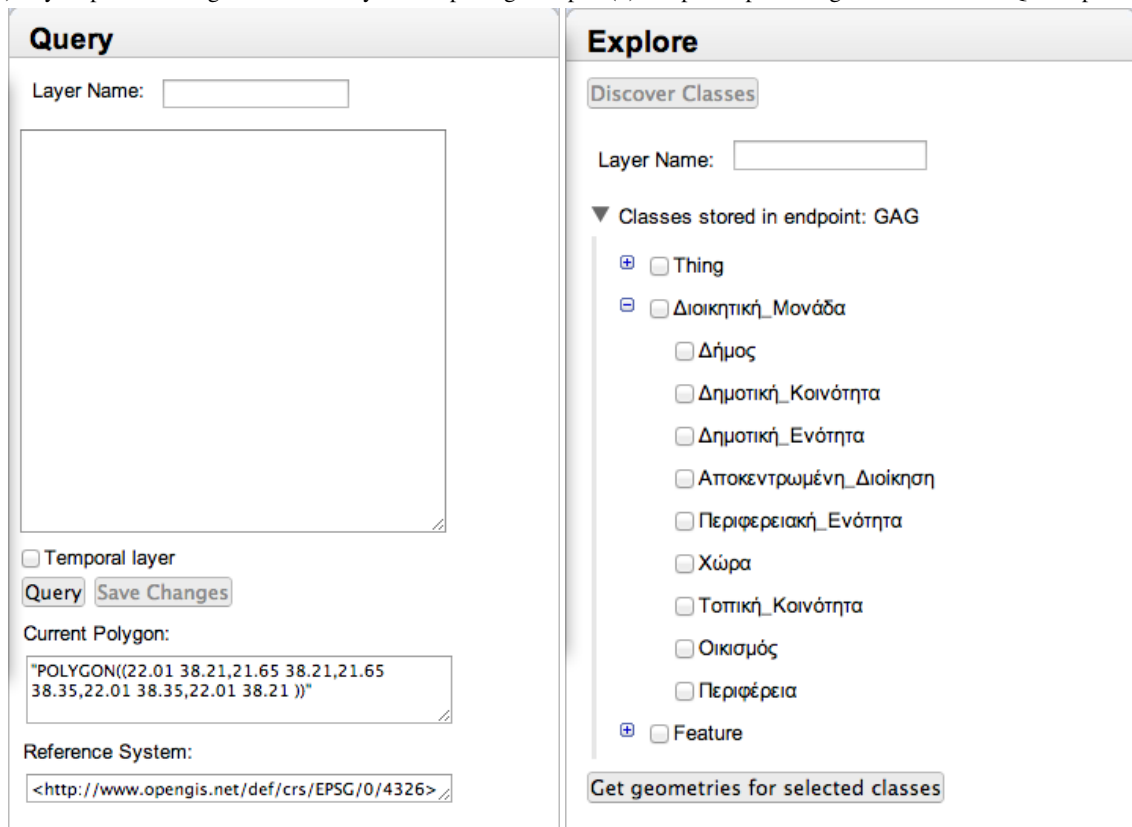
The back-end part (the middle turquoise-like rounded rectangle of Figure 1a), which runs on the server side, is responsible for undertaking the heavy computational tasks that implement the functionalities discussed above. The back-end is composed of 5 components: the endpoint connector, the ontology manager, the map registry, the time manager, and the KML translator. These components are discussed in the following.

#### Endpoint connector

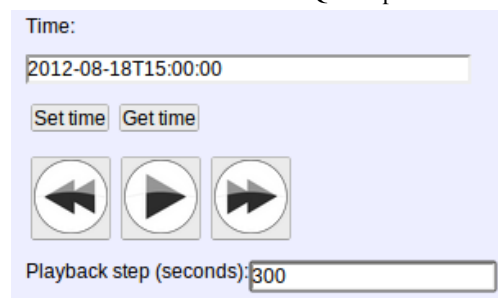
The *endpoint connector* of Sextant undertakes the communication with SPARQL endpoints that are pub-



(a) Layers panel: management of the layers comprising a map (b) Endpoints panel: registration of SPARQL endpoints



(c) Query panel: formulation and execution of SPARQL queries (d) Explore panel: exploration of the class hierarchy of a SPARQL endpoint



(e) Time manager panel: moving backward and forward temporal filters of queries

Figure 2: The various panels of Sextant

licly accessible on the web through a URI. The minimum requirements that a SPARQL endpoint should meet is to be compliant with the specification documents of the SPARQL 1.1. protocol [26] and the SPARQL query results XML format [27]. The endpoint connector supports also other SPARQL query results formats, such as JSON, CSV, and TSV, the specification documents of which are contained in [28, 29]. The endpoint connector maintains a list of SPARQL endpoints that have been registered by the user using the endpoints panel of the front-end part of Sextant (see Figure 2b). Furthermore, it is responsible for executing SPARQL queries (e.g., a query formulated by the user through the query panel depicted in Figure 2c) and receiving the query results in the SPARQL XML format.

### Ontology manager

Sextant models the content of a map according to the map ontology of Figure 3. The map ontology is available at <http://sextant.di.uoa.gr/ontology>. According to the ontology, a map comprises an ordered set of layers, the content of which may derive either from the evaluation of an stSPARQL/GeoSPARQL query on a SPARQL endpoint or directly from a standard file format for representing geospatial information, such as KML. A layer may also derive from the evaluation of standard SPARQL queries using other vocabularies such as the W3C GeoXG<sup>19</sup> [31] and NeoGeo<sup>20</sup>. In such cases, however, one has to provide an adapter for transforming the representation of a geometry to a standard OGC representation format, such as Well-Known Text or GML, the two OGC geospatial data formats supported by stSPARQL and GeoSPARQL or adapt the SPARQL query appropriately as it will be demonstrated in Example 3 of Section 3.

The map ontology of Sextant employs also the temporal ontology dictated by the data model stRDF and the query language stSPARQL for the modeling of valid time [7] (see the pink part of Figure 3). This ontology enables the introduction of *user-defined time* and *valid time of a triple* in RDF data. User-defined time does not carry any special semantics. Valid time is the time an event takes place or a fact is true in the application domain. Time is modeled as *instants* or *intervals* and is represented using values of the datatypes `xsd:dateTime` and `strdf:period` respectively. One may use all the temporal features of stSPARQL<sup>21</sup> to

query linked spatiotemporal data encoded in stRDF, such as the temporal extension functions corresponding to the thirteen temporal relations of Allen's interval algebra [32], the temporal aggregate functions, or the extension functions for constructing new temporal elements. In this way the full capabilities of SPARQL endpoints using the spatiotemporal RDF store Strabon can be exploited.

The *ontology manager* of Sextant is the component that is responsible for maintaining the description of a map as described above. The ontology manager communicates with the map registry component (described next) to persistently store or retrieve the RDF description of a map. The following example presents the RDF description that Sextant maintains for the map of Figure 1b.

**Example 1.** The following RDF triples, given in the Terse RDF triple language (Turtle) [33], correspond to an excerpt of the RDF description of the content of the map depicted in Figure 1b and have been produced by the ontology manager component of Sextant by populating the map ontology described above. The content of the map is described in detail in Section 5.2 where the application utilizing it is presented.

```
@prefix rdf:
  <http://www.w3.org/1999/02/22-rdf-syntax-ns#>.
@prefix maponto:
  <http://geo.linkedopendata.gr/map/ontology/>.
@prefix mapid:
  <http://geo.linkedopendata.gr/map/id/>.

<mapid:mulrcpb74onu1smi_>
  a <maponto:Map> ;
  <maponto:hasLayers> <mapid:mulrcpb74onu1smi_list>.

<mapid:mulrcpb74onu1smi_list>
  a maponto:Layers ;
  rdf:_1 <mapid:mulrcpb74onu1smi_l10> ;
  rdf:_2 <mapid:mulrcpb74onu1smi_l11> ;
  rdf:_3 <mapid:mulrcpb74onu1smi_l12> ;
  rdf:_4 <mapid:mulrcpb74onu1smi_l13> ;
  rdf:_5 <mapid:mulrcpb74onu1smi_l14> .

<mapid:mulrcpb74onu1smi_l14>
  a <maponto:Layer> ;
  <maponto:producedBy> <mapid:mulrcpb74onu1smi_q4> ;
  <maponto:isTemporalLayer> false ;
  <maponto:hasKmlFile>
    <http://test.strabon.di.uoa.gr/sextant/kml-tmp/
      n_38j9n.kml>.

<mapid:mulrcpb74onu1smi_q4>
  a <maponto:Query> ;
  <maponto:hasEvaluator> <mapid:mulrcpb74onu1smi_e4>;
  <maponto:hasValue> ""<SPARQL-query>"" .

<mapid:mulrcpb74onu1smi_e4>
```

<sup>19</sup>The W3C GeoXG incubator group has also developed a geospatial ontology [30].

