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GeoSPARQL 1.1: An Almost Decadal Update to the Most Important Geospatial LOD Standard

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Abstract: In 2012 the Open Geospatial Consortium published GeoSPARQL defining "an RDF/OWL ontology for [spatial] information", "SPARQL extension functions" for performing spatial operations on RDF data and "RIF rules" defining entailments to be drawn from graph pattern matching. In the 8+ years since its publication, GeoSPARQL has become the most important spatial Semantic Web standard, as judged by references to it in other Semantic Web standards and its wide use for Semantic Web data. An update to GeoSPARQL was proposed in 2019 to deliver a version 1.1 with a charter to: handle outstanding change requests and source new ones from the user community and to "better present" the standard, that is to better link all the standard's parts and better document & exemplify elements. Expected updates included new geometry representations, alignments to other ontologies, handling of new spatial referencing systems, and new artifact presentation. In this paper, we describe motivating change requests and actual resultant updates in the candidate version 1.1 of the standard alongside reference implementations and usage examples. We also describe the theory behind particular updates, initial implementations of many parts of the standard, and our expectations for GeoSPARQL 1.1's use.

Keywords: GeoSPARQL; GeoSPARQL 1.1; spatial; geospatial; Semantic Web; RDF; OWL; OGC; Open Geospatial Consortium; standard; ontology.

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1. Introduction

The GeoSPARQL standard, issued in 2012 by the Open Geospatial Consortium (OGC)[1] is one of the most popular *Semantic Web* standards for spatial data.[2] The original release - GeoSPARQL 1.0 [4] - contained:

- a *specification* document
  - the main GeoSPARQL document defining, in human-readable terms and with code snippets, most elements of the standard including ontology elements, geospatial functions that may be performed on Resource Description Format (RDF)[5] data via SPARQL[6,7] queries, entailment rules in the Rules Interchange Format (RIF)[8] for RDF reasoning and requirements & abstract tests for testing ontology data and function implementations
- an RDF/OWL[9] *schema*
  - the GeoSPARQL ontology - Semantic Web data model - in an RDF file

[1] https://www.ogc.org
[2] References to GeoSPARQL in other well-known standards, such as DCAT2 [1] and CIDOC-CRM [2,3] suggests it is popular, as do the incoming links in Linked Open Vocabularies https://lov.linkeddata.es/dataset/lov/vocabs/gsp and the list of implementors that includes most of the popular triplestore vendors, a list of which has been compiled here: https://github.com/opengeospatial/ogc-geosparql/issues/59

- an RDF *vocabulary*
  - the Simple Features Vocabulary for "defining SimpleFeature geometry types" taken from [10] in RDF/OWL terms, also in an RDF file

In this form, GeoSPARQL 1.0 has been used widely; however, requests for updates to it have been received by the OGC. In this publication, an extension of the workshop paper [11], we discuss the motivations behind updating GeoSPARQL 1.0 in Section 2, content of the planned GeoSPARQL 1.1 release[3] in Section 3 and reference implementations and use cases in Sections 4 and 5. Finally, in Section 6, we provide an outlook to further feature requests which are likely to be tackled in future GeoSPARQL releases or replacements.

2. Motivation to update GeoSPARQL

The OGC & World Wide Web Consortium's (W3C) *Spatial Data On The Web Working Group* (SDWWG) published a list of Best Practice points[4] for rating web-based spatial data. Through the use of that rating system and other work, the SDWWG noted that: "A best practice for returning geometries in a specific requested CRS has not yet emerged". Given the scope of GeoSPARQL 1.0, this statement indicates that GeoSPARQL 1.0 had not then 'solved' web-based spatial data publishing. The group also informally captured specific suggested updates for GeoSPARQL[5], however no updates to GeoSPARQL itself were then made.

The authors note that in the 3+ years since that statement's publication, GeoSPARQL 1.0 has become far more widely supported by Semantic Web databases (so-called "triplestores") and other Semantic Web applications, as evidenced by frequent attempts to benchmark geospatial-aware triplestores for GeoSPARQL compliance and performance [13–16]. Some further notes on GeoSPARQL support is provided in Section 6.1.

In 2019, the OGC reconstituted the *GeoSPARQL Standards Working Group* (SWG) to update GeoSPARQL. The motivation for work within the area of GeoSPARQL, that of spatial *Semantic Web* data more generally, and some specific fault fixes and proposed extensions to GeoSPARQL 1.0 are captured in an OGC White Paper [17]. Some, but not all, of the SDWWG's issues raised were taken up by the SDW, for example, the *Best Practices* [12] aspiration that "A possible way forward is an update for the GeoSPARQL spatial ontology. This would provide an agreed spatial ontology, i.e., a bridge or common ground between geographical and non-geographical spatial data...". This issue is specifically addressed in GeoSPARQL 1.1's extensions for scalar spatial data.

Other *Best Practices* issues raised such as "it makes sense to publish different geometric representations of a spatial object that can be used for different purposes" are partly addressed; GeoSPARQL 1.1 indeed indicates how to use multiple geometric representations of geometries in relation to a single feature, but concepts such as defining *roles* for geometries, with respect to features, have not been implemented.

The SWG's Charter - their final scope of work - is also published by the OGC [18] and this guided the SWG's activities. Specific actions of the SWG and their staging are explained through the use of a publicly-available online task tracking system within the SWG's working online code repository[6].

At a high-level, proposed updates to GeoSPARQL by both the SDWWG and the SWG may be categorized as one of the following:

- new geometry serializations
  - GeoJSON, KML and other now-popular formats missing from GeoSPARQL 1.0
  - the possibility to convert between literal formats in-query

[3] See the GeoSPARQL working repository for the latest candidate release form of GeoSAPRQL 1.1: https://github.com/opengeospatial/ogc-geosparql
[4] See https://w3c.github.io/sdw/bp/ for an accessible version of the points online and [12] for the corresponding academic publication
[5] https://www.w3.org/2015/spatial/wiki/Further_development_of_GeoSPARQL
[6] https://github.com/opengeospatial/ogc-geosparql/projects/1

- new and specialized ontology classes and properties
  - more nuanced spatial data representation and alignment with other systems
- more spatial functions
  - implementing functions well-known in non-`Semantic Web` spatial systems
- scalar spatial properties
  - area, volume, etc. alongside geometries
- better handling of Spatial (Coordinate) Reference Systems (SRS)
  - allowing for automated coordinate serialization conversions
- Internet protocol-based selection of different geometries for features

Some of these proposed updates were predicted in GeoSPARQL 1.0, with the *Future Work* section listing several of the points above. The SWG's *Charter*, anticipating that the more obvious updates such as new geometry serializations would certainly be implemented, listed the following extra areas of investigation that emerged from SWG proponent's discussions:

- revising "upper ontology" GeoSPARQL structure - how its classes relate to fundamental concepts in ontology
- alignments to other ontologies, perhaps *W3C Time Ontology in OWL* [19]
- catering for very different SRSes, such as Discrete Global Grid Systems

Specifically ruled out of scope in the *Charter* was any investigation of property graphs. Recent (last several years) discussions in the OGC and elsewhere about property graphs motivated a consideration of them, however, the SWG proponents felt that while property graphs might be important for future *Semantic Web* spatial data systems, there was more than enough work scoped for initial SWG work (several revisions of the standard) to initially exclude this area of investigation.

After initial meetings, the SWG determined to make multiple versioned releases of GeoSPARQL updates with different goals:

- **1.1**: extensions that are fully compatible with GeoSPARQL 1.0
- **1.2**: fully or mostly compatible extensions but which are larger additions to the standard's conceptual coverage
- **2.0**: future GeoSPARQL likely incompatible with GeoSPARQL 1.0

The reason for expecting a future, incompatible, GeoSPARQL 2.0 is that early SWG attendees thought spatio-temporal relations and fundamental ontology elements in GeoSPARQL either could or should be remodeled, which might break the current, familiar, `Feature/Geometry` class relations. Details of these potential changes haven't been fully expounded at the time of this paper, however initial SWG attendees' intuition is that a future GeoSPARQL 2.0, or perhaps a renamed GeoSPARQL replacement, might generalise spatial concepts and move away from only, or primarily, *geo*spatial, or perhaps focus not just on `Feature/Geometry` relations but look to generalised mechanisms for describing dimensions of features of which *geometry* is just one of many, and *temporality* might be another. See Section 6 for further details.

Originally unexpected, an area of updates to standard presentation was considered by the SWG. Motivation from conceptual work within the W3C and OGC for the presentation of multi-part standards and the desire by the OGC's "Naming Authority"[7] to publish standards more systematically and in more machine-readable forms, as well as

[7] The Naming Authority https://www.ogc.org/projects/groups/ogcnasc has the remit to "..ensure an orderly process for assigning URIs for OGC resources, such as OGC documents, standards, XML namespaces, ontologies." and also acts as a process evangelist, promoting, as it sees, better standards publication practice.

programs of work such as the OGC's "Test Bed 17: Model Driven-Standards"[8], this has resulted in the profile declaration explained in the next section.

3. Updates in GeoSPARQL 1.1

In 2021, the GeoSPARQL SWG addressed many of the GeoSPARQL change requests in the 1.1 release. All of the changes reported here are now visible in the current working draft of GeoSPARQL 1.1 standard, the specification document and the other standard parts [20]. It is expected that the candidate standard will remain essentially unchanged through to final publication, barring perhaps minor updates due to wider implementation feedback. This section lists work completed only (see Section 6.1 for further notes on final GeoSPARQL 1.1 work) and will point out new features, possibilities and applications of the elements included in the GeoSPARQL 1.1 update. At first we discuss the new structure of the standard's specification (Section 3.1), describe relevant extensions to the ontology model and query language in Sections 3.2 and 3.3.

3.1. Profile Declaration

One of the first SWG actions was to link GeoSPARQL 1.0 elements through a *profile* declaration, where a *profile* is a formally-defined variant of a *standard*. *profile* and *standard*, as well as relations between them and their parts are defined by *The Profiles Vocabulary* [21].

Initial motivation for this was twofold: the SWG's recognition that GeoSPARQL 1.0 consisted of multiple parts, not all of which were easy to discover, so some GeoSPARQL users were unaware of GeoSPARQL resources, some of which have been accidentally duplicated or partly re-implemented, and the desire for machine-readable forms of as many of the standard's parts as possible

Descriptions of multi-part standards using the *The Profiles Vocabulary* are anticipated by the OGC as being their future *best practice* method for standards delivery[9].

