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## Key Points:

- Geospatial data sets were exposed to Virtual Observatory
- QGIS plug-ins interface to Virtual Observatory was developed

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## Bridging the Gap Between Geographical Information Systems and Planetary Virtual Observatory

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**Abstract** Virtual Observatory tools are specifically designed for astronomical data, but they can be adapted to work with geospatial data by providing existing Geographical Information System tools with Simple Application Messaging Protocol interface. Open source QGIS package was chosen as a platform for this. The Simple Application Messaging Protocol interface was made with Python plug-ins. Geospatial data were exposed to Virtual European Solar and Planetary Access via a dedicated German Astronomical Virtual Observatory Data Center Helper Suite server and several tables exposing existing Open Geospatial Consortium—compliant planetary services were published to Virtual European Solar and Planetary Access providing a variety of geospatial data types: vector data and spectral cube rasters, as well as Open Geospatial Consortium Web Map Service of planetary maps.

**Plain Language Summary** Geospatial Science and Astronomy are closely related fields which nevertheless use different tools, standards, interfaces, formats, and protocols. Heterogeneous Astronomical data are accessed routinely via standard system largely known as Virtual Observatory, whereas in Planetary Science, capabilities of cross-mission and cross-archive data discovery are lacking. The present work tries to bridge these two communities by leveraging on commonalities in data types and tools while exposing Geospatial data sets to the Virtual Observatory and creating necessary interfaces in Geographical Information Systems.

## 1. Introduction

Solar System exploration through planetary missions generates many disjoint data sets—some are rasters originating from imaging experiments; others contain vector features obtained from point measurements or derived from imaging experiments. These data sets include geospatial as well as nonsurface and are made available via core digital archives accessible through Planetary Spatial Data Infrastructure (Laura et al., 2017), developed primarily by the Mapping and Planetary Spatial Infrastructure Team (Naß et al., 2017). However, the Planetary Spatial Data Infrastructure is in its infancy and is driven by the core data services such as the International Planetary Data Alliance, the Planetary Science Archive (PSA), and the Planetary Data System (PDS), which provide the backbone of the data and standards (Laura et al., 2017). Data access to these archives is provided by FTP and HTTP access, with data discovery by implicit tools such as the Planetary Image Atlas at PDS imaging node (<https://pds-imaging.jpl.nasa.gov/>), Orbital Data Explorer of the PDS Geosciences node (<http://ode.rsl.wustl.edu/>), PDS Planetary Image Locator Tool (<https://pilot.wr.usgs.gov/>), and the PSA search interface (<https://archives.esac.esa.int/psa>). Programmatic access to PSA and Data ARchive and Transmission System was enabled with International Planetary Data Alliance Planetary Data Access Protocol. However, this protocol has a limited set of search parameters, so the Europlanet began development of a more flexible protocol EPN-TAP, derived from IVOA's TAP protocol to fulfill the needs of the planetary science community (Erard, Cecconi, Le Sidaner, Berthier, Henry, Chauvin, et al., 2014). Since TAP protocol is already well supported by Astronomical software, EPN-TAP makes it possible to reuse the existing Astronomical Virtual Observatory tools (Cui & Zhao, 2007) to conduct

data mining over planetary, rather than astronomical data archives (Erard, Cecconi, Le Sidaner, Berthier, Henry, Molinaro et al., 2014).

Linking of data enterprises is critical to truly build an interoperable data infrastructure, yet the technical implementations for cross-mission and cross-archive data discovery are lacking (Laura et al., 2017). This problem has been addressed in Astronomical community by means of International Virtual Observatory Alliance (IVOA) registry of registries (RofR) and IVOA standardized protocols for uniform data access such as TAP, allowing heterogeneous data access through Virtual Observatory (VO) interfaces (Nandreakar-Heinis et al., 2014). IVOA standards create an interoperability environment allowing for transfer of resulting data and making them available to the client (Quinn et al., 2004).

Many of the VO and Planetary Spatial Data Infrastructure aspects are similar, as both communities operate on spatially enabled data, perform transformations in spherical coordinates, image warping, and reprojection, and spectroscopic analysis. However, there exists a gap in tools and capabilities since Geospatial data are generally plotted on an oblate spheroid with major and minor radii, while in Astronomy, the data are plotted on an imaginary Sky Sphere with no radius. This fundamental difference means that direct transformations between astronomical and geospatial coordinate systems are impossible. The adaptation of Astronomical data standards and software to read and display geospatial data is an area of ongoing research (Erard et al., 2017). In this paper we present a system of QGIS plug-ins, web interfaces, and data discovery services that allows geospatial data discovery via European Virtual Observatory architecture and integration of QGIS into VESPA software suite.

The VO framework can be adapted for use in planetary science by creation of standards and services providing discovery and access to planetary geospatial data that also adhere to Terrestrial Open Geospatial Standards (Hare, 2011; Hare et al., 2018) used by Geographical Information Systems (GIS). Currently, these standards are being integrated into the European VO by Surfaces Task of the EuroPlanet Research Initiative H2020 Virtual European Solar and Planetary Access (VESPA) (Erard, Cecconi, Le Sidaner, Berthier, Henry, Chauvin, et al., 2014). VESPA is an activity reaching into all science aspects of the Solar System studies, aiming to set up a distributed collaborative system based on IVOA standards and to provide a uniform interface to query all Solar System data together at once (Erard et al., 2017). Such an interface would enable scientific interdisciplinary interoperability, for example, to study interaction between heliophysics and planetary science (Hughes et al., 2018).