<sup>20</sup><http://geovocab.org/>

<sup>21</sup><http://www.strabon.di.uoa.gr/stSPARQL#temporals>

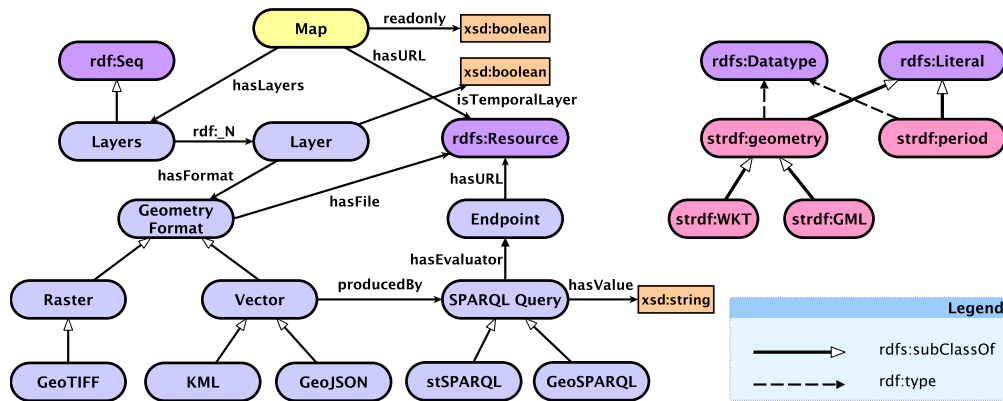


Figure 3: Map ontology

```
a <maponto:Endpoint> ;
  <maponto:hasURL>
    <http://geo.linkedopendata.gr/gag-endpoint/Query>.
```

### Map registry

The *map registry* component of Sextant is responsible for storing the RDF descriptions of map products that are modeled according to the map ontology described previously. For this, it employs a Strabon Endpoint (i.e., a SPARQL endpoint using as a back-end the geospatial RDF store Strabon) which can be either locally or publicly accessible. However, there is no dependency on the type of the SPARQL endpoint as long as it is compliant with the SPARQL 1.1 Graph Store HTTP Protocol [34]. The justification, though, for employing a Strabon Endpoint is that we plan to extend the map ontology to include also metadata about a map produced in Sextant (e.g., spatial and temporal extent) in order to offer search capabilities on spatial and temporal attributes, a feature that involves evaluation of GeoSPARQL or stSPARQL queries. A more detailed discussion on this choice can be found in Section 7.

### Time manager

The *time manager* component of Sextant is responsible for automatically moving forward (or backward) time filters of SPARQL queries. Considering that a SPARQL query defines a layer on Sextant and that a layer may present information that is valid during a specific time period, the *time manager* makes it easier for a user to select the time period for which a layer shows information. Using this component, Sextant is also able to periodically retrieve data that comes from a dynamic data feed and to provide a map product that is being automatically updated at predefined intervals.

Suppose that a user needs to monitor an environmental event (e.g., the sea level, a fire front) that is currently happening. Such data usually comes from sensors and is being updated at predefined intervals (e.g., every five minutes). A user can initialize a map layer by posing at a specific time (e.g., at 15:05) the SPARQL query in the left part of Figure 4. Also, the user can define, using the time manager, that this layer should be updated every five minutes. So every five minutes, the time manager would move forward the time filter of the query and retrieve new data. For example, at 15:10 the query in the right part of Figure 4 will be posed to update the map layer. The functionality provided by the timeline, created using the Timemap Javascript library (see the bottom right part of Figure 1b), enables a user to navigate through data with a temporal dimension. A user can move the timeline forward and backward and hide or display features on the map according to their valid time span. This functionality is very useful for exploring archive data. A user can create a temporally enhanced layer, load all archive data once and then browse this data using the timeline. However, if the user needs to monitor a dynamic feed of data, then new data is constantly arriving at an endpoint. In such cases, the functionality of the timeline is not enough. The needed functionality is provided by the time manager panel (see Figure 2e) that frequently updates the temporal filters of queries and re-evaluates them. Following this approach fresh data is added on the timeline of a map when needed.

The time manager panel enables the user not only to move backward and forward the timeline but also retrieve new data by changing the temporal filters of queries. Each time the button “next” (or “previous”) is pressed then the time manager component scans all queries, that define a layer, for datetime values and it

445 adds (or subtracts) a time step to these values. Then, it  
re-poses the new queries to the corresponding endpoints  
and re-visualizes the new results on the map. The time  
step can be defined (in seconds) by a user via the corre-  
sponding text field of the time manager panel. Finally,  
450 by pressing the button “play” a user can set Sextant to  
“go forward” every “time step” seconds, so that a prod-  
uct map is automatically updated while time is passing.

### KML translator

Sextant is armed with a component, named *KML*  
455 *translator*, that translates the results of GeoSPARQL  
and stSPARQL queries from the SPARQL query re-  
sults XML format to the KML file format. With re-  
spect to the representation of time, the KML stan-  
dard defines the abstract element `kml:TimePrimitive`  
460 which is realized by the two elements `kml:TimeStamp`  
and `kml:TimeSpan` for the representation of tempo-  
ral instants and intervals respectively. Sextant trans-  
lates the temporal primitives of stRDF that were men-  
tioned previously into these two elements. In partic-  
ular, Sextant translates any temporal instant ex-  
pressed using the datatype `xml:dateTime` into the el-  
ement `kml:TimeStamp`, whereas it translates any tem-  
poral interval expressed using the datatype of stRDF  
470 `strdf:period` into the KML element `kml:TimeSpan`.  
An example of this transformation is provided in Fig-  
ure 5. The translation of geometries with datatypes  
one of the `strdf:WKT`, `strdf:GML`, `geo:wktLiteral`,  
or `geo:gmlLiteral` to the respective elements of the  
KML specification is straightforward and is omitted.  
475 However, such a translation is depicted in Figure 5 and  
is marked with an orange rectangle.

The KML translator is also responsible for translating  
specific RDFS datatypes defined by Sextant<sup>22</sup> to KML  
elements, in order to provide the following capabilities.  
480 First, the KML translator enables coloring different ge-  
ographic features of the same layer according to their the-  
matic features, instead of a common color style for the  
whole layer. Second, it enables visualizing raster im-  
ages that are dynamically retrieved by a SPARQL query.  
485 To do so, Sextant introduces the following datatypes:

- The datatype `sextant:mapColor` is attached to  
literals that hold a KML color code as defined in  
the corresponding KML standard<sup>23</sup>. This datatype  
is used in Sextant to define the color style of geo-  
490 graphic features.

<sup>22</sup><http://sextant.di.uoa.gr/ontology>

<sup>23</sup>[https://developers.google.com/kml/documentation/  
kmlreference#color](https://developers.google.com/kml/documentation/kmlreference#color)

- The datatype `sextant:imageURL` is attached to  
literals that hold the URL of raster images. This  
datatype is used in Sextant as a means of overlay-  
ing a raster image on a map.

495 In order to enable different color style of geographic  
features of the same layer, Sextant scans result tuples for  
variables with datatype `sextant:mapColor`. For each  
unique color code, found in results, the KML translator  
creates a `kml:ColorStyle` element and attributes it to  
corresponding geographic features. An example of this  
transformation is shown in Figure 5 (marked in a green  
rectangle). This capability proves very useful because it  
enables visualizing on a map thematic attributes of ge-  
ographic features. For example, the CORINE dataset  
defines geographic features and the land use/land cover  
of each feature. In order to visualize this information  
on a map it is usual to attribute a specific color to every  
land use/land cover type. Instead of loading a different  
layer for every land use/land cover type and applying a  
common color style for the whole layer, Sextant can uti-  
lize `sextant:mapColor` values, attributed to each land  
use/land cover type and load only one layer to visualize  
all the information.

Raster images are also very important and useful to  
be depicted on map products. The first version of Sex-  
tant enabled visualizing static raster images by pro-  
viding their public URL. Simply loading a raster file  
(e.g., GeoTIFF, PNG) would be enough for visualizing  
static information. However, visualizing raster images  
that may dynamically change over time is also useful.  
The KML translator enables Sextant to visualize dy-  
namic information from raster layers by retrieving the  
URL of a raster file from results of a SPARQL query.  
Raster image URL are expressed using the datatype  
505 `sextant:imageURL` and KML translates every image  
URL into a `kml:GroundOverlay` which is overlaid on  
the map. An example of this translation is shown in  
Figure 6. This way, each time the query is posed to an  
endpoint and different results are retrieved the overlaid  
raster layer changes.