As the elements of GeoSPARQL 1.1 have been created, they too have been described using the Profile Vocabulary and GeoSPARQL 1.0 has been indicated as being a profile of, that is a subset of, GeoSPARQL 1.1, since all GeoSPARQL 1.0 elements are present in GeoSPARQL 1.1.

The profile declaration for GeoSPARQL 1.0 and all of its parts will be published alongside those of GeoSPARQL 1.1, currently expected in early 2022. currently all draft 1.0 and 1.1 resources are available in the SWG's online code repository[10].

The 1.1 releases' profile resources, described using roles given in the *The Profiles Vocabulary* are:

1. a *profile declaration*
   - the definition of the profile, links to the things it profiles and a listing of its parts
   - in human (HTML) and machine (RDF) readable forms
2. a *specification* resource
   - as per GeoSPARQL 1.0, the normative document of the GeoSPARQL standard
   - contains requirements and conformance classes
   - presented as a document in human-readable form (a PDF) but also containing normative code (*schema*) snippets and function definition tables and examples
3. an RDF/OWL model *schema* resource
   - the GeoSPARQL 1.1 ontology, in both RDF and HTML forms

[8] The Testbed 17 work package "Model Driven Standards" (https://portal.ogc.org/files/?artifact_id=95726#ModelDrivenStandards) focused on generating documents from models but also partly developed test implementations of formally-defined, multi-part, standards, such as GeoSPARQL 1.1

[9] This is ascertained through personal communication with the OGC's Naming Authority staff, one of whom was a co-editor of *The Profiles Vocabulary*

[10] https://github.com/opengeospatial/ogc-geosparql

4. several *vocabulary* resources
   - mainly derived from the *schema*
   - presented in human- and machine-readable forms of the Simple Knowledge Organization System (SKOS) taxonomy model [22]
   - there are vocabularies for Functions, Rules, Conformance Classes in addition to GeoSPARQL 1.0's Simple Features definitions
5. JSON-LD 'context' *mapping*s
   - mappings between local names and fully qualified ontology identifiers for the GeoSPARQL 1.1 ontology and also the Simple Features definitions vocabulary
6. a *validation* resource
   - a series of Shapes Constraint Language (SHACL) [23] shapes for RDF data validation

All elements of the GeoSPARQL 1.1 profile are listed and linked to in the *profile declaration*'s current, draft, online location:

- GeoSPARQL 1.1 draft profile declaration

When finally published, this resource will be available at its namespace IRI location: *http://www.opengis.net/def/geosparql*.

3.2. Ontology extensions

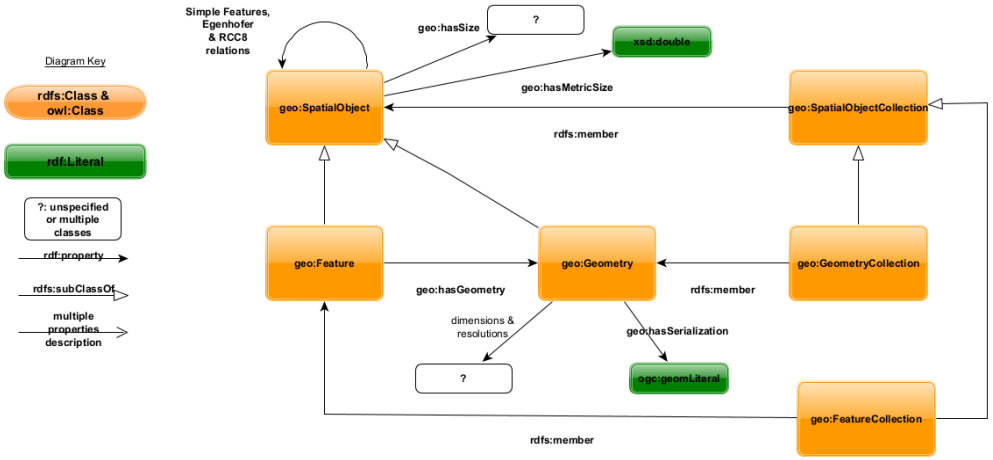

Figure 1. GeoSPARQL 1.1 ontology overview diagram including classes new properties. After GeoSPARQL 1.1's own overview diagram

GeoSPARQL 1.1 extends the GeoSPARQL ontology with the addition of multiple new properties and three collection classes. Initially, the SWG proposed a `SpatialMeasure` class to represent scalar spatial measurements too, but this was ultimately not added in favour of a series of 'size' properties only. See Figure 1 for an overview of the current, which is a redrawing of GeoSPARQL 1.1's ontology overview diagram.

3.2.1. Scalar spatial properties

Scalar properties of spatial objects, such as a volume, length, can now be indicated in GeoSPARQL 1.1 with either a 'metric' property - one that indicates a literal value in metres - or a non-metric property that may indicate a measurement value and a unit of measure. The metric/non-metric property pairs are all sub properties of a generic 'size' property and have the domain of `geo:SpatialObject` meaning they can be used with either `geo:Feature` or `geo:Geometry` instances. Properties pairs defined are:

- `geo:hasSize` & `geo:hasMetricSize` - generic property
- `geo:hasLength` & `geo:hasMetricLength`

- `geo:hasPerimeterLength` & `geo:hasMetricPerimeterLength`
- `geo:hasArea`, & `geo:hasMetricArea`
- `geo:hasVolume` &
- `geo:hasMetricVolume`

The dual definition of metric and non-metric properties is aimed at allowing both simple and more detailed use. The metric properties are informally preferred for use. The SWG considered their inclusion only, however the non-metric options were ultimately included to allow for the use of historic units for which no conversion to the metric system is known. Listing 1 shows two metric/non-metric pairs in use for area and perimeter length and Figure 2 includes scalar spatial measure examples alongside other ontology implementation examples.

Code Listing 1: Scalar spatial properties for the Australian federal electoral district of Brisbane.

```
PREFIX ex: <http://example.com/thing/>
PREFIX geo: <http://www.opengis.net/ont/geosparql#>
PREFIX qudt: <http://qudt.org/schema/qudt/>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX unit: <http://qudt.org/vocab/unit/>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>

ex:brisbane
    a geo:Feature ;
    rdfs:label "Brisbane Electorate" ;

    geo:hasMetricArea "57486676"^^xsd:double ;
    geo:hasArea [
        qudt: "5748.6676"^^xsd:float ;
        qudt:unit unit:HA ; # hectare
    ] ;

    geo:hasMetricPerimeterLength "43832"^^xsd:double ;
    geo:hasPerimeterLength [
        qudt:numericValue "27.235942"^^xsd:float ;
        qudt:unit unit:MI ; # mile
    ];
.
```

Inclusion of scalar spatial measurements within GeoSPARQL itself addresses concerns raised by the user community (see the SWG's *Charter*) that scalar spatial use with GeoSPARQL was occurring but that it was un-standardised or unguided and thus not necessarily interoperable. The particular pattern of non-metric scalar spatial measure chosen emulates common patterns for such measurements in ontologies such as the W3C's *SOSA* [24].

3.2.2. New geometry properties

GeoSPARQL 1.1 introduced more sub properties of `geo:hasGeometry`. Where GeoSPARQL 1.0 defined only a single property of it, `geo:hasDefaultGeometry`, GeoSPARQL 1.1 defines `geo:hasCentroid` to indicate geometries with the role of centroid, and other, similar properties. Figure 3 shows multiple geometries for a single feature and Listing 2 shows a representation of them in RDF with these new properties used.

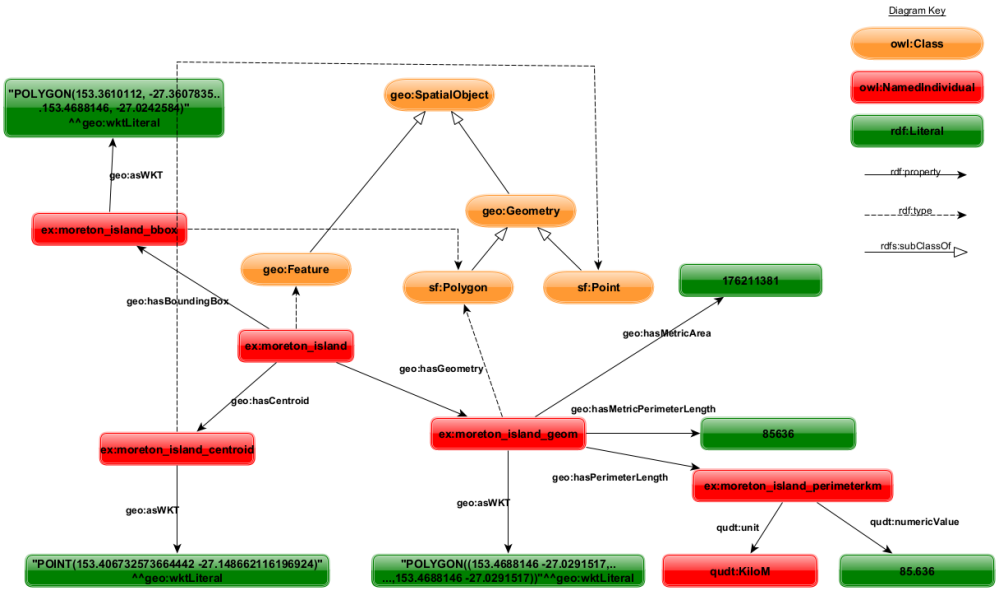

Figure 2. Excerpt of the GeoSPARQL 1.1 ontology including one example feature

Code Listing 2: A possible RDF representation of the elements in Figure 3

```
PREFIX ex: <http://example.com/thing/>
PREFIX geo: <http://www.opengis.net/ont/geosparql#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>

ex:brisbane
    a geo:Feature ;
    rdfs:label "Brisbane Federal Electorate" ;
    geo:hasGeometry [
        a geo:Geometry ;
        geo:asWKT """POLYGON ((
                153.099932 -27.445258,
                ... ,
                153.099932 -27.445258
            ))"""^^geo:wktLiteral ;
    ] ;
    geo:hasCentroid [
        a geo:Geometry ;
        geo:asWKT """POINT (
                153.030431 -27.438943
            )"""^^geo:wktLiteral ;
    ] ;
    geo:hasBoundingBox [
        a geo:Geometry ;
        geo:asWKT """POLYGON ((
                152.975299 -27.480651,
                153.099932 -27.480651,
                153.099932 -27.404039,
                152.975299 -27.404039,
                152.975299 -27.480651
            ))"""^^geo:wktLiteral ;
    ] ;
.
```