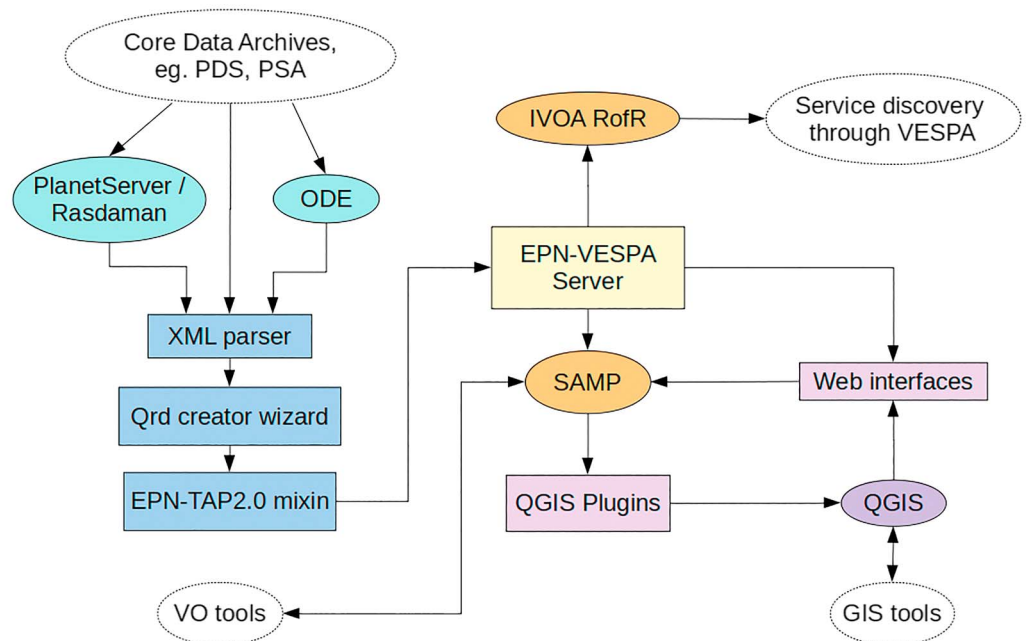
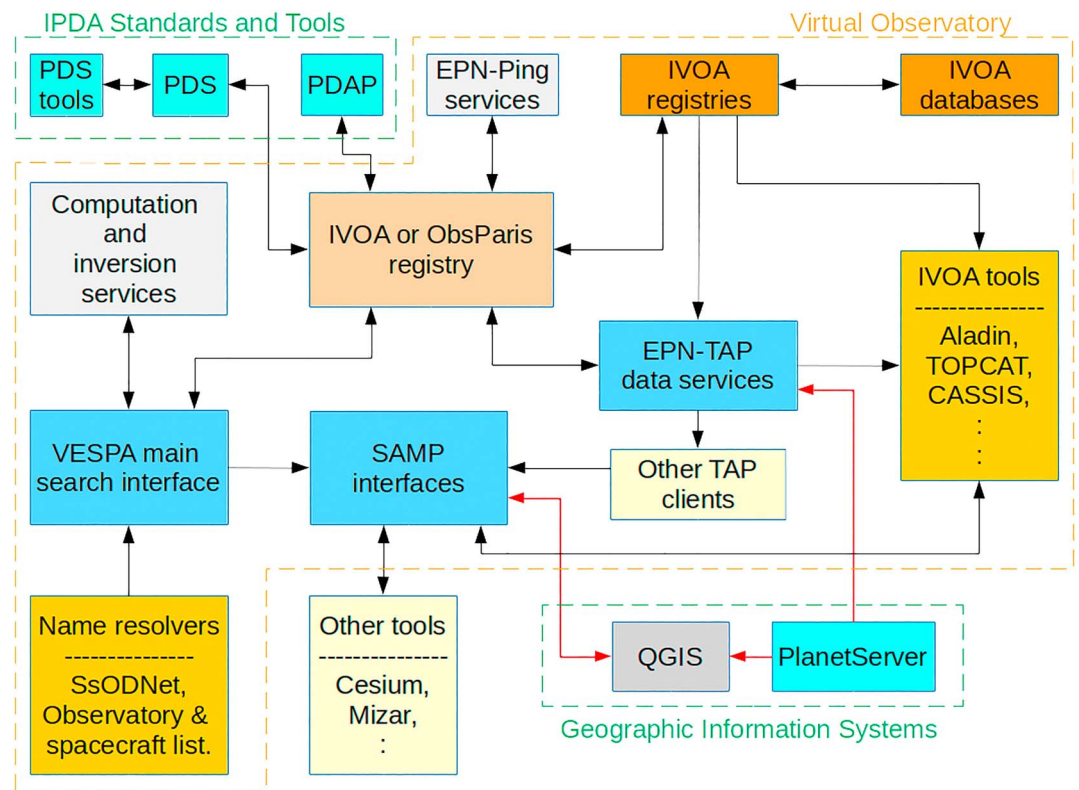
Various utilities for data mining and analysis, such as Tool for OPERations on Catalogues And Tables (TOP-CAT), Aladin, and Centre d'Analyse Scientifique de Spectres Instrumentaux et Synthétiques (CASSIS), compose the VESPA suite of tools. The modular design allows different teams to focus on development of software specific to their field, while interoperability is provided via the Simple Application Messaging Protocol (SAMP) interface (Erard et al., 2017). A simplified relational diagram of the VESPA architecture is shown in Figure 1 (top).

This paper presents IVOA-centric approach, in which the data from the core data archives such as PDS and PSA are exposed to the community by publication to VESPA, while at the same time, geospatial tools were enabled to connect to the VO software framework—thus bridging the gap between Astronomical and Planetary software. The data and metadata to populate EPN-TAP tables were obtained from the Core Data Archives and their derived services and catalogs such as the Orbital Data Explorer and the Planet-Server (<http://access.planetserver.eu/>). The EPN-TAP tables were published to EPN-VESPA DaCHS Server, which was registered with the IVOA RofR to allow its discovery through the main VESPA interface. The interoperability of GIS with the VO software suite is ensured through QGIS plug-ins enabling SAMP, the interoperability protocol of the Virtual Observatory, allowing it to receive the data catalogs sent from a VO data mining client such as TOPCAT or TAPHandle. The tables provide subgranular access through a link to ad-hoc web interfaces that provide capabilities such as accessing spectra at a point and forwarding this data to other VO applications via SAMP. This workflow is shown in Figure 1 (bottom).

## 2. Tools

### 2.1. GAVO DaCHS and the IVOA RofR

Data publication to VESPA can be done by means of the German Astronomical Virtual Observatory (GAVO) Data Center Helper Suite (DaCHS). GAVO DaCHS is a Python server designed to provide VO-compliant access to data through a variety of IVOA standard protocols (Demleitner et al., 2014) of which we only use EuroPlaNet Table Access Protocol (EPN-TAP) (Erard, Cecconi, Le Sidaner, Berthier, Henry, Molinaro et al., 2014) version 2.0.



**Figure 1.** (top) A simplified relational diagram showing VESPA architecture, after Erard et al. (2017); dashed boxes show domains of IPDA, VO, and GIS; red connectors designate interfaces developed as part of this work. (bottom) Workflow; square boxes show contributions in this paper. PDS = Planetary Data System; PDAP = Planetary Data Access Protocol; EPN =EuroPlaNet; IVOA = International Virtual Observatory Alliance; IPDA = International Planetary Data Alliance; TAP = Table Access Protocol; TOPCAT = Tool for Operations on Catalogues And Tables; CASSIS = Centre d’Analyse Scientifique de Spectres Instrumentaux et Synthétiques; VESPA = Virtual European Solar and Planetary Access; SAMP = Simple Application Messaging Protocol; PSA = Planetary Science Archive; RofR = registry of registries; XML = Extensible Markup Language; VO = Virtual Observatory; GIS = Geographical Information Systems; ODE = Orbital Data Explorer.