### 2.3. Collaboration capabilities

One of the key features of Sextant that makes it  
an attractive tool to end-users, and especially to do-  
main experts of the EO and Environment domains, is  
its capabilities for collaborative viewing and editing  
of a map produced by Sextant. This is achieved first  
by populating the map ontology as described above  
in Section 2.2, and, second, by publishing the map  
as a web resource under a specific URI of the form  
510 `http://<domain>/Sextant/?map=<mapid>`, where



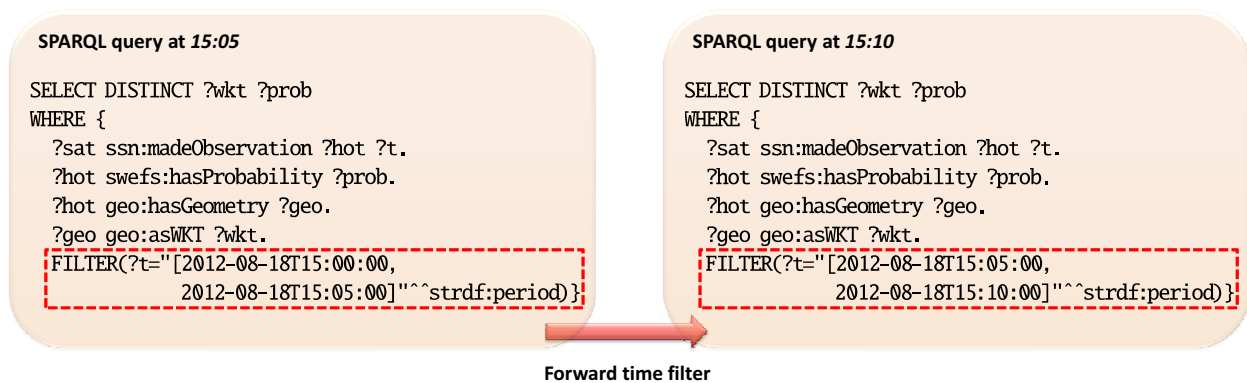


Figure 4: Forward time filter of SPARQL query

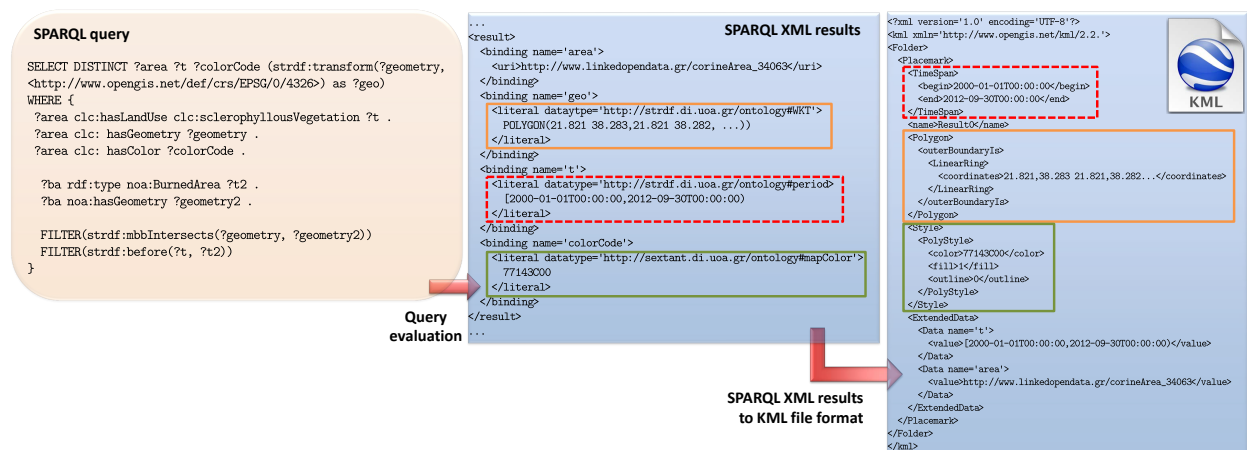


Figure 5: Translation of SPARQL XML results to KML for vector data

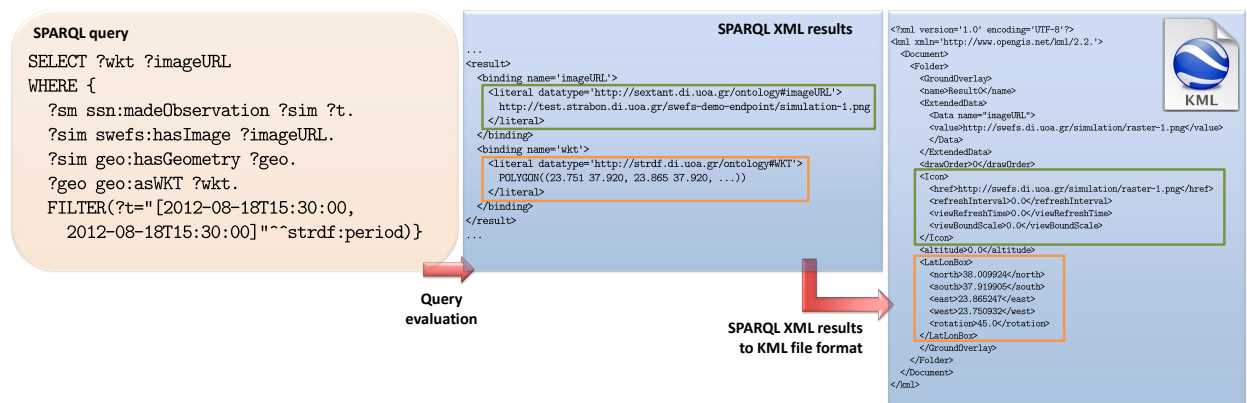


Figure 6: Translation of SPARQL XML results to KML for raster images

<domain> corresponds to the domain name the Sextant web application may be accessed and <mapid> corresponds to the map identifier of the viewing or editing map (see Figure 7a). This URI can then be shared among users for collaborative viewing and editing of the map in Sextant. This feature of sharing a map and allowing collaborative editing among users through a URI is demonstrated in Section 5 where the URI of maps produced in Sextant are given to the reader to appreciate its collaborative capabilities. The capabilities of Sextant with respect to collaboration are limited, though, in the sense that real-time collaborative editing (e.g., like what is offered by revision control systems, such as SVN and Mercurial) is not supported.

Collaborative editing of a map is not limited to Sextant only. Since Sextant is interoperable with GIS tools, collaboration can be achieved also using well-known desktop or web-based applications, such as QGIS, ArcGIS, and Google Maps by leveraging the export facility of Sextant. Sextant can export a map in the KML file format so as to be imported in the aforementioned tools (see Figure 7b). Therefore, a user is not confined to using Sextant, while she is able to use the GIS tool of her preference. Correspondingly, Sextant provides an import facility for importing KML files into Sextant, which models and describes them according to its underlying map ontology. You can see such an example in Figure 7c, where we created a map using Google Maps and then we imported the KML file into Sextant.

### 3. The power of queries in Sextant

This section is devoted to examples that demonstrate how a user can visualize in Sextant temporal and geospatial information that is present in linked datasets which are offered by a conventional SPARQL endpoint, e.g., Sesame. Examples with queries modeled after the query languages stSPARQL and GeoSPARQL are given later in Section 5.

Although Sextant has been designed to work with geospatial extensions of RDF and SPARQL, namely stRDF, stSPARQL, and GeoSPARQL, many users might want to use standard SPARQL when querying linked datasets with temporal and/or geospatial information (i.e., the corresponding SPARQL endpoint might not support such extensions), or it might be the case that these datasets do not follow the modeling of geospatial and temporal information dictated by these extensions, i.e., they might employ other vocabularies, such as W3C GeoXG and NeoGeo that were mentioned previously.

At the cost of losing some functionality with respect to querying temporal information, Sextant is still able to visualize temporal information even in cases where temporal information is not modeled according to stRDF or the employed SPARQL endpoint is other than Strabon, which implements the stRDF data model and stSPARQL query language. This can be accomplished by adapting a SPARQL query to use the datatypes `xml:dateTime` and `strdf:period`. In case the underlying SPARQL endpoint is powered by Strabon, this can be accomplished by using the constructor for temporal periods offered by stSPARQL:

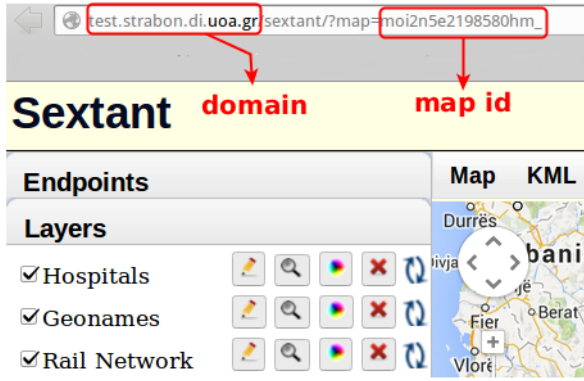
```
strdf:period strdf:period(xsd:dateTime start,
                          xsd:dateTime end)
```

This is demonstrated in the following example.