The SWG recognised that there could be many more subproperties of `geo:hasGeometry` added to GeoSPARQL 1.1 than the few they did ultimately add. However, no inclusion/exclusion

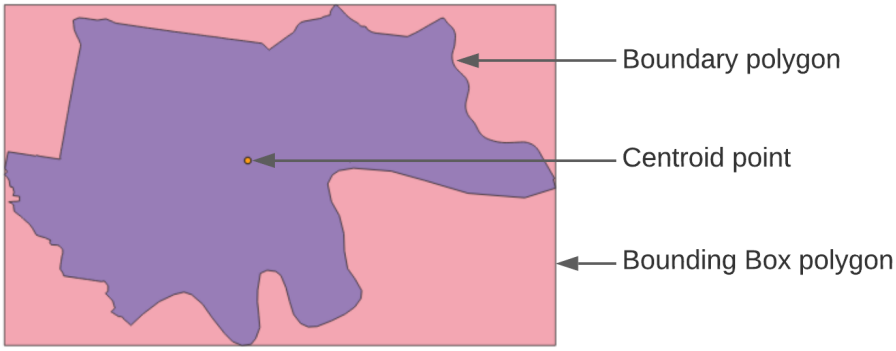

Figure 3. Geometries of the Australian federal electoral district of Brisbane. GeoSPARQL 1.0 contained only the property `geo:hasGeometry` to indicate a `geo:Geometry` instance for a `geo:Feature` instance. GeoSPARQL 1.1 contains the specialised properties of `geo:hasCentroid` & `geo:hasBoundingBox` which can indicate geometries with particular roles. See Listing 2 for an RDF representation of this figure's elements.

logic was determined by the group nor properties deliberately excluded. One path for future exploration in this area mooted but not implemented for GeoSPARQL 1.1 was the concept of geometry roles - the nature of a geometry's role with respect to a feature - and the SWG discussed creating a geometry roles vocabulary. This is noted again in Section 6.

3.2.3. Topological relations

GeoSPARQL 1.1 does not define any new topological relations or properties for them, however the new specification version does include much more supporting material for users of these relations and GeoSPARQL in general, in particular examples of real-world geometry data represented in RDF according to GeoSPARQL 1.1. The Figures Figure 4 and its associated Listing, Listing 3, show the sorts of examples given in the GeoSPARQL 1.1 specification document (Annex C) as well as the GeoSPARQL repository of extended examples[11].

3.2.4. Support for collections

GeoSPARQL 1.1 introduces support for collections of Features (geo:FeatureCollection) and Geometries (geo:GeometryCollection) which are both subclasses of the more general class geo:SpatialObjectCollection. This allows for the grouping of features and geometries by specific attributes and defined object collections in data are also required by standards such as the OGC's *Features* API [25].

While the GIS community commonly organises geospatial features in the form of collections including in software such as ArcGIS[12] or QGIS[13], before the inclusion of specific collection classes in GeoSPARQL 1.1., GeoSPARQL data users had to implement virtual collections from the results of SPARQL queries for compatibility with many of their tools. This required more work on behalf of tool maintainers for tools such as the SPARQLing Unicorn QGIS plugin [14].

The SWG recognised that there is little semantic difference between virtual and defined collections, from an OWL modelling point of view, however they also recognised that other users of Semantic Web data may find defined collections much easier to use, hence their ultimate inclusion. This follows recent Semantic Web standards practice, for example the creation of an extension to the W3C's *SOSA* ontology for observation collections [26].

It needs to be remarked that the support of geometry collections in GeoSPARQL 1.1 does not replace the previously defined class sf:GeometryCollection defined in the GeoSPARQL 1.0

[11] https://github.com/opengeospatial/ogc-geosparql/tree/master/1.1/examples
[12] https://www.arcgis.com/
[13] https://www.qgis.org/
[14] https://github.com/sparqlunicorn/sparqlunicornGoesGIS

Code Listing 3: A possible RDF representation of the elements in Figure 4 in the JSON-LD format which imports the GeoSPARQL 1.1 profile's JSON-LD context resource which allows for simpler JSON data representation through the use of locally-defined names. Supplementary context statements are also included for the example's namespace and supporting namesaces - RDFS.

```
{
    "@context": [
        "https://raw.githubusercontent.com/opengeospatial/
        ogc-geosparql/master/1.1/contexts/geo-context.json",
        {
            "rdfs": "http://www.w3.org/2000/01/rdf-schema#",
            "label": "rdfs:label",
            "ex": "http://example.com/thing/"
        }
    ],
    "@graph": [
        {
            "@id": "ex:brisbane",
            "@type": "Feature",
            "sfContains": {"@id": "ex:mcconnel"},
            "sfTouches": {"@id": "ex:petrie"},
            "sfOverlaps": {"@id": "ex:clayfield"},
            "label": "Brisbane Federal Electorate"
        },
        {
            "@id": "ex:mcconnel",
            "@type": "Feature",
            "sfDisjoint": {"@id": "ex:petrie"},
            "sfWithin": {"@id": "ex:brisbane"},
            "label": "McConnel State Electorate"
        },
        {
            "@id": "ex:petrie",
            "@type": "Feature",
            "sfDisjoint": {"@id": "ex:mcconnel"},
            "sfTouches": {"@id": "ex:brisbane"},
            "label": "Petrie Federal Electorate"
        },
        {
            "@id": "ex:clayfield",
            "@type": "Feature",
            "sfOverlaps": {"@id": "ex:brisbane"},
            "label": "Clayfield State Electorate"
        }
    ]
}
```

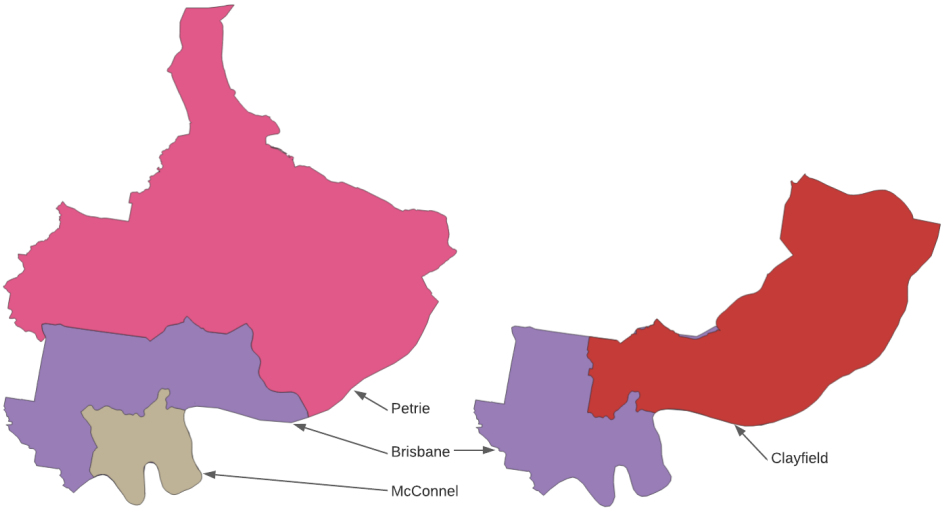

Figure 4. Geometries of the Australian federal electoral districts of Petrie and Brisbane and the state electorate of McConnel (left) and Brisbane again and the state electorate of Clayfield (right). Brisbane is also the same as in Figure 3. Topological spatial relations that may be declared either between these geometries directly or between the features that these are geometries for. Possible relations for these are: Brisbane `geo:sfContains` McConnel, McConnel `geo:sfWithin` Brisbane, Brisbane `geo:sfTouches` Petrie and McConnel `geo:sfDisjoint` Petrie. See Listing 3 for an RDF representation of this figure's elements.

Simple Features vocabulary. The geo:GeometryCollection class can be used to group geometries which have been defined natively in RDF. The sf:GeometryCollection class is used to define a GeometryCollection within a geometry literal, e.g. WKT Listing 4, which is therefore not modeled in RDF. Listing 4 exemplifies a GeometryCollection within a WKT geometry literal.

Code Listing 4: GeometryCollection in WKT

```
GEOMETRYCOLLECTION (
    POINT (40 10),
    LINESTRING (10 10, 20 20, 10 40),
    POLYGON ((40 40, 20 45, 45 30, 40 40))
)
```

However, GeoSPARQL 1.1 improves the access to geometry collections defined in literal types by defining new SPARQL extension functions:

- geof:geometryN - allows the retrieval of the nth geometry inside a `sf:GeometryCollection` instance
- geof:numGeometries - allows the retrieval of the number of geometries contained in a `sf:GeometryCollection` instance

3.3. New geometry literal types

Three new geometry serializations are introduced in GeoSPARQL 1.1:

1. **GeoJSON** (Geo-JavaScript Object Notation) [27]
2. **KML** (Keyhole Markup Language) [28]
3. **DGGS** (Discrete Global Grid System) [29]

3.3.1. GeoJSON & KML

GeoJSON & KML have been much anticipated and were requested by the SDWWG and many users of GeoSPARQL, due to those formats' popularity. The DGGS format is more forward-looking in that it is not driven by user demand but by predicted demand.

An example GeoJSON geometry, a point, representing the location of the centroid of the Brisbane electoral district from Figure 3 is given in Listing 5 and that geometry's inclusion in GeoSPARQL 1.1. RDF is given in Listing 6.

Code Listing 5: GeoJSON point geometry

```
{
    "type":"Point",
    "coordinates":[153.030431, -27.438943]
}
```

Code Listing 6: A representation of the centroid point of the Brisbane electoral district from Figure 3 in RDF (Turtle serialization) using the GeoJSON literal data from Listing 5

```
PREFIX ex: <http://example.com/thing/>
PREFIX geo: <http://www.opengis.net/ont/geosparql#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>

ex:brisbane
    a geo:Feature ;
    rdfs:label "Brisbane Electorate Centroid" ;
    geo:hasCentroid [
        a geo:Geometry ;
        geo:asGeoJSON
            """{
                "type":"Point",
                "coordinates":[153.030431, -27.438943]
            }"""^^geo:geoJSONLiteral ;
    ] ;
.
```

In GeoSPARQL 1.1, geometry data formats that allow for feature information, such as GeoJSON, are limited to representing geometries only, to avoid possibly conflicting literal and RDF information. This is in keeping with GeoSPARQL 1.0 which imposed the same restriction on GML data. In the example in Figure 3, GeoJSON is used to indicate the geometry type - `"type":"Point"` - as well as give the geometry's coordinates, but not feature annotations, such as name.