DaCHS allows importing data in a variety of formats. The ingestion of data into the DaCHS is governed by resource descriptors. These are Extensible Markup Language (XML) files provided by the user, commonly called `q.rd`. They contain resource metadata describing the table and its columns, as well as services and procedures implemented for it. When a table is imported, administrative and default documentation pages are automatically created (Demleitner et al., 2014).

Catalogs can be deployed to the VO as metadata tables ingested into DaCHS. The main VESPA web interface (<http://vespa.obspm.fr>) and the data mining utilities such as TOPCAT discover EPN-TAP-compliant services by querying the VO registries. The list of registries is maintained by the IVOA RofR, consequently registering a publishing registry with RofR makes its published services visible to the VO community (Benson et al., 2009). Using GAVO DaCHS to support EPN-TAP protocol bridges the gap by allowing discovery of geospatial data using astronomical software.

### 2.2. EPN-TAP 2.0 Mixin

Accessing data on our server can be done with VO desktop tools such as TOPCAT (Taylor, 2005) and Aladin Sky Atlas (Boch et al., 2011) and web-based interfaces such as Main VESPA interface and TapHandle (Erard et al., 2017), as well as the local Astronomical Data Query Language (ADQL) and Table Access Protocol (TAP) form and HTTP GET services (Demleitner et al., 2014) and a Python interface (Graham et al., 2014). EPN-TAP 2.0 protocol defines names and metadata of the required columns. Compliance with this standard was ensured through an `//epntap2` mixin. The mixin predefines Unified Content Descriptors (Derriere et al., 2005), names, headers, descriptions, data types, and other metadata. The mixin validates the table and ensures that the required fields are created by default if not defined in a resource descriptor (Demleitner et al., 2014). The use of the mixin simplifies the contents of resource descriptor (`q.rd`), hence reducing the likelihood of a mistake. The mixin is provided with the GAVO DaCHS version 1.0 and has also been made available on GitHub (Minin et al., 2018).

### 2.3. QGIS

QGIS (QGIS Development Team, 2016) is a free and open-source GIS. It provides a graphical user interface to the Geospatial Data Abstraction Library (GDAL/OGR contributors, 2018), supports Geographic Resources Analysis Support System (GRASS Development Team, 2008) and System for Automated Geoscientific Analyses (Conrad et al., 2015) geoprocessing libraries, and makes extensive use of Python in user-contributed plug-ins (Pejović et al., 2014). QGIS is a project of the Open Source Geospatial Foundation (Goel et al., 2015), which is an umbrella organization for the development of open-source geospatial software. Since promotion of the OGC standards is one of the main goals of the Open Source Geospatial Foundation (Song et al., 2008), we choose QGIS as the GIS contact point for interfacing with VESPA, and hence the point at which the gap is bridged into the geospatial community.

### 2.4. PlanetServer and Rasdaman

PlanetServer (<http://access.planetserver.eu/>) is an open-source online tool for plotting hyperspectral data on planetary surfaces (Marco Figuera et al., 2018). It currently supplies projected and atmospherically corrected Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) (Murchie et al., 2007) coverages for Mars and projected Moon Mineralogy Mapper (M3) (Green et al., 2011) coverages for Moon. The client side of the PlanetServer uses NASA's Web WorldWind (Pirotti et al., 2017) as its visualization engine. The server side relies on the Rasdaman Raster Data Manager (Baumann et al., 2018) to deliver hyperspectral data to the user by Web Coverage Processing Service (WCPS) requests (Baumann, 2010). The NASA's Web WorldWind client obtains the basemap and topography from Web Map Service (WMS) and the polygons of coverage footprints from a JavaScript Object Notation (JSON) file supplied by an Apache Tomcat server (<http://tomcat.apache.org/>). When selecting a polygon, a WCPS request is sent to Rasdaman which returns a corresponding image (combination of derived products) that is plotted as overlay. The band combination can be changed by the user. When the user clicks inside a coverage, coordinates of a click are used to formulate a WCPS query; the returning array is plotted on a graph. PlanetServer is used as an exemplary demonstration of bridging the gap by enabling WCPS protocol for planetary data originating from the PDS (Marco Figuera et al., 2018).

### 2.5. VO Tools

Data on VO servers can be accessed from a variety of tools (Demleitner et al., 2015). A desktop and a web client were used to access data on our server during project development—TOPCAT and TapHandle. TOPCAT is a desktop Java application for data discovery through TAP services, querying, table operations, and

simple plotting. TOPCAT supports a variety of data formats such as VOTables, Flexible Image Transport System (FITS), and Structured Query Language (SQL) relational databases (Taylor, 2005). TapHandle is a web interface that provides access to TAP services via ADQL and can pass data sets to connected applications through SAMP (Michel et al., 2014). Aladin Sky Atlas was used in this project for visualization of geospatial data in VO. Aladin is a desktop application written in Java, providing an interactive environment to explore and visualize astronomical data. It can display FITS images of arbitrary size, display and play raster data cubes as a movie (Boch et al., 2008), and display and generate Hierarchical Progressive Survey image surveys (Allen et al., 2016). There is a simple scripting language and support for SAMP (Boch et al., 2008). AladinLite is a web application programming interface with many of the features of Aladin desktop. AladinLite is written in HTML5 canvas and JavaScript which makes it embeddable on a web page (Boch & Fernique, 2014). Much of the data we provide through our services are hyperspectral raster cubes. We chose CASSIS as a VO tool for working with large spectral surveys, since its developers are actively involved in VESPA (Erard et al., 2017). CASSIS supports the Simple Spectral Access Protocol for getting observational data, SAMP for interfacing with other VO applications and services, and TAP for linking with the Virtual Atomic and Molecular Database Center database (Vastel et al., 2015). Since all of the VO tools support the SAMP protocol, it is also the point at which the gap is bridged into the Astronomical community.

### 2.6. Software Libraries

The support for SAMP in QGIS plug-ins was obtained through Astropy and for web applications through **SAMPJS** libraries. Astropy is an open-source Python package providing support for generalized containers for gridded and tabular data, SAMP interface, and input and output to a variety of VO formats such as FITS and VOTables. It also contains functions for transformations of celestial coordinates and time, World Coordinate System support, and unit conversions (Robitaille et al., 2013). **SAMPJS** is a JavaScript library for using the SAMP Web Profile (communication layer suitable for web clients running within a browser sandbox) from within web pages (Fitzpatrick et al., 2013). These software libraries were used to construct the bridge between VO and GIS.