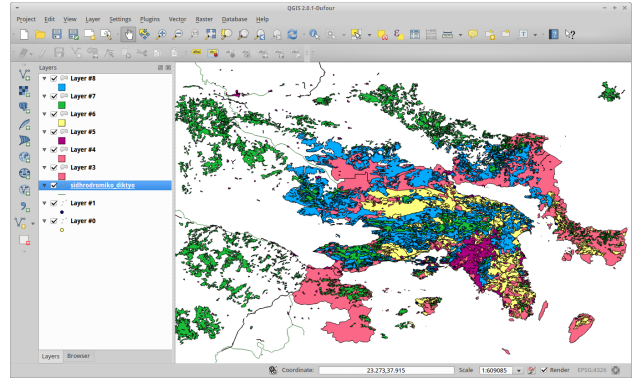
**Example 2.** This example demonstrates how one can visualize spatiotemporal information in Sextant when the temporal information is not modeled according to the data model stRDF. The following query asks for features inside the region of Patras, Greece, the land cover of which has been characterized as sclerophyllous vegetation by the CORINE Land Cover project, as well as for the time period this characterization is valid. We assume that the temporal validity of the land cover characterizations made by CORINE land cover uses the imaginary predicates `ex:startTime` and `ex:endTime` to mark the starting and ending time points of such intervals. Also, the modeling of geospatial information for spatial features follows the one dictated by GeoSPARQL.

```
SELECT ?area ?wkt
      (STRDT(
        CONCAT("[", ?start, ",", ?end, "]"),
        strdf:period) AS ?period)
WHERE {
  ?area rdf:type geo:Feature ;
        clc:hasLandUse
          clc:sclerophyllousVegetation ;
        geo:hasGeometry ?geo ;
        ex:startTime ?start ;
        ex:endTime ?end .
  ?geo rdf:type geo:Geometry ;
        geo:asWKT ?wkt .
  FILTER (geo:sfWithin(?wkt,
    "POLYGON((21.70 38.23, 21.70 38.33,
    21.91 38.33, 21.91 38.23,
    21.70 38.23))"^^geo:wktLiteral))
}
```

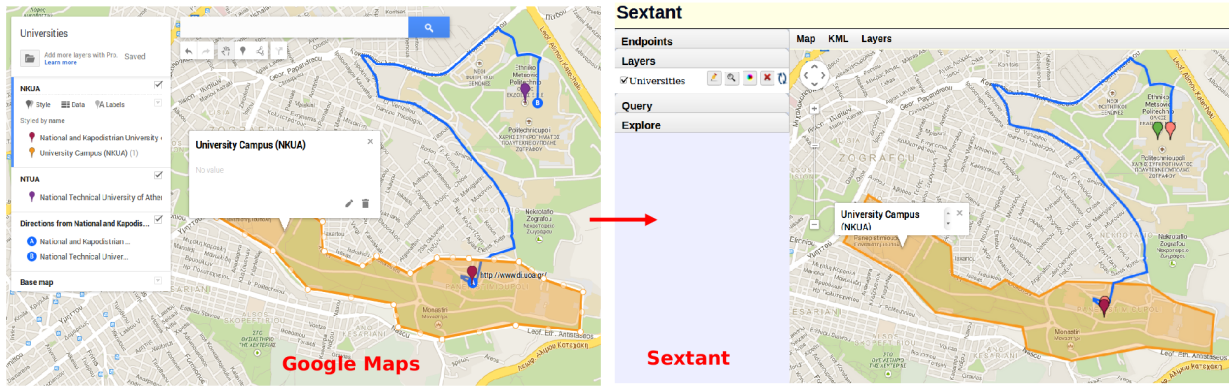
The XML results of the above SPARQL query can be transparently translated into the KML file format by Sextant. This is accomplished in the SELECT clause of the query, where a temporal period with datatype `strdf:period` is constructed based on the starting and ending time points of the requested features. This



(a) Map sharing functionality



(b) Export to KML and display in QGIS



(c) Map created with Google Maps and then imported into Sextant

Figure 7: Collaboration capabilities of Sextant

is done using the built-in functions of SPARQL 1.1, CONCAT<sup>24</sup> and STRDT<sup>25</sup>. In contrast, if the underlying SPARQL endpoint was Strabon, one could use in the SELECT clause the more readable constructor period, strdf:period(xsd:dateTime, xsd:dateTime). The corresponding clause in that case would have been the following:

```
SELECT ?area ?wkt
      (strdf:period(?start, ?end) as ?period)
```

The following example demonstrates how one can visualize features in Sextant the geometry of which is modeled using a datatype other than strdf:WKT or geo:wktLiteral.

**Example 3.** The following query can be posed against the SPARQL endpoint of DBpedia at <http://dbpedia.org/sparql> to ask for all airports and their

names in English, in the region of Attica, Greece. The SPARQL endpoint of DBpedia is powered by a Virtuoso endpoint and the geometry of spatial features is modeled in a number of ways. For the case of airports, the geometry is offered both as an untyped literal encoded in WKT and also expressed in the vocabulary of W3C GeoXG. See for example the description page at [http://dbpedia.org/page/Ellinikon\\_International\\_Airport](http://dbpedia.org/page/Ellinikon_International_Airport) that corresponds to one of the airports returned by that query. The query below uses the modeling of geometries as untyped literals encoded in WKT<sup>26</sup>.

```
SELECT ?airport ?name (STRDT(
  CONCAT(?geo,
    "http://www.opengis.net/def/crs/OGC/
    1.3/CRS84"), strdf:WKT) AS ?g)
```

<sup>26</sup>Throughout the article the prefix-namespace declaration part of a SPARQL query has been omitted from all SPARQL queries for the sake of readability. A prefix-namespace association list is maintained in Table A.1 of Appendix A.

<sup>24</sup><http://www.w3.org/TR/sparql11-query/#func-concat>

<sup>25</sup><http://www.w3.org/TR/sparql11-query/#func-strdt>

```

675 WHERE {
    ?airport rdf:type dbpedia:AirportsInGreece ;
            wgs84_pos:geometry ?geo ;
            rdfs:label ?name .
    FILTER(lang(?name) = "en" &&
680         bif:st_distance(bif:st_geomfromtext(
            "POINT(23.757 38.019)", ?geo) < 50)
    }

```

The following query is semantically equivalent to the previous one, but it accesses the properties `wgs84_pos:lat` and `wgs84_pos:long` to get the latitude and the longitude of the location of the airports, respectively. This is the GeoXG vocabulary that is used by DBpedia to model a point geometry.

```

690 SELECT ?airport ?name (STRDT(
    CONCAT("POINT(", ?long, " ", ?lat, ")",
    ";http://www.opengis.net/def/crs/OGC/
    1.3/CRS84"), strdf:WKT) AS ?g)
WHERE {
    ?airport rdf:type dbpedia:AirportsInGreece ;
695         wgs84_pos:lat ?lat ;
        wgs84_pos:long ?long ;
        rdfs:label ?name .
    FILTER(lang(?name) = "en" &&
        bif:st_distance(bif:st_geomfromtext(
700         "POINT(23.757 38.019)",
        bif:st_point (?long, ?lat)) < 50) }

```

Sextant can be used to visualize the content of any SPARQL endpoint regardless of the underlying modeling for the geometries as soon as its transformation to the modeling of stSPARQL or GeoSPARQL is expressible in SPARQL 1.1. Otherwise, one has to implement an adapter in Sextant for transforming the representation of a geometry to a standard OGC representation format and integrate it into the KML translator component described in Section 2.2.

#### 4. Linked geospatial datasets

In this section we describe the geospatial datasets that our group has made available in RDF and published as linked data at the Greek Linked Open Data portal<sup>27</sup> and the Datahub portal<sup>28</sup>, as well as other linked geospatial datasets available on the web, such as GeoNames. These datasets are used in the applications described next in Section 5 to demonstrate the usefulness of our tool Sextant for the browsing and visualization of such data.

<sup>27</sup><http://linkedopendata.gr/>

<sup>28</sup><http://datahub.io/organization/teleios>

*CORINE 2000.* The CORINE Land Cover (CLC) project is an activity of the European Environment Agency (EEA) that collects data regarding the land cover of 38 European countries. The project uses a hierarchical scheme with three levels to describe land cover with a mapping scale of 1:100,000. Level one is the most generic and comprises 5 categories (e.g., artificial surfaces, agriculture areas), level two comprises 15 categories (e.g., urban fabric, industrial, transport units), and the last level is the most detailed one comprising around 45 categories (e.g., continuous urban fabric, discontinuous urban fabric).

*Urban Atlas.* Urban Atlas (UA) is also an activity of the EEA that provides reliable, inter-comparable, high-resolution land use maps for 305 Large Urban Zones and their surroundings (urban areas with population greater than 100,000 people). The geometric resolution of UA is higher than that of CLC (1:10,000). UA uses a 4-level hierarchical scheme based on the CLC nomenclature. The first and second levels comprise 4 categories, the third level comprises 12 categories, while the fourth level comprises 7 categories.