Keyhole Markup Language (KML) is a well-known, XML-based, GML-like, geometry format and its use in GeoSPARQL 1.1 is straightforward.

3.3.2. DGGS Literals

Discrete Global Grid system (DGGS) descriptions of spatial objects are able to be represented in GeoSPARQL 1.1 using literals too and their inclusion in GeoSPARQL 1.1 took far more consideration than either GeoJSON or KML. Listing 7 gives an *AusPIX*[15] DGGS representation of the area of the Brisbane electoral district from Figure 3.

[15] https://w3id.org/dggs/auspix

Code Listing 7: An DGGS (*AusPIX*) geometry serialization example in RDF (Turtle) of the area of the feature in Figure 3

```
PREFIX ex: <http://example.com/thing/>
PREFIX geo: <http://www.opengis.net/ont/geosparql#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>

ex:brisbane
    a geo:Feature ;
    rdfs:label "Brisbane Electorate Centroid" ;
    geo:hasGeometry [
        a geo:Geometry ;
        geo:asDGGS
            """<https://w3id.org/dggs/auspix>
            CELLLIST ((
                R8338506 R8338507
                R8338508 R8338516
                R8338530 R8338531
                R8338532 R8338534
                R8338540
            ))"""^^ex:auspixLiteral ;
    ] ;
.
```

GeoSPARQL 1.1 does not provide for specific DGGS literals, for example *AusPIX*, directly but only for an abstract DGGS literal with the `geo:dggsLiteral` datatype and the relevant `geo:asDGGS` geometry property, hence the use of the example namespace `http://example.com/thing/` in Listing 7. This is because the DGGSes that currently exist, of which *AusPIX* is just one, have vastly different representation formats. Users of GeoSPARQL 1.1's `geo:asDGGS` geometry property are expected to indicate the particular DGGS being used by implementations of custom literal datatype properties, as per Listing 7.

To assist with understanding what DGGS data is, Figure 5 shows the data from Listing 7 as well as finer DGGS approximations of the Brisbane electoral district's boundary polygon.

DGGS such as *AusPIX* represent areas, points, lines and other geometric shapes with collections of 'cells' of different sizes. Cells are defined for multiple 'levels' with Level 3 cells tesselating within Level 2 cells. There is no theoretical limit to level number, therefore cell size and thus resolution.

3.3.3. Appropriateness of DGGS data as geometry literals

The appropriateness of the addition of GeoJSON and KML to GeoSPARQL 1.1 as new geometry literal formats was uncontroversial, with the single consideration of substance being the exclusion of information other than geometry information from GeoJSON, as indicated above.

The inclusion of a placeholder or abstract property and datatype for DGGS literals was quite controversial due to differing perceptions of what DGGS data represents. The SWG members do not all agree that DGGS data represents geometries or features and there is no straightforward theoretical case to be made for either due to DGGS' novelty and mechanisms that are vastly different from traditional spatial data systems.

The SWG decided that the criteria for geometry representation in GeoSPARQL 1.1 was that the literals had to be able to act as geometry objects in order to satisfy at least some major proportion of the GeoSPARQL functions. Essentially, anything that could be used for spatial relations calculation and spatial aggregates could be treated, at least by GeoSPARQL 1.1, as a geometry literal.

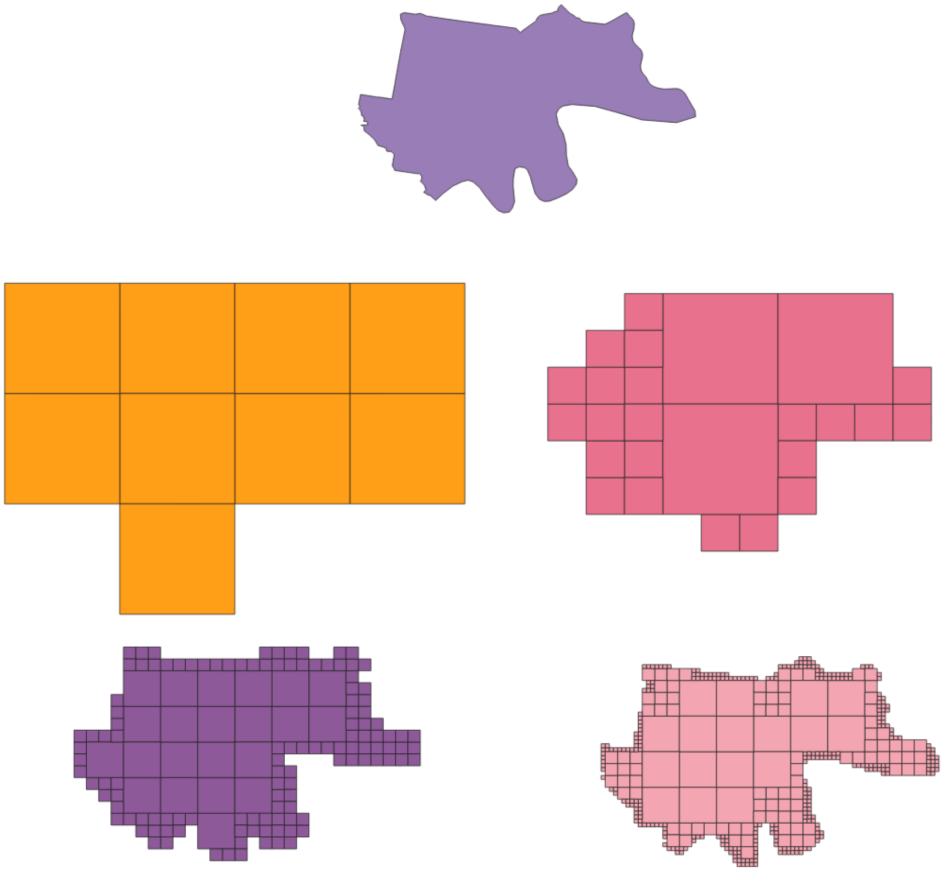

Figure 5. *AusPIX* Discrete Global Grid System representations of the Brisbane electoral district area geometry. The original polygon is represented at the top with the four lower images showing *AusPIX* DGGS cells at higher and higher resolutions, so-called levels 7, 8, 9 & 10.

During the first half of 2021, within the lifetime of the SWG, a software library was produced that implemented all the `Simple Features` functions, except for `geof:sfCrosses` (see Section 4.1 for the implementation description). While not all *Simple Features* functions were implemented for, nor were functions for the other families of spatial relations, the SWG determined that, given the implementation evidence so far, *AusPIX* DGGS data could indeed act as geometry literals, from GeoSPARQL's point of view and thus DGGS literals could satisfactorily act as geometries, at least from GeoSPARQL's point of view. The SWG's discussion on this matter is captured in their online code repository's https://github.com/opengeospatial/ogc-geosparql/issues/112.

3.4. New geometry conversion functions

GeoSPARQL 1.1 provides the conversion functions geof:asWKT, geof:asGML, geof:asKML, geof:asGeoJSON and geof:asDGGS to convert between different literal types while considering the literal types capabilities. For example, a conversion of a WKT literal in the EPSG:25832 coordinate system to either KML or GeoJSON will result in the geometry being converted to the World Geodetic System 1984, as this is the only coordinate reference system valid in the two respective literal types. Hence, a conversion from GeoJSON or KML to WKT will stay in the World Geodetic System 1984 coordinate reference system. To still be able to convert geometries to other coordinate reference systems, GeoSPARQL 1.1 adds the *geof:transform* function, which converts a

geometry literal to another coordinate reference system if the literal formats allow such a transformation.

Another addition is a projection function, which allows changing dimensionalities of geometries is likely to be included[16].

With these additions, future triplestore implementations become very flexible in providing a variety of geometry conversions even without being dependent on another intermediate web service for coordinate/format conversions.

3.5. Spatial Aggregate functions

While spatial aggregation functions are the norm in many non-semantic geospatial databases such as PostGIS or Oracle Spatial, at the time of defining the GeoSPARQL 1.0 standard, aggregation functions had not yet been introduced into the SPARQL standard, but have been with SPARQL 1.1 [6]. Spatial aggregation functions similar to traditional (relational database) aggregation functions such as AVG, MAX, or MIN allow aggregated results of geometry queries, for example, to create the union of a set of selected serialized geometries. While calculating these aggregates is certainly possible outside of a semantic database, and thus GeoSPARQL, the inclusion of the functions provides distinct advantages:

1. No client-side library is needed to create an aggregated geometry result
2. Fewer/more appropriate results are returned, for example a union result
3. Federated SPARQL queries can aggregate results from multiple endpoints

In addition to *geof:union*, *geof:envelope* and *geof:convexHull* defined in GeoSPARQL 1.0 for use within SPARQL `FILTER` operations, 1.1 defines *geof:aggUnion* as well as *geof:aggBoundingCircle*, *geof:aggCentroid*, *geof:aggConcatLines* - concatenating a set of overlapping linestrings - and *geosf:aggConcaveHull* that can return aggregated results. Listing 8 shows one new function in use.

Code Listing 8: Aggregation Function example SPARQL query

```
# returns circle bounding all geometries of Feature <x>
SELECT (geof:aggBoundingCircle(?geo) AS ?circ)
WHERE {<x> geo:hasGeometry/geo:asWKT ?geo .}
```

Functions to retrieve min/max values of geometries' coordinates are added: *geof:minX* & *geof:maxX*, *geof:minY* & *geof:maxY* and *geof:minZ* & *geof:maxZ*.

3.6. Comparison of query capabilities

Coincident with GeoSPARQL 1.1 development, the OGC API Features standard [30] is being developed that proposes feature collections functions filtering. While it proposes the use of the Common Query Language (CQL) for filtering, it is also open to other query language implementations such as GeoSPARQL. When comparing the filter capabilities of CQL to GeoSPARQL, one can observe that the two query languages provide comparable spatial functionality (cf. Table 1), however the CQL proposed supports spatiotemporal operators, which may be an addition to GeoSPARQL to be further explored in its continuous development process. To exemplify the relationship between CQL and the GeoSPARQL query language, the SWG will release a Best Practice document[17], which includes exact descriptions on the equivalences between the two query languages.