## 3. Methods

### 3.1. EPN-VESPA Server

Our services run on a dedicated server. In order to separate the development from the live services, our server is running two VirtualBox (<https://www.virtualbox.org/>) Virtual Machines, each of which is running a DaCHS server on one port and an Apache server with auxiliary data (forms, viewers, etc.) on another. An apache server on a host machine redirects requests for the subdomains **epn1**, **aux1**, **epn2**, and **aux2** of the **epn-vespa.jacobs-university.de** to an appropriate port on a guest machine, thus allowing for firewall penetration.

### 3.2. q.rd Creator Wizard

As **q.rd** is an Extensible Markup Language (XML) file with a complicated internal structure, manually writing it is time-consuming and prone to error. To simplify the process of creating and ingesting new table into DaCHS, we have developed a **q.rd** creator web application. It was made available on our server (<http://aux1.epn-vespa.jacobs-university.de/qrdcreator2/>) as well as on github (Minin et al., 2018). It supports creation of all the columns required by the EPN-TAP 2.0, most of the optional columns, and allows users to define their own.

The wizard produces a **q.rd** for data supplied as Comma-Separated Values (CSV), the values entered in the form can be either the column names or Python expressions for computing the values. For each parameter defined in the EPN-TAP 2.0 specification, the wizard automatically configures the column metadata by binding it to its definition in the **//epntap2** mixin. For user-defined parameters, the values for column name, its Unified Content Descriptor, and column description must be set manually. The wizard allows saving the intermediate work by serializing the form into a JSON file, and loading it back later. After filling out the form, the user can click on the “**generate q.rd**” button, which outputs the text for the **q.rd** below.

### 3.3. XML Parser

To help collecting information from existing WMS providers such as the Astrogeology maps of the United States Geological Survey, we have created a WMS parser. The XML accessible via WMS **GetCapabilities** and WCS **DescribeCoverage** requests is parsed with Python using **xml.dom.minidom** module. The

elements are found by their tag names, and data obtained from their child nodes are then used to generate a CSV table for ingestion into DaCHS. An example of XML parser is provided on GitHub (Minin et al., 2018).

### 3.4. Heterogeneous Data Set Publication

A granule is one row of a table served by EPN-TAP. It provides one unit of data, usually a link to a single data set (e.g., one image) located on other servers and services such as WMS and WCS, for example, for CRISM and M3 coverages on PlanetServer. We provide data sets of three basic types: vector data sets containing polygon features, web maps accessible via WMS interfaces, and coverages stored on Rasdaman and accessible as WCS and WCPS.

For vector features, the geometry was stored in the **s\_region** column, and user-defined additional fields were created to describe any parameters not defined in EPN-TAP 2.0 protocol.

For WMS, the field **thumbnail\_url** provides a WMS request for a map of small scale, the field **external\_link** contains a Uniform Resource Locator (URL) to a minimal JavaScript WMS web viewer for that map which allows zooming and panning; whereas the field **access\_url** contains a link to the **GetCapabilities** request for the server acting as an endpoint for interfacing with QGIS.

For Coverages accessible via WCPS, the footprints in **s\_region** make it possible to send them via SAMP to VESPA plotting applications. The field **access\_url** contains the download link for the entire data cube in Geographical Tagged Image File Format. The cube can be readily opened in QGIS. However, since the extraterrestrial Coordinate Reference Systems are not yet supported by the OGC standard, the Coordinate Reference System transformation is supplied as a **proj4** (Evenden, 2005) string in the field **spatial\_coordinate\_description**. The **thumbnail\_url** provides small, browse product images of Red Green Blue combination which can be viewed in a browser or other image viewing applications. The **external\_link** points to a web-based tool enabling basic preview and exploration of the coverages. It allows for zooming, sampling individual spectra, and broadcasting them via SAMP.

## 4. Results

### 4.1. Data Sets Made Available

#### 4.1.1. Vector Data

##### 4.1.1.1. mars\_craters

This is a copy of the Robbins Crater database (Robbins & Hynek, 2012). User-defined fields describe crater diameter, depth, its name, degradation state, crater, and ejecta morphology. Parameters **c1min** and **c2min** are equal to the **c1max** and **c2max**, respectively, and indicate the center of the crater. The footprint is stored in **s\_region** field and is computed from crater diameter as a circle around the crater center.

##### 4.1.1.2. mars\_craters\_lagain

This table contains the revisions to the Robbins crater database (Lagain & Marmo, 2018). The footprints are constructed similarly to **mars\_craters** table. The **granule\_uid** is the same as in **mars\_craters**, so the tables can be joined by this attribute.

##### 4.1.1.3. pangaea\_x

This table demonstrates sharing of the terrestrial analog data. It consists of a drone survey of terrestrial volcanic planetary analog terrains in Lanzarote, Spain (Rossi et al., 2018; Unnithan et al., 2017). It contains Space-Time Coordinates of areal photograph; **s\_region** shows approximate field-of-view, **access\_url** points to download link on Zenodo (<https://zenodo.org/>). User-defined fields provide camera orientations.

#### 4.1.2. Web Map Services

##### 4.1.2.1. usgs\_wms

Listed here are various global mosaics for most planetary bodies in the Solar System from Astrogeology WMS Map Layers (Hare et al., 2014). Each granule represents a separate WMS layer. Granules are grouped by the name of the system (e.g., maps of Tethys and Titan both have 'Saturn' as their **granule\_gid**). The **obs\_id** refers to the WMS layer name, **granule\_uid** is the layer title, **external\_link** points to a minimal JavaScript WMS web viewer for that map, **access\_url** contains a link to the WMS **GetCapabilities** request serving as an endpoint for interfacing with QGIS. The WMS can be imported to QGIS by either copying the **getCapabilities** URL or via a VESPA plug-in (Minin & Marmo, 2018).

#### 4.1.3. Web Coverage Processing Services (Spectral Cube Rasters)

##### 4.1.3.1. crism

This is a catalog of CRISM hyperspectral coverages accessible via links to the PlanetServer (Marco Figuera et al., 2018), providing the basic metadata, footprints, coverage previews, download links to the entire

cubes in Tagged Image File Format, and a link to a subgranule viewer. Band's wavelengths are provided in the field **wavelengths** in the same format as used by the Temporal/Spectral Profile Tool (<https://plugins.qgis.org/plugins/temporalprofiletool/>).