*Greek administrative geography.* This dataset describes the administrative divisions of Greece according to Kallikratis<sup>29</sup>, the most recent administrative reorganization of Greece. The hierarchical administrative organization of Greece is as follows. Below the country level, there are seven *decentralized administrations*, which are composed by thirteen *regions* divided into several *regional units* each. In addition, every regional unit consists of one or more *municipalities* which, in turn, comprise *municipal units*. The dataset has been populated with relevant data (e.g. population, geographical boundaries) that are available in the Greek geodata portal<sup>30</sup>.

*Water bodies.* This dataset contains information about the water bodies (e.g., rivers, lakes) of Greece following the directive 2000/60/EC of the European Parliament and of the Council. The kind of information that is included in this dataset is the location of water surfaces in Greece, accompanied by auxiliary information, such as the name of the river/lake, the area, etc. The source of this dataset is also provided by the Greek geodata portal in shapefiles.

<sup>29</sup>[http://en.wikipedia.org/wiki/Administrative\\_divisions\\_of\\_Greece](http://en.wikipedia.org/wiki/Administrative_divisions_of_Greece)

<sup>30</sup><http://geodata.gov.gr/>

*Public Buildings.* This dataset provides information regarding buildings of public administration categorized according to the services they provide (e.g., government buildings, municipalities, municipality service centers, schools, etc.). The exact location of these buildings is also provided in this dataset. The source of this dataset is provided by the Greek geodata portal in shapefiles.

*Fire hotspots and burned areas.* This dataset contains information for the area of Greece related to real time hotspot detection and burnt area mapping that is derived from image processing algorithms on satellite images and is available by the National Observatory of Athens. Due to license restrictions, a sample of the primary source data (shapefiles) has been provided to us which we transformed into RDF and linked it with other linked geospatial datasets. We use this dataset in Section 5.2 to assess the environmental damage caused by fires with respect to the land cover of areas.

*GeoNames.* GeoNames<sup>31</sup> is a gazetteer that collects both spatial and thematic information for various place-names around the world. It contains over 10 million geographical names and consists of over 8 million unique features of which 2.8 million are populated places and 5.5 million are alternate names. All features are categorized into one out of nine feature classes (e.g., ADM1, ADM2, ADMH1, ADM5) and further sub-categorized into one out of 645 feature codes. GeoNames contains feature attributes such as names of places in various languages, elevation, population and others from various sources. Users may manually edit, correct, and add new names using a user friendly interface.

## 5. Applications of Sextant

Sextant is a user-friendly tool that can make the production of thematic maps a quick and easy task. The following sections include small, nevertheless, real application scenarios where Sextant has been proved useful to experts in the Earth Observation and Environment domains. The first two scenario were developed in the context of project TELEIOS.

### 5.1. Emergency response

The first scenario is based on a real user scenario in which an expert of an emergency response agency like the Center of Satellite Based Crisis Information<sup>32</sup>

(ZKI) or the National Observatory of Athens<sup>33</sup> (NOA) would like to quickly compile a map in response to an emergency event, for example a flood, a tsunami, an earthquake, or a forest fire. A typical map product that ZKI produced on August 25, 2009 for assessing the area burnt as a result of the fires of the period from August 21 to August 24, 2009 in Attica, Greece is presented in Figure 8a and may be found at <http://www.zki.dlr.de/map/1034/>. Such a map, apart from depicting burnt areas, is annotated with other kinds of information to aid experts in assessing the severity of the fire event. Typical information includes the road network, land use/cover, toponyms, population, and other more detailed information concerning map production and the data sources that were used.

We used Sextant to produce the map presented in Figure 8b that is similar to the one produced by ZKI. The major difference between the two maps is that the one produced by Sextant is based on the linked geospatial datasets of Section 4 and other data sources available on the web in KML format (e.g., railway network). This allows an emergency response manager to quickly compile a map based on “open source intelligence” until more precise, detailed data becomes available, i.e., after contacting local authorities. In particular, the map of Figure 8b comprises 9 layers each one described in the following:

1. Location, name, and address information of hospital buildings taken by the Public Buildings RDF dataset.
2. Name and population of toponyms in Attica, Greece taken from the GeoNames RDF dataset.
3. The rail network of Greece taken from the Greek geodata portal in the form of a KML file<sup>34</sup>.
4. The part of the E75 European route corresponding to Greece, taken from the CORINE Land Cover RDF dataset.
5. Name and population of the municipalities of Attica taken from the Greek Administrative Geography RDF dataset.
6. Areas of Attica characterized as *urban fabric* by the CORINE Land Cover project, taken from the respective RDF dataset.

<sup>33</sup><http://www.noa.gr/indexen.html>

<sup>34</sup>[http://geodata.gov.gr/datasets/attachments/37468daf-d548-49f7-bce9-55b77661ea63/kml/sidhrodromiko\\_diktyo.zip](http://geodata.gov.gr/datasets/attachments/37468daf-d548-49f7-bce9-55b77661ea63/kml/sidhrodromiko_diktyo.zip)

<sup>31</sup><http://www.geonames.org/>

<sup>32</sup><http://www.zki.dlr.de/>

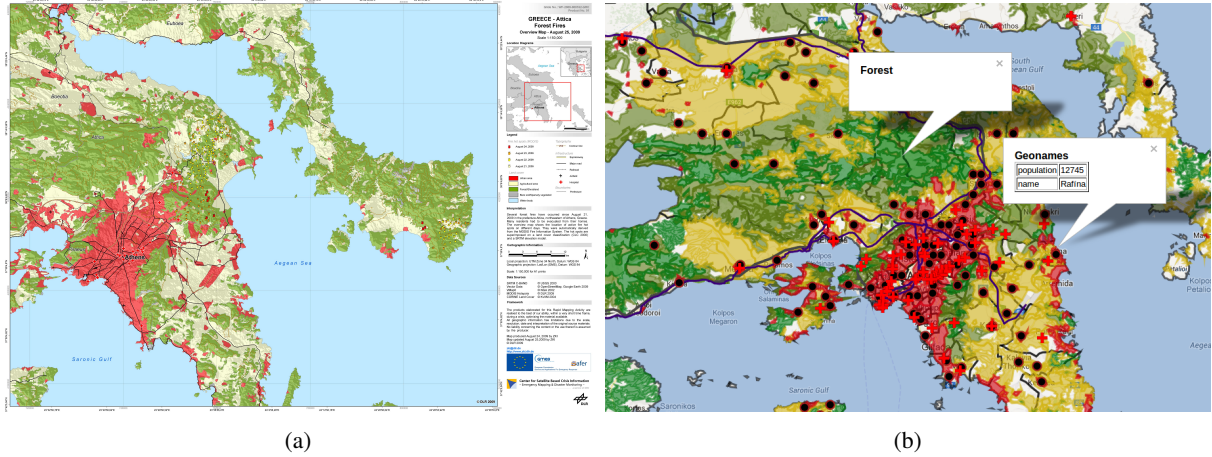


Figure 8: Fire products of 2009 in Attica, Greece produced by (a) ZKI and (b) Sextant

7. Areas of Attica characterized as *agricultural* by the CORINE Land Cover project, taken from the respective RDF dataset.

8. Areas of Attica characterized as *forests* by the CORINE Land Cover project, taken from the respective RDF dataset.

9. Areas of Attica characterized as *shrubland* by the CORINE Land Cover project, taken from the respective RDF dataset.

All of the above layers, the content of which is based on an RDF dataset, have been produced by evaluating a GeoSPARQL query on a SPARQL endpoint storing the respective dataset. An example for the last layer is shown next.

**Example 4.** The last layer of the map depicted in Figure 8b containing areas in the region of Attica that have been characterized by the CORINE Land Cover project as “shrubland” may be produced by the evaluation of the following SPARQL query that uses the vocabulary of GeoSPARQL.

```
SELECT ?wkt
WHERE {
  GRAPH <http://geo.linkedopendata.gr/corine> {
    ?area clc:hasLandUse ?landUse .
    ?landUse rdf:type ?l3 .
    ?l3 rdfs:subClassOf ?l2 .
    ?area geo:hasGeometry ?geometry .
    ?geometry geo:asWKT ?wkt .

    FILTER (geof:sfIntersects(?wkt, "POLYGON((
      24.10 37.92, 22.80 37.92, 22.80 38.60, 24.10
      38.60, 24.10 37.92))"^^geo:wktLiteral))
```

```
FILTER (?l2 = clc:ShrubsAndOrHerbaceous
VegetationAssociations>) } }
```

To ease maintenance, we have opted for using a single SPARQL endpoint and storing each dataset used for the construction of the map depicted in Figure 8b to a different named graph. Therefore, the above query uses the named graph corresponding to the CORINE Land Cover RDF dataset, which is identified by the URI <http://geo.linkedopendata.gr/corine>.

The produced map depicted in Figure 8b may be accessed at [http://test.strabon.di.uoa.gr/sextant/?map=m0i2n5e2198580hm\\_](http://test.strabon.di.uoa.gr/sextant/?map=m0i2n5e2198580hm_).