Another interesting comparison can be made between the query capabilities of GeoSPARQL and the Simple Features for SQL specification [10]. To date, we can conclude that feature parity with the Simple feature specification has been reached with regards

[16] https://github.com/opengeospatial/ogc-geosparql/issues/231
[17] https://opengeospatial.github.io/ogc-geosparql/bestpractice/bestpractice_cql.html

Category	CQL Expression	GeoSPARQL Expression
Query Parameter	limit=5	LIMIT 5
Literal Value	"A string"	"A string"8sd:string
Comparison predicate	name IS NOT NULL	EXISTS {?item my:name ?name }
Spatial Operators	CONTAINS(geometry1,geometry2)	FILTER(geof:sfContains(?geometry1,?geometry2))

Table 1: Examples of equivalences between CQL and GeoSPARQL for a literal value, query parameters and comparison predicates in FILTER expressions

to the expression of geospatial relations using properties and using filter functions. Features still missing in the GeoSPARQL 1.1 standard are functions which specifically address attributes of special geometry types. In that way, it is not possible to access specific points of LineStrings (such as start and end points) and their closedness in-query and the access of polygonal rings and single coordinates of points using query functions. These functions are planned to be implemented in an upcoming, possibly minor update to GeoSPARQL 1.1.

3.7. SHACL shapes for graph validation

Since the adoption of SHACL [23] as the recommended way to represent constraints on RDF graphs by W3C, the semantic web community has created shapes for a variety of knowledge domains. These shapes fulfill different purposes from checking the graph structure for consistency, to checking contents of the graph. Included with GeoSPARQL 1.1, there are SHACL shapes that validate the graph structure as defined in GeoSPARQL 1.1 in the following aspects:

1. *Encouragement of a unified Geometry instance structure:* GeoSPARQL 1.1 encourages that geo:Geometry instances only link to one serialization. The intention behind this rule is that not all Geometry serializations that GeoSPARQL 1.1 supports are 1:1 convertible. Users are still free to use more than one serialization attached to a Geometry, but should be warned about the fact that serilaizations may not be 100% equivalent. A simple example of this non-equivalence can be seen when a geometry is associated to a WKT literal in a non CRS84 coordinate reference system and a GeoJSON literal. Because of a limitation of the GeoJSON literal to only accept one coordinate reference system, the literal values of these to literals cannot be equivalent.
2. *Rudimentary checks of literal contents:* Geometry literal contents are checked for plausibility. These checks do not contain the parsing of geometry literals and its validation but aim to check whether the contents of the geometry literal seem to be correct according to its literal type
3. *Correct usage of GeoSPARQL classes*: Several SHACL shapes test the proper usage of GeoSPARQL classes. In particular, SpatialObjectCollections are expected to have at least one member relation, and geo:Feature instances are expected to be associated to at least one geo:Geometry instance, whereas each Geometry instance is expected to relate to at least one Geometry serialization
4. *Geometry property consistency:* Further SHACL shapes test for the consistency of values and cardinality of properties of a geo:Feature or geo:Geometry. For example, one SHACL shape tests the consistency of dimensionality properties of a geo:Geometry.

For the scope of the standard, GeoSPARQL 1.1 stops at the definition of the aforementioned SHACL shapes. However, the SWG has identified the need for various research communities to define checks of geometry relations and further consistency checks of Geometry contents and their relations to each other. Independently of the efforts of the SWG [31] introduced GeoSHACL for exactly this purpose and the SWG intends to found

a community group for the collection of further useful validation shapes. Shapes will be created in a new Github Repository[18].

We illustrate the usefulness of the defined GeoSPARQL 1.1 SHACL shapes using a minimum example in Listing 9.

Code Listing 9: SHACL shape validation case: A geometry with a wrong literal type, two serializations, a missing connection to its corresponding feature and a non-connected FeatureCollection

```
ex:electorateCollection rdf:type geo:FeatureCollection .
ex:brisbane
    a geo:Feature ;
    rdfs:label "Brisbane Electorate Centroid" ;
.
ex:brisbane_geom
        a geo:Geometry ;
        geo:asGeoJSON
            """{
                "type":"Point",
                "coordinates":[153.030431, -27.438943]
            }"""^^xsd:string ;
        geo:asWKT """POINT(153.030431 -27.438943)"""^^geo:wktLiteral ;
        geo:asKML """POINT(153.030431 -27.438943)"""^^geo:kmlLiteral ;
.
```

The example shows possible common mistakes in GeoSPARQL graphs with respect to the aspects mentioned previously. Each mistake cannot be detected using OWL reasoning approaches. While an empty `geo:FeatureCollection` and a non-connected feature instance are not necessarily wrong instances in a graph, we deem these as useless; hence they produce violations in a SHACL validation. Compared to this, using the wrong literal type (xsd:string) or a wrong literal content (geo:kmlLiteral for WKT content) is a clear error in applying the standard specification. The last issue, representing two serializations connected to a geometry, is something noteworthy. Either the author of the given data is aware that geometries in different serializations are not necessarily equivalent as precisions and CRS conversions might differ, or the author should consider creating different instances of geometry that can represent different aspects of geospatial data quality.

3.8. JSON-LD contexts

GeoSPARQL 1.1 provides JSON-LD [32] contexts for the Simple Features and GeoSPARQL vocabularies allowing for the publication of simpler representations of GeoSPARQL data. Listing 3 provides example data as context-less JSON which can still be interpreted as RDF through its linking to the GeoSPARQL 1.1 JSON-LD context resource. Context-less JSON is simpler than the more verbose JSON-LD for systems to produce and for developers to understand. Presentation of a JSON-LD context for GeoSPARQL is also aimed at assisting implementors of APIs that wish to present both Linked Data API and OGC API Features [25] interfaces: the context-less JSON will be far easier to incorporate into both required specifications' outputs. Tests of such systems are in development[19].

[18] https://github.com/opengeospatial/ogc-geosparql-shapes

[19] See https://github.com/surroundaustralia/ogcldapi for a combination of a Linked Data and OGC API framework and http://floods.surroundaustralia.com for an instance of its use. This system plans to move its RDF payloads to context-less JSON

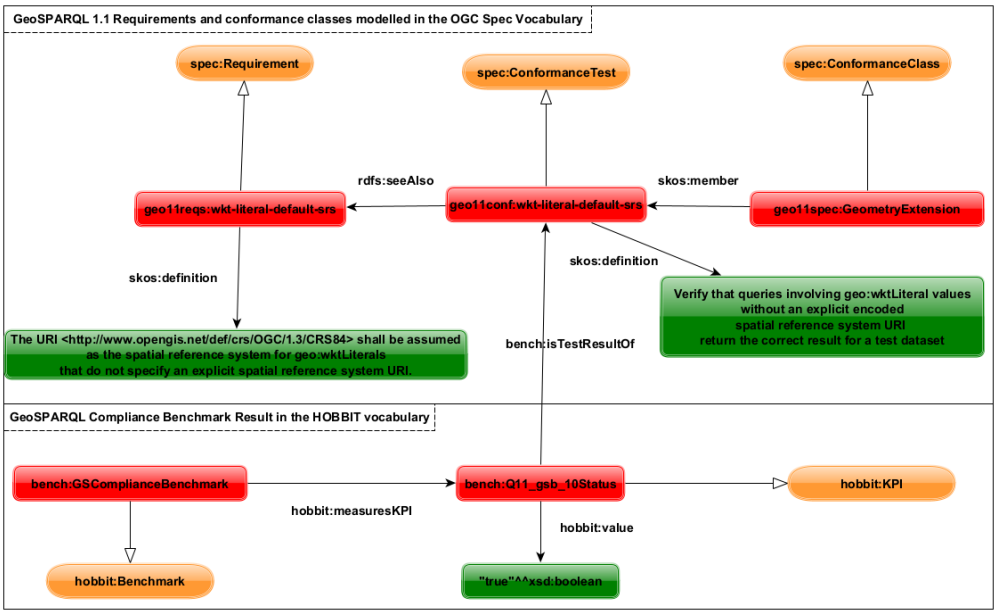

Figure 6. Requirements vocabulary applied to benchmark results of the GeoSPARQL compliance benchmark applied in the HOBBIT platform. Benchmark results can be mapped to RDF concepts representing requirements and conformance classes of the to-be-tested specification

3.9. Requirements and conformance class vocabulary

As the OGC mandates, all GeoSPARQL requirements and conformance classes are described using a URI. However, in the GeoSPARQL 1.1 specification, these unique identifiers are also modeled in RDF as part of the standard's profile specification. This allows the combination of said vocabularies with different other RDF resources.

To date, we can see the usefulness of this design in two cases:

3.9.1. Compliance Benchmarking

Good practices of standards of any kind are that they are first defined and then implemented in reference implementations. To test whether the reference implementation and all following implementations fulfill the criteria that the given standard sets, compliance benchmarking can be used.[13] created the first compliance benchmark for GeoSPARQL 1.0 using the HOBBIT benchmarking platform [33]. Once an execution of the GeoSPARQL compliance benchmark is finished, it may produce a benchmark result in RDF[20]. Since the definition of the GeoSPARQL 1.1 requirements and conformance class vocabulary, these results can now be related to the actual definitions of GeoSPARQL requirements in RDF as shown in Figure 6. The provision of benchmark results connected to requirements of a standard in RDF makes these results accessible as a machine-readable resource.

3.9.2. Partial data conformance claims

In addition to systems claiming to implement GeoSPARQL functions, data may claim conformance to GeoSPARQL's ontology. Such claims may be tested both with RDF reasoners and also with the use of the SHACL validators that GeoSPARQL 1.1 provides (see Section 3.7). Since GeoSPARQL contains many parts, useful data may be created that is conformant to only part of GeoSPARQL and the vocabulary of conformance classes allows for the indication of conformance of data to parts of GeoSPARQL, not just the whole.

[20] https://github.com/hobbit-project/platform/issues/531

Additionally, particular GeoSPARQL user communities might create more constrained SHACL validators to ensure that GeoSPARQL data conforms to a particular implementation pattern from a set of possible patterns. One example is the pattern whereby each `geo:Feature` is only associated with at most one `geo:Geometry`. In this case, a community could define additional conformance classes, like those in GeoSPARQL, and indicate data' conformance to them too.

4. Reference implementations

In this section we describe reference implementations which implement the GeoSPARQL 1.1 specification either fully or to a certain extent.

4.1. RDFLib DGGS

The *rHEALPix DGGS Simple Feature functions* Python package [34] is a library of functions built in mid 2021 to demonstrate that DGGS geometries within the *rHealPix* DGGS family [35], of which *AusPIX* is a member, could be used in the calculation of *Simple Features* topological relations. Using these function and RDF and SPARQL capability from the RDFlib[21] Python package, the *RDFlib GeoSPARQL Functions for DGGS* [36] was then built that exposes DGGS geometry-based *Simple Features* calculation functions to RDFlib's SPARQL interpreter via SPARQL extension functions. Listing 10 shows Python application code demonstrating the use of *RDFlib GeoSPARQL Functions for DGGS* with some *AusPIX* data.