#### 4.1.3.2. m3

This table is similar to **crism** but exposes M3 coverages on the PlanetServer instead.

## 4.2. Subgranule and WMS Viewers

For WMS or WCPS, the scope of data on the service is usually extensive beyond what could be effectively visualized with a browse image in the **thumbnail\_url**. Consequently, a simple JavaScript interactive interface to assess data on a subgranule level is provided on an auxiliary server (**aux1** and **aux2**) and pointed to in the **external\_link** field, so that data can be explored at a finer scale or at higher dimensionality. The WMS viewer is a minimal JavaScript web interface made with the OpenLayers (<https://openlayers.org/>) library allowing zooming, panning, and displaying cursor coordinates. It consists of a web page which takes as arguments the path to the map, the layer name, and the title to display. The URL to the map server is hard-coded into the page.

This viewer was modified to work with High Resolution Stereo Camera WMS image data provided by Freie Universität Berlin (Walter et al., 2018); however, since those WMS do not span the whole globe, the coordinates and zoom level have to be supplied in the URL parameters.

The WCPS subgranule viewer provides a minimal web-based interface to zoom on a preview image of a spectral cube of a coverage, access the spectra at individual pixels, and to forward it to VO analysis tools such as CASSIS. This web application takes value from **granule\_uid** as a callback parameter and then requests the rest of the granule metadata using a synchronous ADQL query sent to the DaCHS server to return data as JSON for this granule. The JSON table is converted to a dictionary where column names become keys and the values of the only row become dictionary values. The value of **preview\_url** is used to obtain the browse image from the WCPS server, which is then plotted on the HTML5 canvas. The canvas is assigned event listeners and functions to allow zooming with a mouse wheel.

When a user clicks on the coverage, the canvas coordinates, zoom level, and **c1min**, **c1max**, **c2min**, **c2max** values are used to determine the geographic coordinates corresponding to the mouse click. The geographic coordinates are converted to the projected Coordinate Reference System provided by the **spatial\_coordinate\_description** using a **Proj4js** library (<http://proj4js.org/>), and a WCPS query is sent to the PlanetServer. The response of the server is plotted on a graph below the image using the **D3.js** library (<https://d3js.org>). The spectra can then be saved as a VOTable or sent to CASSIS via SAMP. As the Binary Large Objects are sand-boxed in a browser and cannot be opened by other applications, the VOTable with the spectrum is saved on a server using **PHP** (<http://www.php.net/>), and the link to it is passed with a SAMP broadcast of the **table.load.votable** message.

## 4.3. QGIS Plug-ins

### 4.3.1. SAMP Hub and SAMP Client

Two tools are positioned on the same toolbar, one runs the SAMP Hub and the other listens to the broadcast (Minin & Marmo, 2018). These tools provide a GIS-VO interfaces essentially transforming QGIS into VO suite of tools (see Figure 1). The SAMP Hub plug-in allows running SAMP Hub directly from QGIS. The SAMP Hub implements a class inheriting from **astrophy.vo.samp.hub** which opens a separate window and runs from a separate thread.

The SAMP Client instantiates **astrophy.vo.samp.SAMPIntegratedClient**. When receiving a SAMP message with an MType (Taylor et al., 2009) of **table.load.votable**, the plug-in downloads a VOTable from the link transmitted by the SAMP message and first checks if the **access\_format** is *'application/x-wms'*—if this is the case, the WMS is loaded onto the table of contents in Portable Network Graphics format with EPSG:4326 Coordinate Reference System. If the access format is not *'application/x-wms'*, then the table is assumed to have polygons in the **s\_region** field, the Space-Time Coordinate String (Rots, 2009) in the **s\_region** is decomposed into coordinate pairs and, together with the data in other columns, it is used to create a GeoJSON (<http://geojson.org/>) file. The GeoJSON is converted to SpatiaLite, saved in a temporary folder, and added as a vector layer.

### 4.3.2. GAVO Image and GAVO Coverage

We have developed two plug-ins to access data provided by the tables supplied to QGIS via EPN-TAP 2.0 (Minin & Marmo, 2018). GAVO Image plug-in plots coverage previews over a granule footprint. The image linked to in `thumbnail_url` is downloaded and georeferenced by means of a World File (ESRI, 2018) derived from `c1min`, `c1max`, `c2min`, `c2max`, `image_height`, and `image_width` parameters. The other plug-in, GAVO Coverage, downloads the whole coverage from the field `access_url` while applying `proj4` transformation from the field `coordinate_reference_frame`. Default band combination is set to 1/6, 1/2, and 5/6 of the band range, and stretching is done by min/max contrast enhancement. User can then work with the coverage using built-in GIS tools (e.g., to set custom color stretching values) and other plug-ins available from QGIS repository.

## 5. Use Cases

### 5.1. Plotting Terrestrial Data From Zenodo in Aladin

Field data collected by researchers can be published on Zenodo, giving it a Digital Object Identifier. Creation of a corresponding EPN-TAP table provides an interface to VO, enabling searching this data by location and time. We have produced one such table for drone photographs collected during the 2017 ESA Planetary ANalogue Geological and Astrobiological Exercise for Astronauts campaign (Rossi et al., 2018). To view these photographs in Aladin (minimum version: Beta v10.067), a user would begin by loading a terrestrial basemap by navigating in the “Available data” to the appropriate Hierarchical Progressive Survey of planet Earth. Aladin’s built-in TAP access capability can be used to request data with ADQL from our server (registered with IVOA as `jacobsuni`). The user can center the view on the table by double-clicking on it and use the mouse wheel to zoom. Hovering the mouse over the granule will show the coverage footprint (see Figure 2, top). Clicking on the `access_url` button will load the photograph to Aladin (see Figure 2, middle).