## 5.2. Land cover evolution over time

This section stresses the temporal features of Sextant by describing a real scenario in which an EO scientist studies the changes in the land cover of an area and assesses the damage caused by fires. This scenario is very common in the EO domain, where data is constantly produced by satellite sensors and is associated with metadata containing, among others, temporal attributes, such as the time that an image was acquired. Satellite acquisitions are utilized in related applications such as the CORINE Land Cover programme.

To achieve the goal of our scenario, we combined information derived from the following datasets: the CORINE 2000 dataset, and the fire hotspots and burnt areas dataset. The map consists of three layers as described below.

1. Areas that have been classified as “sclerophyllous vegetation” according to CORINE, a classification that is valid from 2000 to 2012.



2. Hotspots that were detected on July 18, 2012.
3. Areas that were identified as burned from 1 Oct., 2012 (i.e., the end of the fire season) until now, due to the previous fire event on July 18, 2012.

The third layer is produced by issuing the query of the following example.

**Example 5.** The last layer of the map depicted in Figure 9a depicts areas that were identified as burned from October 1, 2012 until now and may be produced by the evaluation of the following SPARQL query that uses the vocabulary of stSPARQL.

```
SELECT distinct (strdf:transform(?geometry,
<http://www.opengis.net/def/crs/EPSSG/0/4326>
as ?geo) ?t
WHERE {
  ?ba rdf:type noa:BurnedArea ?t .
  ?ba noa:hasGeometry ?geometry .
  FILTER (strdf:within(?geometry,
    "POLYGON((21.70 38.23, 21.70 38.33,
    21.91 38.33,21.91 38.23,
    21.70 38.23))"^^strdf:WKT))
  FILTER (strdf:during("NOW", ?t))}
```

In the query above, the spatial and temporal features of stSPARQL are used as follows. Function `strdf:within` is used to refine the area of interest and retrieve only the areas located within a specific polygon. Then, we want the areas that were characterized as “burned areas” and they are still considered as burned, so the current timestamp which is expressed using the temporal constant “NOW” should be during the valid time of the triple that denotes that an area is burned. This temporal relation is expressed using the temporal function `strdf:during`.

The scientist can also use the time slider offered by Sextant to display/hide the above information according to her temporal criteria for observing when and how the land cover of an area has evolved so that she can be assisted in damage assessment.

The produced map depicted in Figure 9a may be accessed at [http://test.strabon.di.uoa.gr/sexTant/?map=mulrcpb74onu1smi\\_](http://test.strabon.di.uoa.gr/sexTant/?map=mulrcpb74onu1smi_).

### 5.3. Visualizing environmental data

In this scenario, we describe how one can explore publicly available linked environmental data in a visual way and overlay it with other useful geospatial datasets, a process that can prove useful, since thematic maps depicting data regarding environmental issues is crucial

in many scientific fields and environmental organizations, like EEA, or projects, such as GLOBCOVER<sup>35</sup>, the aim of which is to develop detailed maps of the Earth’s global land cover.

The map depicted in Figure 9b consists of the thirteen layers described below.

1. Areas characterized as *Discontinuous Dense Urban Fabric* by the Urban Atlas dataset.
2. Areas characterized as *Railways and Associated Land* by the Urban Atlas dataset.
3. Areas characterized as *Continuous Urban Fabric* by the Urban Atlas dataset.
4. Areas characterized as *Discontinuous Low Density Urban Fabric* by the Urban Atlas dataset.
5. Areas characterized as *Sports and Leisure Facilities* by the Urban Atlas dataset.
6. Areas characterized as *Green Urban Areas* by the Urban Atlas dataset.
7. Areas characterized as *Isolated Structures* by the Urban Atlas dataset.
8. Areas characterized as *Forests* by the Urban Atlas dataset.
9. Areas characterized as *Fast Transit Road and Associated Land* by the Urban Atlas dataset.
10. The national forests of Greece taken from the Greek geodata portal in the form of KML file<sup>36</sup>.
11. The rivers of Greece taken from the Greek geodata portal in the form of KML file<sup>37</sup>.
12. Burned Areas from 1 Oct., 2012 (i.e., the end of the fire season) until now, due to the previous fire event on July 18, 2012.
13. Protected areas included in the NATURA 2000 dataset that is provided in KML by the Greek geodata portal<sup>38</sup>.

<sup>35</sup><http://due.esrin.esa.int/globcover/>

<sup>36</sup>[http://geodata.gov.gr/datasets/attachments/c6cc176a-94e4-4f1e-bf62-47a9531ad783/kml/ethikoi\\_drymoi.zip](http://geodata.gov.gr/datasets/attachments/c6cc176a-94e4-4f1e-bf62-47a9531ad783/kml/ethikoi_drymoi.zip)

<sup>37</sup><http://geodata.gov.gr/datasets/attachments/ec4efe37-76bb-426f-af38-36d57d39dfba/kml/potamoi.zip>

<sup>38</sup><http://geodata.gov.gr/datasets/attachments/289263ce-04be-4e88-941c-81ea79da7169/kml/natura.zip>

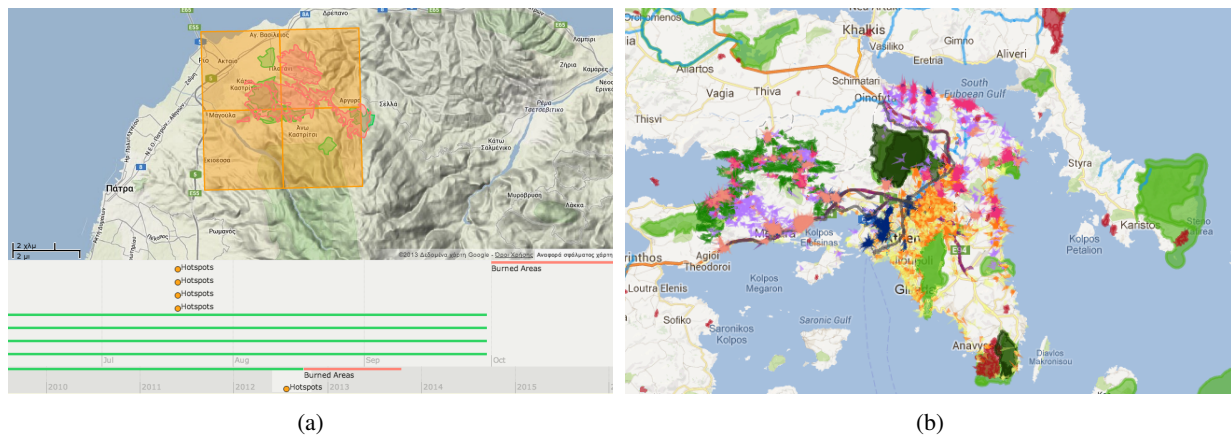


Figure 9: Screenshots from Sextant depicting (a) the evolution of the land cover and (b) a thematic map created using linked environmental data and KML files

**Example 6.** The layer displaying the green urban areas according to the Urban Atlas dataset may be produced by the evaluation of the following query that uses the vocabulary offered by GeoSPARQL.

```
SELECT ?wkt
WHERE {
  ?z ua:hasLandUse ua:greenUrbanAreas.
  ?z geo:hasGeometry ?g.
  ?g geo:asWKT ?wkt.

  FILTER (geof:sfIntersects(?wkt,
    "POLYGON((24.73 37.57, 22.13
    37.57, 22.13 38.95, 24.73
    38.95, 24.73 37.57 ))"
    ^^geo:wktLiteral)) }
```

The produced map depicted in Figure 9b may be accessed at [http://test.strabon.di.uoa.gr/sexTant/?map=m6rn4booji88dh5a\\_](http://test.strabon.di.uoa.gr/sexTant/?map=m6rn4booji88dh5a_).

#### 5.4. Monitoring dynamic geographic data

In the last scenario, we describe how Sextant can be used to monitor dynamic environmental data, that are updated in real time. This scenario is based on a real use case which is studied in the context of the project Sensor Web Fire Shield (SWeFS). The SWeFS research project aims at delivering a novel Sensor Web platform for addressing the serious threat of forest fires. The produced map, that is depicted in Figure 10, can be accessed at [http://test.strabon.di.uoa.gr/swefs-demo-sexTant/?map=mse9671f0gvqh6r9\\_](http://test.strabon.di.uoa.gr/swefs-demo-sexTant/?map=mse9671f0gvqh6r9_) and consists of three layers described below.

1. A flammability map for the area of Hymettus.
2. Real time hotspot detections.

3. A raster image visualizing the future expansion of a fire front.

The first layer is a static one. A flammability map defines geographical areas and the major category of vegetation that covers each area. These vegetation categories are called *fuel types* and are important for the task of fire monitoring, because they indicate how drastically a fire front can expand in each area. In order to visualize this information on a Sextant layer we assign a `sextant:mapColor` value to each fuel type. Example 7 shows RDF triples defining that chaparral areas are depicted with dark green color and timber areas with brown color.