[21] RDFlib is a widely-used, open source, Python programming language, RDF manipulation toolkit: https://github.com/RDFLib/rdflib

Code Listing 10: Python programming code showing the use of the *RDFlib GeoSPARQL Functions for DGGS*. After [36].

```
# import elements from RDFlib and this package (gsdggs)
from rdflib import Literal, Graph, Namespace, URIRef
from gsdggs import DGGS

EX = Namespace("http://example.com/")
GEO = Namespace("http://www.opengis.net/ont/geosparql#")

# Define the DGGS Geometries, add them to an in-memory RDF graph
g = Graph()
g.add((
    URIRef('https://geom-a'),
    GEO.asDGGS,
    Literal('CELLLIST ((R0 R10 R13 R16 R30 R31 R32 R40))', EX.
                                        ausPixLiteral)))
g.add((
    URIRef('https://geom-b'),
    GEO.asDGGS,
    Literal('CELLLIST ((R06 R07 R30 R31))', EX.ausPixLiteral)))
g.add((
    URIRef('https://geom-c'),
    GEO.asDGGS,
    Literal('CELLLIST ((R11 R12 R14 R15))', EX.ausPixLiteral)))

# Query the in-memory graph
q = """
    PREFIX geo: <http://www.opengis.net/ont/geosparql#>
    PREFIX dggs: <https://placeholder.com/dggsfuncs/>

    SELECT ?a ?b
    WHERE {
        ?a geo:asDGGS ?a_geom .
        ?b geo:asDGGS ?b_geom .

        FILTER dggs:sfWithin(?a_geom, ?b_geom)
    }"""
# Interate through and print results
for r in g.query(q):
    print(f"{r['a']} is within {r['b']}")
```

At the time of writing, all *Simple Features* topological relations functions were implemented except for `sfCrosses`, but this is expected to be implemented soon: this appears to be held up by programming issues only, not theoretical issues. While only the *rHealPix* DGGS family has currently been catered for, there appears to be no theoretical reason why other DGGSes, such as H3[22] could not also be catered for.

4.2. GeoSPARQL-Jena

The GeoSPARQL implementation of the Apache Jena software library GeoSPARQL-Jena [37] provides, according to recent benchmarks [13], the only complete implementation of the GeoSPARQL 1.0 specification. In addition, GeoSPARQL-Jena has been extended in a prototypical use case to support raster data in [38]. This implementation not only featured prototypical raster support in GeoSPARQL-Jena but also aimed at the implementation of a variety of functions defined in the *Simple Features* implementation standard. Work is underway, by members of the SWG, to implement DGGS topological

[22] https://eng.uber.com/h3/

relations functions in Jena in a mirror implementation to that in RDFlib described above. A combination of the DGGS algorithms from the RDFlib implementation and the raster handling from [38] will likely provide the first implementation of an RDF library and accompanying triple store to provide full support of the GeoSPARQL 1.1 specification within Jena.

4.3. SPARQLing Unicorn QGIS Plugin

Another implementation already making use of the GeoSPARQL 1.1 specification is the SPARQLing Unicorn QGIS Plugin [39]. This plugin is, to the authors' knowledge, the only client library to make geospatial vector data accessible as vector layers in the popular, open source, QGIS desktop GIS software[23]. The plugin aims to provide three main functions: 1. Querying Linked Data; 2. preparing geodata for publication as Linked Data resources; and 3. the enrichment of geospatial data from Linked Data resources.

To extend the query capabilities of the plugin for GeoSPARQL 1.1, support for KML and GeoJSON literals has been added, as has support for the processing and review of geo:FeatureCollection and geo:GeometryCollection instances (cf. Figure 7) in a given triplestore.

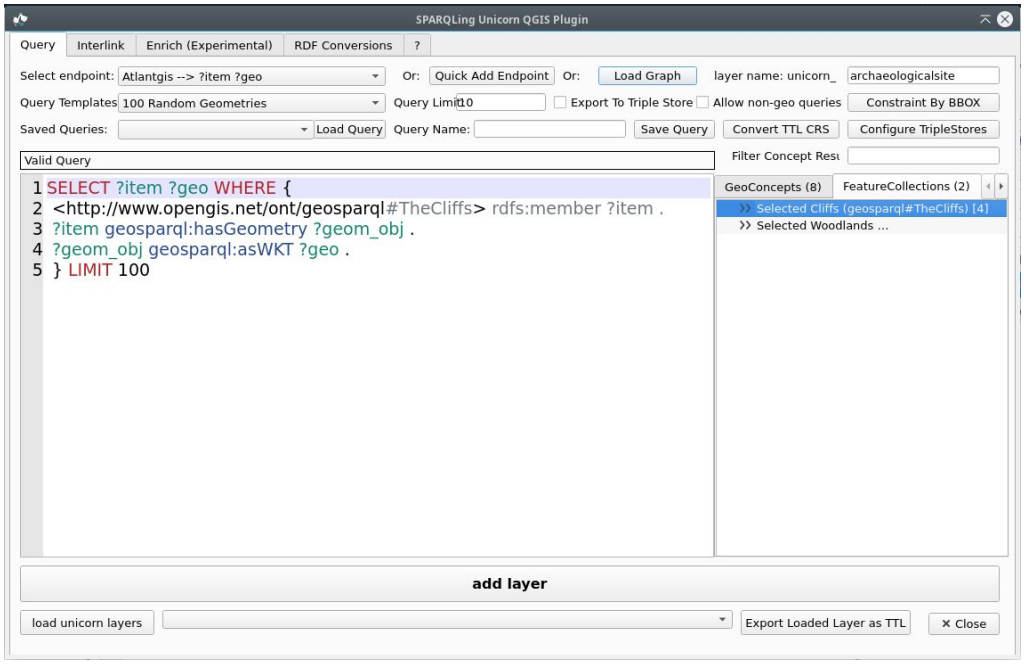

Figure 7. The SPARQL Unicorn QGIS Plugin extended with support for FeatureCollections and GeometryCollections as defined in GeoSPARQL 1.1

As an aspect of data processing and integration, the plugin implements the newly defined literal formats in its Linked Data conversion dialog (cf. Figure 8). This dialog allows converting geometry literals in Linked Data to other CRS supported by QGIS or to other geometry literal formats within the specifications of GeoSPARQL 1.1, as mentioned in Section 3.3.

With this implementation, the general public is able to discover, access, prepare and convert GeoSPARQL1.1-prepared data.

5. Examples of usage of GeoSPARQL 1.1

In this Section we illustrate use of the new parts of GeoSPARQL 1.1.

[23] https://qgis.org/en/site/

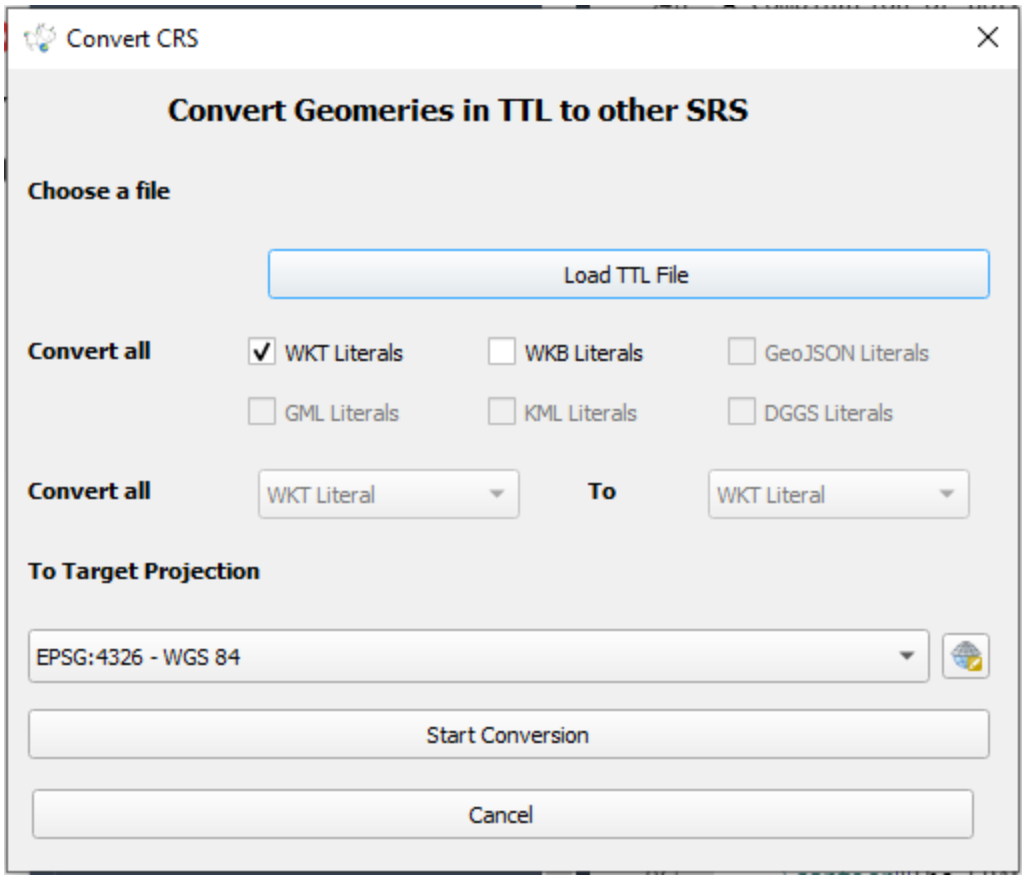

Figure 8. In-development conversion dialog for geospatial Linked Data files aiming at full GeoSPARQL 1.1 literal conversion support

5.1. Profile Declaration

The Australian government is currently conducting a project defining a "National Data Exchange Standard" (NDES) for biodiversity data, validators which are used in an online Application Programming Interface (API) system[24]. The system obtains the multiple validators required for use from the many standards that the NDES profiles, including GeoSPARQL, via Linked Data link-following methods which requires that standards are made available online in machine-readable form (RDF), with RDF predicates linking to any resources with the role *validator* that they define and also that standards are linked together forming a dependency-based *profile hierarchy*. With such information online, the NDES API is able to recurse through the profile hierarchy, retrieve all defined *validation* resources and then compound them for use automatically, saving system update and maintenance time if/when standards update validators.