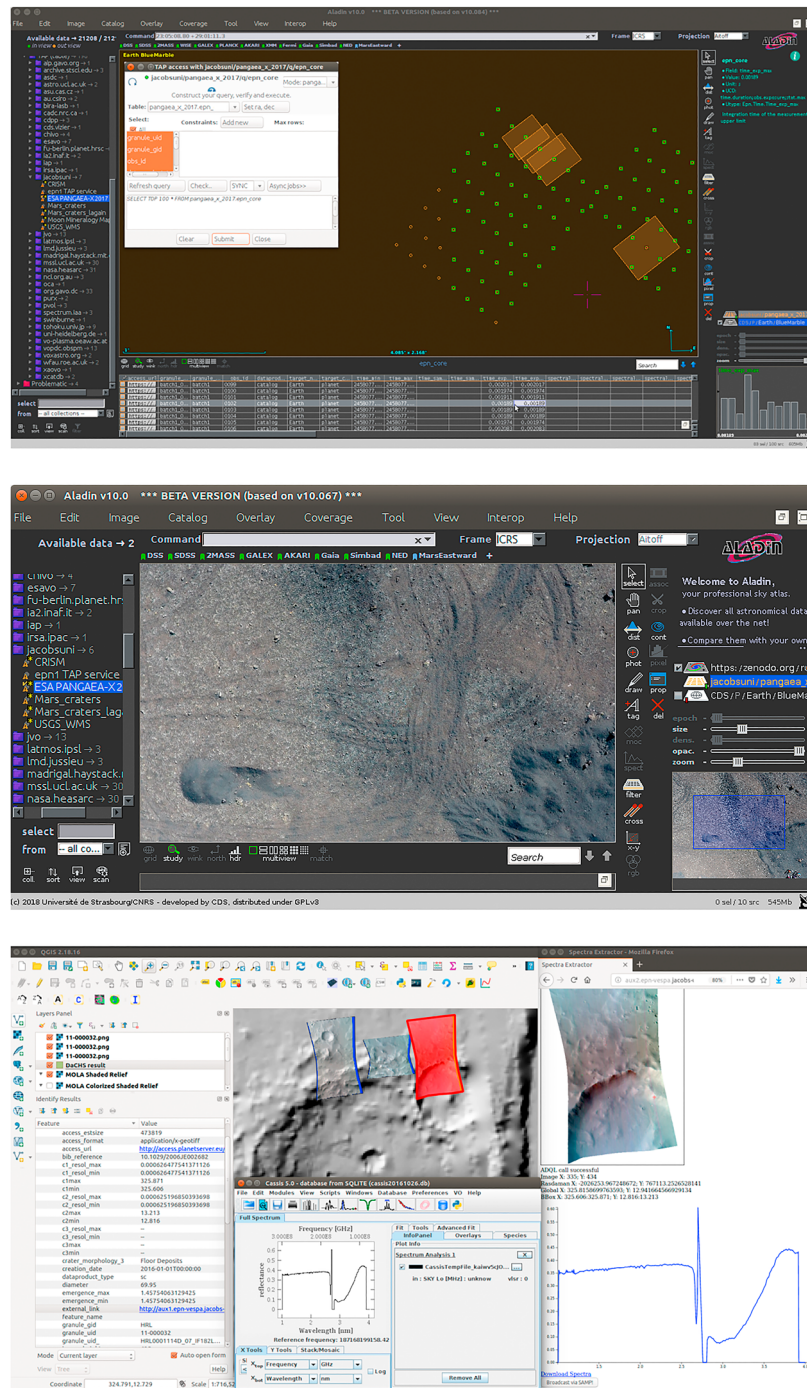
### 5.2. Spectral Analysis of Mars Craters

In this case study (a complimentary video tutorial to which can be found at <https://www.youtube.com/watch?v=Jlso7MkdwYs>), we will be using an ADQL query to select CRISM coverages overlaying craters and access subgranule data for spectral analysis in CASSIS. The ADQL supports complex geospatial queries over these polygons, allowing, for example, to find intersections between craters and available coverages. Using ADQL to select vector features is in many ways analogous to OGC’s Web Feature Service protocol, allowing for selection by geometry and attributes. Similar to cross-layer filtering capability provided by the `querylayer` module of the Geoserver (<http://geoserver.org/>), DaCHS server can do queries using complex geometrical operations on different layers, for example, selecting features on one layer that intersect features on another layer. The ADQL geospatial operations are done in spherical geometry using the spatial SQL implementation of PostgreSQL PgSphere extension (<http://pgsphere.github.io/>). PgSphere is an extension of PostgreSQL similar to PostGIS extension (<https://postgis.net/>), they can achieve similar results but implement different indexing algorithms (Schubert et al., 2013).

The user begins by querying the main VESPA interface for target ‘Mars’. The interface will show the table `usgs_wms` as one of the results. The user can now start QGIS, launch the SAMP Hub and SAMP Client, and then send the table from VESPA to QGIS. The WMS will be added to the table of contents. Complex ADQL queries combining several tables cannot be run from the main VESPA interface yet and need to be executed via a direct TAP interface such as TAPHandle, TOPCAT, or the built-in ADQL form service ([http://epn1.epn-vespa.jacobs-university.de/\\_\\_system\\_\\_/adql/query/form](http://epn1.epn-vespa.jacobs-university.de/__system__/adql/query/form)). For example, the following query will select first 20 coverages from sensor ‘L’ that cover craters of diameters between 50 and 80 km while also preserving some useful attributes preserved from the craters table, such as crater name, diameter, or morphology.

```
SELECT TOP 20
craterT.granule_uid, craterT.diameter, craterT.feature_name,
craterT.crater_morphology_3, crismT.* FROM (
SELECT * FROM mars_craters.epn_core
WHERE diameter > 50 AND diameter < 80) AS craterT
INNER JOIN (
SELECT * FROM crism.epn_core WHERE sensor_id='L') AS crismT
ON (1=INTERSECTS(crismT.s_region,craterT.s_region))
```





**Figure 2.** (top) Loading a data set from EPN1 server to Aladin using built-in Table Access Protocol access. (center) Opening image in Aladin through access\_url field. (bottom:) Plotting granule previews in QGIS, using attribute table to open subgranule viewer, selecting spectra at a point, and sending it via Simple Application Messaging Protocol to Centre d'Analyse Scientifique de Spectres Instrumentaux et Synthétiques.

With a SAMP Hub running and QGIS SAMP Client waiting, the output of the ADQL query can be sent from the TAP client to QGIS via SAMP. The user can then plot previews of images using the GAVO Image plug-in. The user can apply the QGIS identify tool to examine the feature attributes in more detail. Clicking on a URL in the **external\_link** field will open the subgranule viewer, where the user can select spectra at a point and either save it as a VOTable or send it to SAMP for processing with another application such as CASSIS (Figure 2, bottom). Alternatively, GAVO Coverage plug-in can be used to download the

entire coverage and plot it in QGIS, in which case the spectra can be viewed using Temporal/Spectral Profile Tool (<https://plugins.qgis.org/plugins/temporalprofiletool/>), list of band values for which is provided in the `wavelengths` field.