**Example 7.** RDF triples defining the color used to visualize fuel types on a flammability map:

```
swefs:chaparral rdf:type swefs:FuelType.
swefs:chaparral swefs:hasColor
  "77143C00"^^sextant:mapColor.
swefs:timber rdf:type swefs:FuelType.
swefs:timber swefs:hasColor
  "77004297"^^sextant:mapColor.
```

This layer is used as a background and two dynamic layers are depicted above it. The second layer of this map consists of real time hotspot detections. Hotspots are characterized by a confidence value indicating the probability that an area is on fire. To visualize this confidence level on the map, `sextant:mapColor` values are attributed to specific ranges of confidence (e.g., hotspots with confidence value between 0.8 and 1 are depicted red). New detections arrive every five minutes and the time manager retrieves these new detections and visualize them on the map. The query used to retrieve this layer at 15:00 on 18/08/2012 is shown in Example 8.



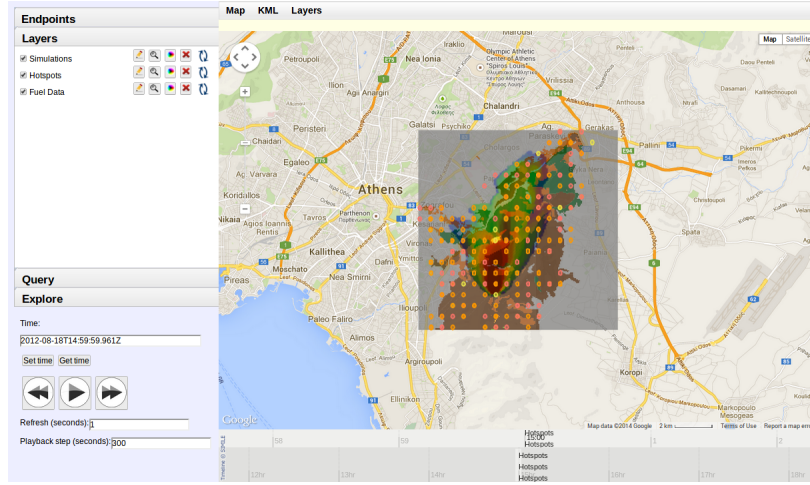


Figure 10: A screenshot from Sextant map depicting dynamic geospatial data

**Example 8.** The layer displaying real time hotspot detections was produced by the evaluation of the following query:

```
SELECT *
WHERE {
  ?hot swefs:hasProbability ?probability.
  ?hot geo:hasGeometry ?geo.
  ?geo geo:asWKT ?wkt.
  ?sat ssn:madeObservation ?hot ?t.

  FILTER(?t="[2012-08-18T15:00:00,
    2012-08-18T15:00:00]"^^strdf:period)
  FILTER(strdf:mbbIntersects(?wkt,
    "POLYGON((23.751 37.920, 23.865
    37.920, ...))"^^strdf:WKT))
}
```

Finally, according to the fuel types and the detected hotspots a fire simulation module of SWeFS generates the third layer of this use case scenario. This layer consists of a raster image, that visualizes the future expansion of the fire front. This raster image is retrieved by query of Example 9 so that it is, also, dynamically updated while time is passing.

**Example 9.** The layer displaying the raster image of the simulation module of SWeFS was produced by the following query:

```
SELECT ?t ?wkt ?image
WHERE {
  ?sm ssn:madeObservation ?sim ?t.
  ?sim swefs:hasGeometry ?geo.
  ?sim swefs:hasImage ?image.
  ?geo swefs:asWKT ?wkt.
```

```
FILTER(?t="[2012-08-18T15:30:00,
  2012-08-18T15:30:00]"^^strdf:period)
}
```

In this scenario, instead of creating an offline map, we stress the creation of a dynamic map which is being updated while new data is arriving. Additionally we show how thematic content of geographic data (e.g., fuel type, fire probability) can be visualized on a map layer by using different colors for different thematic values.

## 6. Related work

In general, the semantic web and linked data area lack tools that can aid researchers and practitioners in exploiting the ocean of currently available linked geospatial and temporal data. This contrasts very unfavorably with the rich and mature technological arsenal of the traditional GIS area and hampers the development of applications based on linked spatiotemporal data. We believe Sextant is a significant step in the direction of filling this gap and devote the rest of this section to discuss related tools both from the semantic web/linked data and the GIS area.

### 6.1. Semantic web and linked data

Although tools for exploring the content of linked geospatial data have made their appearance recently, these tools focus on browsing a single dataset or the content of a single SPARQL endpoint. One of the first efforts is the LinkedGeoData browser<sup>39</sup> which is

<sup>39</sup><http://linkedgedata.org/LGD%20Browser>

the most promising among these tools, offering browsing functionality for Open Street Map (OSM) data and also editing capabilities in the style of the original OSM portal. Map4RDF<sup>40</sup> [21] is another browser for RDF data with geospatial information that supports faceted browsing of RDF data based on the `rdf:type` property, filtering of query results in a specified bounding box, and visualization of statistical data modeled according to the SCOVO vocabulary<sup>41</sup> using predefined statistical indices. A more recent tool is the Facete browser<sup>42</sup> that promises to offer hierarchical faceted search over SPARQL endpoints on RDF properties.

Although the above tools are very useful for exploring the data offered by a single SPARQL endpoint, they have severe limitations when they are faced with the task of exploring the linked geospatial data cloud. This problem is actively being tackled in its general form (i.e., not only in the geospatial domain) by the recent tool LODVisualization<sup>43</sup> which is based on the Linked Data Visualization Model [22] for visualizing RDF data. But, although LODVisualization seems a very promising tool, it has very limited support regarding visualization of geospatial data and construction of meaningful thematic maps.

With respect to visualizing both the geospatial and temporal dimension of linked geospatial data, there is only one effort that we are aware of that studies the modeling and visualization of spatiotemporal data: the French project GEOPEUPLE<sup>44</sup>. As an example, the demo available at <http://www.rotfabrik.free.fr/geopeuple/en/onglets-33038.html> visualizes the evolution of administrative regions in France over the time. To the best of our knowledge, other than this demo, no tool has been made available by the project GEOPEUPLE for public or commercial use.

## 6.2. Geographic Information Systems

The GIS area offers a great number of versatile systems, tools, and applications that one can use to visualize and browse many geospatial datasets at a time that are available in standard formats, such as Esri shapefile, KML, GML, GeoJSON, GeoRSS, GPX, GeoTIFF, etc. Examples of such tools are the open source application QGIS<sup>45</sup> (Quantum GIS), the commercial platform

ArcGIS<sup>46</sup>, the open source applications uDIG<sup>47</sup> (User-friendly Desktop Internet GIS) and TimeMap<sup>48</sup> [35]. From these systems, QGIS extended with the TimeManager<sup>49</sup> plugin, ArcGIS, and TimeMap have the ability to visualize geospatial data with a temporal dimension that is often termed as *time-stamped spatial data*.

The well-known tool Google Earth<sup>50</sup> also offers similar functionalities to the ones we developed in Sextant. Google Earth has been widely adopted by both the GIS community and common users due to its simplicity and versatility in tasks such as Earth exploration and visualization of many geospatial data sources at a time, available in the KML format. Google Earth is able to visualize also temporal information that is associated with spatial objects and encoded in the KML format.

There has been also a number of innovative prototype systems in the 90's and early 00's for visualizing geospatial and temporal data, spatiotemporal and time-series data, as well as visualizing broader classes of computation pertaining to simulations of the Earth's environment, such as atmosphere and ocean. The most prominent of these systems are Descartes [36] and its successor CommonGIS [37], MapTime [38], and Vis-5D [39]. An extensive study of such tools may be found at [40]. Such systems are some of the few that offered early on pioneering data and visual analytics functionality as well. Part of this functionality has gained wider acceptance nowadays, while many of the visualization techniques employed in these systems have been adopted in today's web-based libraries, such as Google Charts<sup>51</sup> and the Google Maps Visualization Library<sup>52</sup>.

There is also the project MapTime<sup>53</sup> that offers a web-based visualization tool which focuses on the visualization of the so-called *deep time*, a concept of time that is more appropriate for representing events that occurred millions or billions of years ago and which is very useful in sciences, such as Geology. In this respect, there are very few existing tools which provide a good visual representation of this kind of time scale.