Even in current draft form, the NDES system polls the GeoSPARQL 1.1 publication for validators. Polling has proved useful to retrieve the latest versions of the validators as the SWG has continued to develop them.

5.2. Use of new geometry formats

The Australian government's "National Map"[25] is a web-based globe that can display spatial data in a number of formats but none that GeoSPARQL supported until this 1.1 version. Now, with GeoJSON geometry literal support, triplestores can be used to store and filter spatial data which the globe can now easily consume and display. A

[24] The API is online in test form at http://ndesgateway.surroundaustralia.com/. This location will likely remain live until July, 2022, at which point it will move to a long-term departmental web location

[25] https://nationalmap.gov.au/

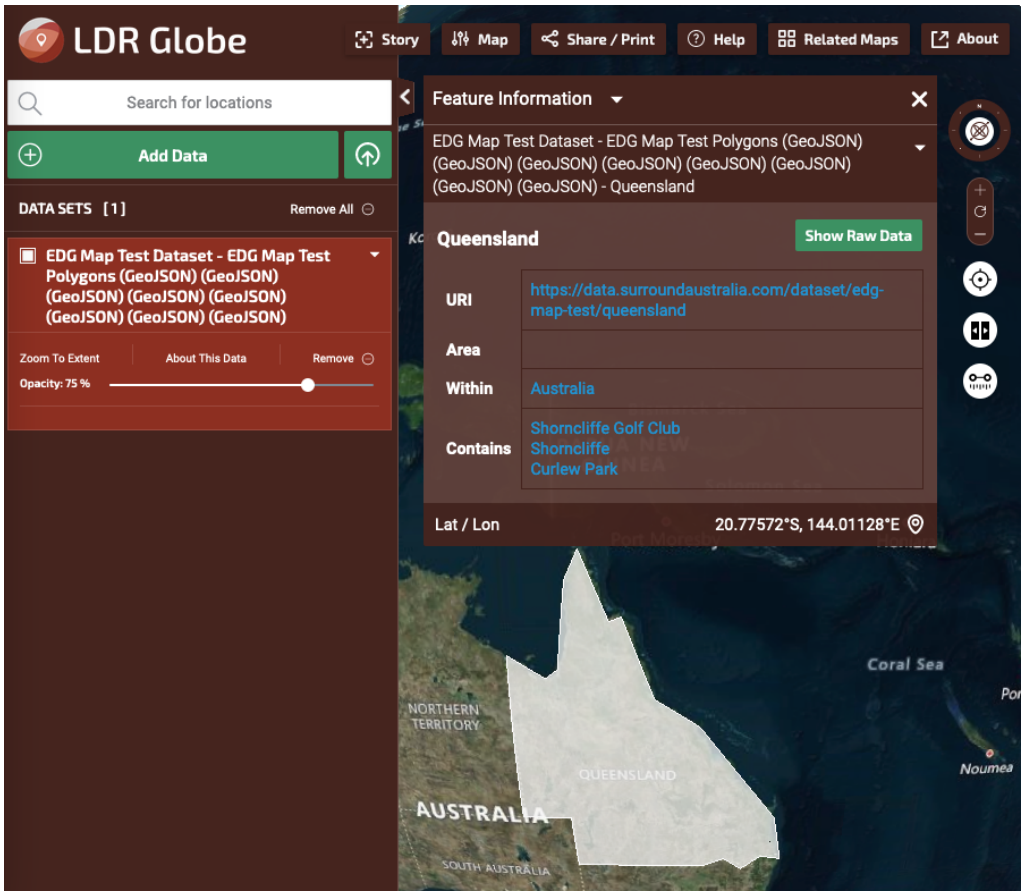

Figure 9. A development version of Australia's "National Map" software showing data sourced from a GeoSPARQL 1.1 RDF dataset. The dialog box on the map interface shows features related to the 'Queensland' feature via *Simple Features* relations such as `geo:sfWithin` that the National Map software has previously not been able to show.

triplestore/Globe implementation is now operational[26] that reads data from a triplestore, within which the geometries of features are stored as GeoJSON. With geometries in that format, only very simple translations of a few RDF properties to JSON for `geo:Feature` instances are necessary for the Globe can display feature metadata, such as labels, as well as the geometries. Figure 9 shows an instance of the Globe listing test polygons for the Australian state of Queensland as well as three features it contains.

With the Globe's triplestore also containing *Simple Feature* relations, it is also now possible to show feature-to-feature links within the globe instance, as shown in Figure 9. These links are actionable and the globe can refocus on features navigated to.

5.3. OGC API Features backend

Traditional spatial data infrastructures are in a transition process from being providers of spatial data via specified web services only to becoming spatial knowledge infrastructures [40,41]. These spatial knowledge infrastructures will provide spatial data in two ways, as illustrated in Figure 10. The first way is the provision of spatial data using geospatial webservices and the second way is the provision of spatial data as Linked Data, the latter being enabled by ontologies such as GeoSPARQL. However, spatial web services are currently being reworked in the OGC API Features specification, which, as elaborated previously in Section 3.2.4, allows for Linked Data backends.

[26] https://globe.surroundaustralia.com/

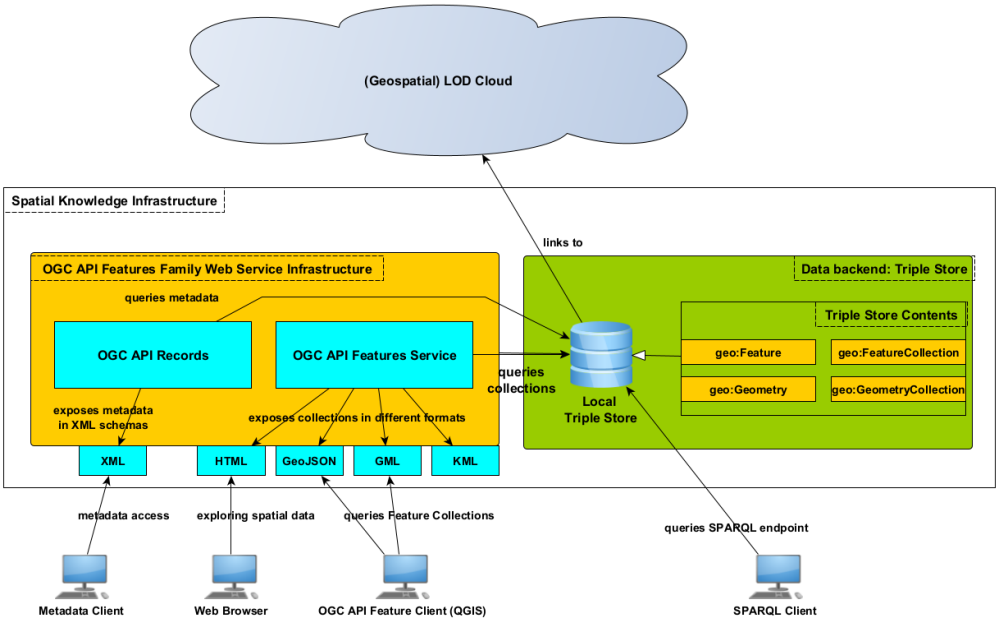

Figure 10. Excerpt of some components of a spatial knowledge infrastructure. A triplestore with GeoSPARQL 1.1. support is provided as a data backend for a OGC API Features powered services infrastructure used by traditional GIS clients

A live example of data delivered according to Linked Data principles, the OGC API Features specification and also a SPARQL Protocol[27] service is Geoscience Australia's Floods API[28], a screenshot of which is shown in Figure 11. Through an application of the CQL to SPARQL mappings that the SWG is creating (see Section 3.6) the Floods API will also be able to respond to CQL queries.

This API uses supplies information according to the required OGC API Features URL structures with very simple queries to a GeoSPARQL 1.1. backend. The simplicity is possible due to GeoSPARQL 1.1's modelling which allows for `geo:FeatureCollection`, `geo:Feature` and `geo:Geometry` instances, the first of which as introduced in GeoSPARQL 1.1 to specifically cater for APIs like the OGC API Features.

APIs such as this Floods API act similarly to previous generation spatial data APIs, such as the well-known Web Feature Service (WFS)[29] from which OGC API Features derives but are also able to present much simpler human User Interfaces (web page), SPARQL endpoints and more data formats.

5.4. DGGS application example

DGGSes represent both vector and raster spatial data is as collections of cell IDs. Since GeoSPARQL 1.1, the storage system for DGGS data may be a triplestore.

Data for the API in Figure 11 are initially recorded as rasters and data for the *Australian Statistical Geographies Standard* (ASGS)[30] dataset is recorded in vector form. Both datasets are able to be stored using the Apache Jena TDB triplestore[31] as GeosPARQL 1.1 data with geometris in the *AusPIX* DGGS format.

The Floods & ASGS datasets are actually stored in the *Loc-I for Disaster Recovery* project's[32] Data Platform with several other raster, and vector datasets, all of which

[27] https://www.w3.org/TR/sparql11-protocol/
[28] http://floods.surroundaustralia.com/
[29] https://www.ogc.org/standards/wfs
[30] https://www.abs.gov.au/websitedbs/D3310114.nsf/home/Australian+Statistical+Geography+Standard+(ASGS)
[31] https://jena.apache.org/documentation/tdb/index.html
[32] https://ldr.surroundaustralia.com/