## 6. Discussion

The photographs from PANGAEA-X-2017 campaign were plotted as polygons aligned with the yaw of the camera as extracted from the EXIF tags. The field-of-view was  $84^\circ$ , the aspect ratio was constant 3:4 for all images, and they were all pointing at nadir. The size of the footprint was determined from the distance to the target. This distance was computed by subtracting from the GPS altitude the Digital Terrain Model (Instituto Geográfico Nacional, 2009) altitude at location. Unfortunately, the margin of error appeared to be of a greater magnitude than the measurement, making it unreliable. In addition to high random error, a systematic error seemed to be affecting all the coverages resulting in computed distance to target being generally too low, sometimes negative. This was mitigated by adding a constant vertical adjustment when computing the footprints.

Certain metadata is lacking from Rasdaman to allow for effectively serving datacubes through VO. For instance, as WCPS does not have support for extraterrestrial Coordinate Reference System, so it cannot be used with Rasdaman's Semantic Coordinate Reference System Resolver, so we provide the definition separately as a `proj4` string in the `coordinate_system_description` field. However, the common coordinate space specified by the OGC is between  $-180$  and  $+180$ , yet the VO standard uses CRS from  $0$  to  $+360$ . This creates problems in VO-GIS interoperability, for instance, `proj4` transformations that would move a coverage into  $+180$  to  $+360$  range are not supported in QGIS. Consequently, coverages cannot be plotted on top of polygons in that range, unless a similar transformation is also applied to footprints. M3 coverages are too large to be served in a single granule, so they are split between several granules with the same group id.

At the same time VO tools such as Aladin approach to georeferencing is different from OGC (world files are not supported nor the `proj4`). It is possible to provide Coordinate Reference System and other metadata by using a FITS header. Work with FITS integration is ongoing, however, its hindered by lack of support in the Geospatial Data Abstraction Library. Workarounds are currently possible with virtual headers. (Marmo et al., 2018).

## 7. Conclusion

This paper presents EPN1 services, tools, and examples of uses. The main focus of development was to enable interoperability of Virtual Observatory and Geographical Information Systems, by bringing together different standards used by each. Our team developed methodology to expose various geographical data to VO community and published diverse planetary and Earth analog data sets to VESPA as proof-of-concept demonstration. We have developed multipurpose tools and methods that allow interfacing GIS with VO and get data from VO to GIS, thus fostering interdisciplinary collaboration and bridging the gap between GIS and VO.

## Acronyms

**ADQL** Astronomical Data Query Language

**CASSIS** Centre d'Analyse Scientifique de Spectres Instrumentaux et Synthétiques

**CRISM** Compact Reconnaissance Imaging Spectrometer for Mars

**CSV** Comma-Separated Values

**EPN-TAP** EuroPlaNet Table Access Protocol

**FITS** Flexible Image Transport System

**GAVO DaCHS** German Astronomical Virtual Observatory Data Center Helper Suite

**GIS** Geographical Information System

**IVOA** International Virtual Observatory Alliance

**JSON** JavaScript Object Notation

**M3** Moon Mineralogy Mapper

**OGC** Open Geospatial Consortium

**SAMP** Simple Application Messaging Protocol  
**TAP** Table Access Protocol  
**TOPCAT** Tool for OPerations on Catalogues And Tables  
**VESPA** Virtual European Solar and Planetary Access  
**VO** Virtual Observatory  
**WCPS** Web Coverage Processing Service  
**WCS** Web Coverage Service  
**WMS** Web Map Service  
**XML** Extensible Markup Language