<sup>40</sup><http://oeg-dev.dia.fi.upm.es/map4rdf/>

<sup>41</sup><http://vocab.deri.ie/scovo>

<sup>42</sup><https://github.com/GeoKnow/Facete>

<sup>43</sup><http://lodvisualization.appspot.com/>

<sup>44</sup><http://geopeuple.ign.fr/>

<sup>45</sup><http://www.qgis.org/>

<sup>46</sup><http://www.esri.com/software/arcgis/>

<sup>47</sup><http://udig.refractory.net/>

<sup>48</sup><http://www.timemap.net/>

<sup>49</sup><http://plugins.qgis.org/plugins/timemanager/>

<sup>50</sup><http://www.google.com/earth/>

<sup>51</sup><https://developers.google.com/chart/>

<sup>52</sup><https://developers.google.com/maps/documentation/javascript/visualization>

<sup>53</sup><http://www.maptime.co.uk/>

## 7. Future directions

There are many directions to pursue in the future to make Sextant more robust, versatile, and appealing to the end-user. These directions are discussed in the following.

*Query builder integration.* Sextant has already received very positive feedback from our user partners in the TELEIOS project, DLR and NOA. However, both of them have spotted the weakness of Sextant in the lack of a tool to aid formulation of SPARQL queries, instead of typing them. In the context of TELEIOS, partner Fraunhofer has been developing a visual query builder for composing stSPARQL queries using an intuitive interface that does not require knowledge of any semantic web technology [41, 42]. In the future, we plan to integrate this query builder (or any similar one that might become available) into Sextant.

*Development of a map registry.* Sextant already employs a map registry for storing the RDF descriptions of map products that are modeled according to the Map ontology described in Section 2. We plan to extend the map ontology to include also metadata about a map produced in Sextant in order to facilitate map sharing and offer search capabilities on the content of a map, such as the creation date or the date in reference to the used data sources (e.g., hotspot products for the fire season of 2012), the spatial extent, a theme categorization (e.g., fires, floods, oil spills, environmental disasters), the author or the organization that created the map, the license under which it might be distributed, etc. This feature is very important and the GIS industry has just started investing on the development of such products. An example is the Esri Geoportal Server<sup>54</sup>, a free and open source product that enables discovery and use of geospatial resources including datasets, raster files, and Web services. The Esri Geoportal Server helps organizations manage and publish metadata for their geospatial resources to let users discover and connect to those resources. What is interesting though is that Esri has also started using semantic web technologies by providing an interface for discovering resources such as the above using the GeoSPARQL query language<sup>55</sup>.

*Post-processing operations of layers.* Offering spatial and temporal operations on layers or maps, such as filtering and transformation of spatial objects, and spa-

tial/temporal joins on two or more layers would increase the browsing and exploration capabilities of Sextant making it a very useful tool for interlinking linked spatiotemporal datasets.

*More tools for visual analytics.* The current version of Sextant offers to users a way to visualize spatiotemporal information on a map by overlaying a number of data sources present in the form of linked open data and file formats for representing geospatial information. Therefore, Sextant may be categorized as a tool offering information visualization. Using the coloring functionality of Sextant, a user may color the layers of a map appropriately to convey a certain interpretation of their content (see for example the application scenaria described in Sections 5.1 and 5.3). Similarly, using the time slider, a user might draw certain conclusions with respect to the evolution of the underlying information (see for example the application scenario described in Section 5.3). However, information visualization as offered by Sextant is only the first step towards supporting of more general methods for enabling the interaction of a user with the data with the aim of driving a user in analyzing the underlying information, appreciating it, and coming to conclusions.

Towards this direction a desirable extension of Sextant would be the ability of producing *statistical maps*, which is very important in the area of geostatistics. Production of statistical maps is a key feature for interpreting the underlying elementary data in a qualitative manner. Statistical maps are heavily used by agencies, such as Eurostat<sup>56</sup>, the leading provider of high quality statistics in Europe, and the United States Census Bureau<sup>57</sup>, the leading provider of quality data about the nation's people and economy. Pursuing this direction in Sextant is also aligned with the recent emphasis put on the development of RDF vocabularies for publishing and querying multi-dimensional data on the web. The most important of these efforts is the RDF Data Cube Vocabulary [43], which is a W3C recommendation as of January 16, 2014.

*Map or cartographic generalization* [44] is another very desirable and helpful feature for visual analytics, which is essentially a process of abstraction and reduction of the complexity of a map. Map generalization is the process of selecting and simplifying a feature's representation in a way that is appropriate to the scale and the purpose of a map. For example, having a view of the world, it would be undesirable to display villages, that

<sup>54</sup><http://www.esri.com/software/arcgis/geoportal>

<sup>55</sup><http://gptogc.esri.com/geosparql/>

<sup>56</sup><http://ec.europa.eu/eurostat/>

<sup>57</sup><http://www.census.gov/>

would be otherwise useful to display (e.g., when one zooms into a very specific area). As another example, a map for bicyclists will emphasize a different selection of the roads as opposed to a map targeted at drivers of trucks or lorries. In this case, it is also useful to support clustering techniques aiming at computing groups of features of the same type and displaying an aggregated view of them while losing with respect to location precision.

Last, a feature that should not be missing by any tool offering visual analytics is the ability to construct a *legend* to accompany a map. Legend information is regarded an integral part of any map product for describing its content. In principle, a legend is used to describe the types of features included in a map by associating a certain meaning to the colors and/or symbols used to represent them. Similar to the purposes of a legend, it is equally important to offer the ability to the users to include other informative content. That could be for example a title, a text description in order to provide the user with a first, quick and easy interpretation of the map, a listing of the data sources used for constructing the map, a location diagram used to give the spatial context of the area displayed on a map<sup>58</sup>, usually by zooming out of it and showing a more indicative and recognizable geographical area, license information and other acknowledgments, and any other piece of information, usually fitting the term metadata, that the producer of a map would like to communicate to its consumers.

*Support of more file formats.* Currently, Sextant is able to work with linked spatiotemporal data, KML, and GeoTIFF files. Other vector formats, such as Esri shapefiles and GeoJSON, and raster formats, such as JPEG JFIF and FITS, can be supported as well to increase the level of interoperability of Sextant with other GIS tools.

*Federated query processing.* It is also very important for a tool for visualizing linked spatiotemporal data to offer the ability to combine spatiotemporal information present in different SPARQL endpoints into a single layer of a map. This requirement calls for the development of federated query processing systems for query languages such as GeoSPARQL and stSPARQL. The availability of such a system would turn Sextant into an even more powerful tool for leveraging the linked spatiotemporal data cloud.

<sup>58</sup>This is a very desirable feature especially for non-interactive maps. A product map that have such a feature is depicted in Figure 8a.

## 8. Conclusions

In this article we presented Sextant, a web-based tool that offers functionalities which are of fundamental importance to leveraging time-evolving linked geospatial data. The functionalities of Sextant include the exploration of time-evolving linked geospatial data, the creation, sharing, and collaborative editing of thematic maps, and finally, the export of maps in OGC standard formats for achieving interoperability with other GIS applications.

We presented some real application scenarios from the Earth Observation and Environment domains to showcase how our tool Sextant can prove useful to a domain expert by demonstrating its browsing and visualization capabilities using linked geospatial data and other geospatial data sources publicly available on the web.

## Appendix A. Table of namespaces

This section maintains a list of prefix-namespace associations that are used in SPARQL queries throughout the article.

Table A.1: Prefix-namespace associations used throughout the article

clc	<a href="http://geo.linkedopendata.gr/corine/ontology#">http://geo.linkedopendata.gr/corine/ontology#</a>
dbp	<a href="http://dbpedia.org/class/yago/">http://dbpedia.org/class/yago/</a>
ex	<a href="http://www.example.org/ontology#">http://www.example.org/ontology#</a>
geo	<a href="http://www.opengis.net/ont/geosparql#">http://www.opengis.net/ont/geosparql#</a>
geof	<a href="http://www.opengis.net/def/function/geosparql/">http://www.opengis.net/def/function/geosparql/</a>
mapid	<a href="http://geo.linkedopendata.gr/map/id/">http://geo.linkedopendata.gr/map/id/</a>
maponto	<a href="http://geo.linkedopendata.gr/map/ontology/">http://geo.linkedopendata.gr/map/ontology/</a>
rdf	<a href="http://www.w3.org/1999/02/22-rdf-syntax-ns#">http://www.w3.org/1999/02/22-rdf-syntax-ns#</a>
rdfs	<a href="http://www.w3.org/2000/01/rdf-schema#">http://www.w3.org/2000/01/rdf-schema#</a>
strdf	<a href="http://strdf.di.uoa.gr/ontology#">http://strdf.di.uoa.gr/ontology#</a>
wgs84-pos	<a href="http://www.w3.org/2003/01/geo/wgs84-pos#">http://www.w3.org/2003/01/geo/wgs84-pos#</a>
xsd	<a href="http://www.w3.org/2001/XMLSchema#">http://www.w3.org/2001/XMLSchema#</a>
sextant	<a href="http://sextant.di.uoa.gr/ontology#">http://sextant.di.uoa.gr/ontology#</a>
ssn	<a href="http://purl.oclc.org/NET/ssnx/ssn#">http://purl.oclc.org/NET/ssnx/ssn#</a>
swefs	<a href="http://swefs.di.uoa.gr/simulation/ontology#">http://swefs.di.uoa.gr/simulation/ontology#</a>

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