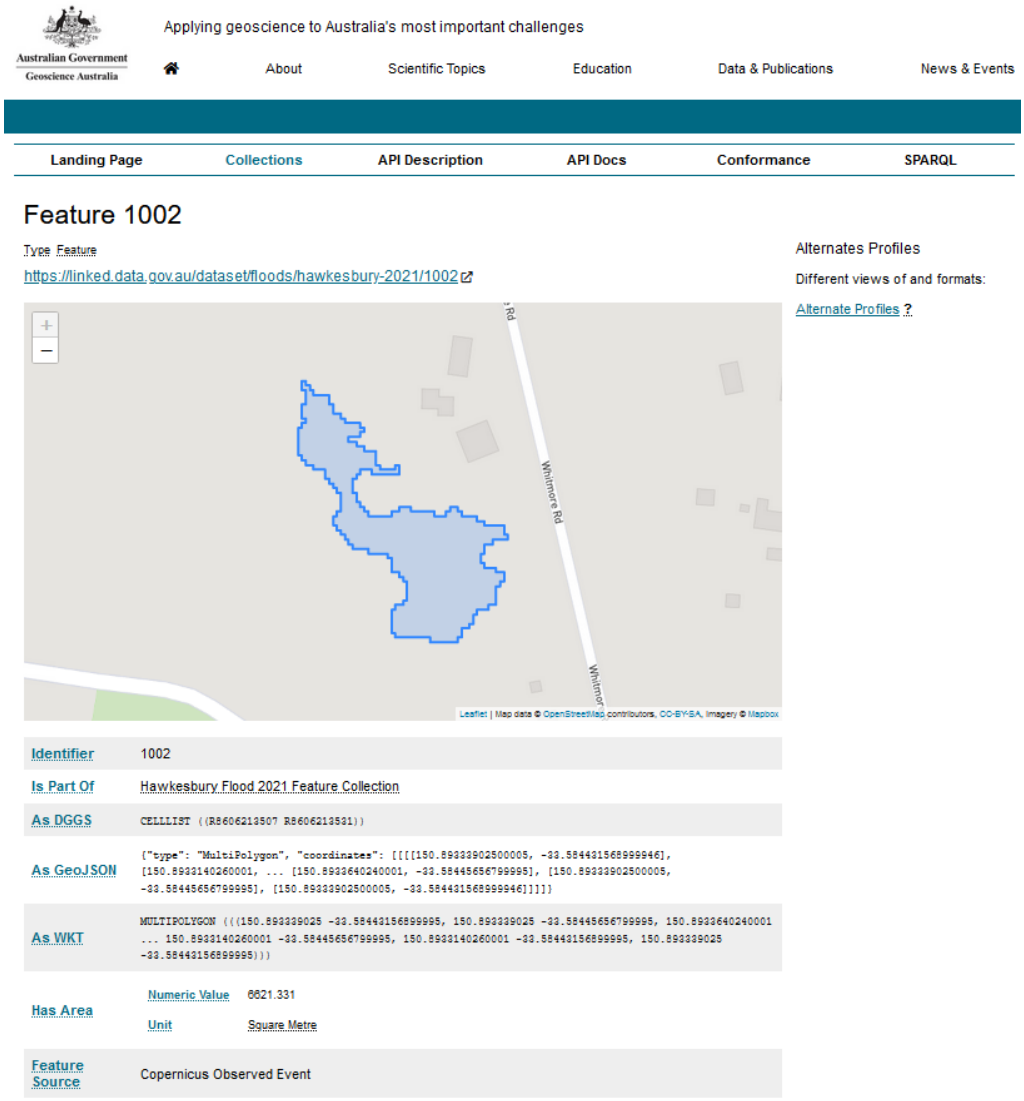

Figure 11. Screenshot of a Linked Data API run by Geoscience Australia that delivers flooded area data online in HTML and RDF forms from a GeoSPARQL 1.1 backend. The API is also an OGC API Features-copatable API since the RDF is converted to (Geo)JSON as needed

can be cross-queried and presented as either features with geometries in vector form, features with geometries in raster form or as cells within regular grids with cell values of data or the IDs of their corresponding features.

The Loc-I platform does require up-front geometry data conversion to DGGS and feature information to GeoSPARQL RDF but then use of the spatial and non-spatial data is extremely simple - SPARQL queries - and all elements of the data can be used in one system.

6. Future Work

6.1. GeoSPARQL 1.1 finalization

GeoSPARQL 1.1 is in the final stages of drafting, as of November 2021. The new elements of the version, with one possible exception detailed below, have been finalized and the major remaining tasks are to:

- send the new version to system implemetors for wider review
- respond to implementors' feedback
- register the new IRIs within version 1.1 with the OGC Naming Authority
- initiate the mandatory OGC standard update notification period

Given the simple nature of most of version 1.1's additions and the fact that SWG members have been able to create at least one implementation of almost all new ontology elements and functions, it is expected that the implementors' wider review won't result in major changes.

6.2. Work beyond GeoSPARQL 1.1

The original intention of the GeoSPARQL SWG, when formed in 2019, was to publish a 1.1 version of GeoSPARQL, and then possible a 1.2 and a 2.0, as described in Section 1. While the scope of GeoSPARQL 1.1 has been in keeping with the original estimates for that version and there are still known un-tackled change requests that the SWG has tagged for a possible 1.2 version[33], the SWG has entertained many thoughts about a more comprehensive tackling of spatial Semantic Web concerns that might require a different direction altogether, for example non-earth geometries, comprehensive handling of rasters[34] or a whole new ontological handling of Coordinate Reference Systems.

If there is a desire for much non-geo work, and if it extends beyond the SPARQL query language, it could be that that neither the 'Geo-' or the '-SPARQL' parts of GeoSPARQL will sensibly apply to it, thus something other than a GeoSPARQL 1.2 or even a 2.0 may be required. The SWG will consult on this matter after GeoSPARQL 1.1's release.

The following subsections provide some more detail on specific GeoSPARQL 1.1+ potential directions.

6.3. Inclusion of further spatial data types

For now, GeoSPARQL 1.1 is a standard to describe 2D and 3D vector data and a single grid reference system. However, members of the SWG have already hinted at the need to represent mobile (e.g. 3D Meshes) and further immobile spatial objects and the inclusion of raster data query capabilities.

6.4. Geometry Roles

As noted in Section 3.2.1, new ontology elements were proposed for GeoSPARQL 1.1 to represent the *roles* of geometries with respect to features. SWG members saw new properties specializing `geo:hasGeometry`, such as `geo:hasCentroid` and `geo:hasBoundingBox`,

[33] See https://github.com/opengeospatial/ogc-geosparql/milestone/2
[34] See Issue 18

as indicating geometries with particular roles and that GeoSPARQL could perhaps allow for an extensible way to indicate role by creating a vocabulary of them, which could be added to, rather than describing them in a number of properties that must remain fixed after a GeoSPARQL version's publication.

Timing and SWG participant effort did not allow for roles to be added in GeoSPARQL 1.1 and their addition may be sensible for a GeoSPARQL 1.2.

6.5. Interoperability with Buildings data

There is a growing appetite for Semantic Web data within the building information modeling (BIM) communities, evidenced by the existence of working groups like the W3C Linked Building Data Community Group[35], and the existence of projects such as BRICK [42], IFC/Ontology mappings [43] and the "Building Topology Ontology"[36]. These all naturally have spatial components and some already use GeoSPARQL 1.0 (BRICK). It is also clear, evidenced by the fact that members of the Linked Building Data Community Group worked with members of the SWG to outline building-related use cases and some shortcomings of GeoSPARQL 1.0 for their purposes in a 'White Paper' in preparation for the formation of the SWG [17], that GeoSPARQL has long been considered important to that community. Unfortunately, not all of this community's needs where met in GeoSPARQL 1.1 so more could be done to support it, for example: the inclusion of other, specialised, topological relations for voids and non-void features; geometry roles (as per the Section above); non-coordinate geometry characterizations, for example cylinders; and sub-surface geometry handling.

6.6. Formalization of spatial reference systems

While it is currently possible to use spatial reference system definitions in literal descriptions, spatial reference system definitions have not been completely formalized using an ontology model as of today. This can be a problem in many ways. For example, a triplestore might store a geometry encoded in a coordinate reference system which is not registered in a well-known repository such as the EPSG Geodetic Parameter Dataset. In these cases, maybe the hosting triplestore might provide custom support for this coordinate reference system, but this support ends once the geospatial data is queried in a federated query scenario. A future version of GeoSPARQL, or a successor to the standard, should be able to describe the contents of spatial reference systems, so that the user can make informed decisions about the appropriateness of the spatial reference system assigned to a given geometry that federated queries may resolve even previously not known coordinate reference system definitions.

6.7. Linked Data Fragments support

GeoSPARQL data collections can be very large, either regarding the number of features or geometries stored, the size of their geometry literals or both. APIs wishing to deliver large numbers of GeoSPARQL feature or geometry instances would benefit from the ability to deliver them in a streaming manner and for this the so-called "Linked Data Fragments" (LDF) [44] approach has been considered. It appears that the LDF approach, if implemented to stream data from an API, would allow for client-side GeoSPARQL topological querying. An example scenario could be that an API user wishes to know if an API contains a feature that *overlaps* a locally held feature. If the API were to stream features from a `geo:FeatureCollection` or as a result of a filtering query, the user could incrementally test for an overlap and cease the streaming session when a match is found.

[35] https://www.w3.org/community/lbd/
[36] https://w3id.org/bot

7. Conclusions

A staged schedule of updates to this important *Semantic Web* spatial standard has been initiated with simple and strictly backwards-compatible changes now in GeoSPARQL 1.1. Reference implementations for all of GeoSPARQL 1.1's nrew features have been made and examples of all elements use can be indicated online. Features discussed for GeoSPARQL 1.2 include the formalization of coordinate reference systems in RDF, the depiction of accurracies and level of detail and the addition of further - possibly also binary - literal types. Work on GeoSPARQL 1.2 will start at the earliest in mid 2022.. GeoSPARQL 2.0, as yet un-specified, is likely to introduce more substantial changes to the standard. Changes proposed for GeoSPARQL 2.0 include broadening the scope of GeoSPARQL to include further kinds of spatial data. To that end, full-featured support for 3D geometries and support for coverages are discussed on the level of data representations. These proposals are related to some growing interest in the semantic web community in representing further geospatial data related to building information [45] and coverage data [38]. More requirements might also be introduced once feedback has been received from the GeoSPARQL 1.1 and 1.2 releases.

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Abbreviations

The following abbreviations are used in this manuscript:

API	Application Programming Interface
BIM	Building Information Modeling
CQL	Common Query Language
CRS	Coordinate Reference System
DGGS	Discrete Global Grid System
EPSG	European Petroleum Survey Group
GeoSPARQL	Geographic SPARQL Protocol And RDF Query Language
GIS	Geographic Information System
GML	Geography Markup Language
HTML	Hypertext Markup Language
KML	Keyhole Markup Language
JSON	JavaScript Object Notation
LDF	Linked Data Fragments
NDES	National Data Exchange Standard
OGC	Open Geospatial Consortium
OWL	Web Ontology Language
QGIS	Quantum GIS
RDF	Resource Description Framework
RDFS	Resource Description Framework Schema
RIF	Rule Interchange Format
SDWWG	Spatial Data On The Web Working Group
SHACL	Shapes Constraint Language
SKOS	Simple Knowledge Organization System
SOSA	Semantic Sensor Network Ontology
SPARQL	SPARQL Protocol And RDF Query Language
SRS	Spatial Reference System
SWG	Standard Working Group
W3C	World Wide Web Consortium
WKT	Well-Known Text
XML	Extensible Markup Language

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