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## References

- Allen, M., Fernique, P., Boch, T., Durand, D., Oberito, A., Merin, B., et al. (2016). An hierarchical approach to big data, arXiv preprint arXiv, 1611.01312.
- Baumann, P. (2010). The OGC web coverage processing service (WCPS) standard. *GeoInformatica*, 14(4), 447–479. <https://doi.org/10.1007/s10707-009-0087-2>
- Baumann, P., Rossi, A. P., Bell, B., Clements, O., Evans, B., Hoenig, H., et al. (2018). *Fostering cross-disciplinary Earth science through datcube analytics*. Cham: Springer International Publishing. [https://doi.org/10.1007/978-3-319-65633-5\\_5](https://doi.org/10.1007/978-3-319-65633-5_5)
- Benson, K., Plante, R., Auden, E., Graham, M., Greene, G., Hill, M., et al. (2009). IVOA registry interfaces version 1.0, IVOA Recommendation.
- Boch, T., & Fernique, P. (2014). Aladin Lite: Embed your Sky in the browser. In N. Manset & P. Forshay (Eds.), *Astronomical data analysis software and systems XXIII* (Vol. 485, pp. 277). Waikoloa Beach Marriott, Hawaii, USA: Astronomical Society of the Pacific Conference Series.
- Boch, T., Fernique, P., & Bonnarel, F. (2008). New developments for Aladin. In R. W. Argyle & P. S. Bunclark (Eds.), *Astronomical data analysis software and systems XVII* (Vol. 394, pp. 217). Lewis: Astronomical Society of the Pacific Conference Series.
- Boch, T., Oberito, A., Fernique, P., & Bonnarel, F. (2011). Aladin: An open source all-sky browser. In I. N. Evans, A. Accomazzi, D. J. Mink, & A. H. Rots (Eds.), *Astronomical data analysis software and systems XX* (Vol. 442, pp. 683). Seaport World Trade Center, Boston, Massachusetts, USA: San Francisco: Astronomical Society of the Pacific.
- Conrad, O., Bechtel, B., Bock, M., Dietrich, H., Fischer, E., Gerlitz, L., et al. (2015). System for automated geoscientific analyses (SAGA) v. 2.1.4. *Geoscientific Model Development*, 8(7), 1991.
- Cui, C. Z., & Zhao, Y. H. (2007). Worldwide R&D of virtual observatory. *Proceedings of the International Astronomical Union*, 3(S248), 563–564.
- Demleitner, M., Harrison, P., Taylor, M., & Normand, J. (2015). Client interfaces to the virtual observatory registry. *Astronomy and Computing*, 10, 88–98. <https://doi.org/10.1016/j.ascom.2015.01.008>
- Demleitner, M., Neves, M. C., Rothmaier, F., & Wambsganss, J. (2014). Virtual observatory publishing with DaCHS. *Astronomy and Computing*, 7, 27–36. <https://doi.org/10.1016/j.ascom.2014.08.003>
- Derriere, S., Gray, N., Mann, R., Preite Martinez, A., McDowell, J., McGlynn, T., et al. (2005). ArXivAn IVOA standard for unified content descriptors version 1.1 e-prints arXiv, 1110.
- ESRI (2018). Understanding world files, [http://webhelp.esri.com/arcimps/9.3/General/topics/author\\_world\\_files.htm](http://webhelp.esri.com/arcimps/9.3/General/topics/author_world_files.htm), accessed: 2018-04-26.
- Erard, S., Ceconi, B., Le Sidaner, P., Berthier, J., Henry, F., Chauvin, C., et al. (2014). Planetary science virtual observatory architecture. *Astronomy and Computing*, 7, 71–80. <https://doi.org/10.1016/j.ascom.2014.07.005>
- Erard, S., Ceconi, B., Le Sidaner, P., Berthier, J., Henry, F., Molinaro, M., et al. (2014). The EPN-TAP protocol for the planetary science virtual observatory. *Astronomy and Computing*, 7, 52–61. <https://doi.org/10.1016/j.ascom.2014.07.008>
- Erard, S., Ceconi, B., Le Sidaner, P., Rossi, A. P., Capria, M. T., Schmitt, B., et al. (2017). Vespa: A community-driven virtual observatory in planetary science. *Planetary and Space Science*, 150, 65–85. <https://doi.org/10.1016/j.pss.2017.05.013>
- Evenden, G. I. (2005). libproj4: A comprehensive library of cartographic projection functions (preliminary draft).
- Fitzpatrick, M., Laurino, O., Paioro, L., & Taylor, M. B. (2013). Application interoperability with SAMP. In D. N. Friedel (Ed.), *Astronomical data analysis software and systems XXII* (Vol. 475, pp. 395). Champaign, Illinois, USA: Astronomical Society of the Pacific Conference Series.
- GDAL/OGR contributors (2018). The GDAL/OGR geospatial data abstraction software library, The Open Source Geospatial Foundation.
- GRASS Development Team (2008). Geographic Resources Analysis Support System (GRASS) software.
- Goel, D., Pandey, N., & Gupta, S. (2015). Proprietary and open source geospatial software, Organized By Department of Civil Engineering, Indian Institute of Technology (Banaras Hindu University), Varanasi-221005 Uttar Pradesh, India p. 48.
- Graham, M., Plante, R., Tody, D., & Fitzpatrick, M. (2014). Pyvo: Python access to the virtual observatory, Astrophysics Source Code Library.
- Green, R. O., Pieters, C., Mouroulis, P., Eastwood, M., Boardman, J., Glavich, T., et al. (2011). The Moon Mineralogy Mapper (M3) imaging spectrometer for lunar science: Instrument description, calibration, on-orbit measurements, science data calibration and on-orbit validation. *Journal of Geophysical Research*, 116, 31. <https://doi.org/10.1029/2011JE003797>
- Hare, T. M. (2011). Standards-based collation tools for geospatial metadata in support of the planetary domain (Ph.D. thesis), Northern Arizona University.
- Hare, T. M., Keszthelyi, L., Gaddis, L., & Kirk, R. L. (2014). Online planetary data and services at USGS astrogeology. *Lunar and Planetary Science Conference*, 45, 2487.
- Hare, T. M., Rossi, A. P., Frigeri, A., & Marmo, C. (2018). Interoperability in planetary research for geospatial data analysis. *Planetary and Space Science*, 150, 36–42. <https://doi.org/10.1016/j.pss.2017.04.004>
- Hughes, J. S., Crichton, D. J., Raugh, A. C., Ceconi, B., Guinness, E. A., Isbell, C. E., et al. (2018). Enabling interoperability in planetary sciences and heliophysics: The case for an information model. *Planetary and Space Science*, 150, 43–49. <https://doi.org/10.1016/j.pss.2017.04.005>
- Instituto Geográfico Nacional (2009). Modelo digital del terreno (5 metros) de España.
- Lagain, A., & Marmo, C. (2018). alagain/martian\_crater\_database 1.1, <https://doi.org/10.5281/zenodo.1203252>

- Laura, J. R., Hare, T. M., Gaddis, L. R., Fergason, R. L., Skinner, J. A., Hagerty, J. J., & Archinal, B. A. (2017). Towards a planetary spatial data infrastructure. *ISPRS International Journal of Geo-Information*, 6(6), 181. <https://doi.org/10.3390/ijgi6060181>
- Marco Figuera, R., Pham Huu, B., Rossi, A. P., Minin, M., Flahaut, J., & Halder, A. (2018). Online characterization of planetary surfaces: Planetserver, an open-source analysis and visualization tool. *Planetary and Space Science*, 150, 141–156. <https://doi.org/10.1016/j.pss.2017.09.007>
- Marmo, C., Hare, T. M., Erard, S., Minin, M., Pineau, F.-X., Zinzi, A., et al. (2018). Fits format for planetary surfaces: Definitions applications and best practices. *Journal of Geophysical Research: Planets*, 5, 640–651. <https://doi.org/10.1029/2018EA000388>
- Michel, L., Louys, M., & Bonnarel, F. (2014). Browsing TAP services with TAPHandle and DataLink. In N. Manset & P. Forshay (Eds.), *Astronomical data analysis software and systems XXIII* (Vol. 485, pp. 15). Astronomical Society of the Pacific Conference Series.
- Minin, M., Erard, S., Cecconi, B., & Le Sidaner, P. (2018). epn-vespa/DaCHS-for-VESPA: Major version zero, available at <https://github.com/epn-vespa/DaCHS-for-VESPA>, <https://doi.org/10.5281/zenodo.1197267>
- Minin, M., & Marmo, C. (2018). epn-vespa/vo\_qgis\_plugin: Qgis plugins providing interface to vespa, available at [https://github.com/epn-vespa/VO\\_QGIS\\_plugin](https://github.com/epn-vespa/VO_QGIS_plugin), <https://doi.org/10.5281/zenodo.1203241>
- Murchie, S., Arvidson, R., Bedini, P., Beisser, K., Bibring, J.-P., Bishop, J., et al. (2007). Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) on Mars Reconnaissance Orbiter (MRO). *Journal of Geophysical Research*, 112, e05S03. <https://doi.org/10.1029/2006JE002682>
- Naß, A., Archinal, B., Beyer, R., DellaGiustina, D., Fassett, C., Gaddis, L., et al. (2017). Creating a road map for planetary data spatial infrastructure. *European Planetary Science Congress*, 11, EPSC2017–414.
- Nandrekar-Heinis, D., Michel, L., Louys, M., & Bonnarel, F. (2014). The table access protocol: Providing standard access to astronomical data. *Astronomy and Computing*, 7–8, 37–44. <https://doi.org/10.1016/j.ascom.2014.08.002>
- Pejović, M., Gospavić, Z., Milovanović, B., & Arsić, I. (2014). Solving a surveying problem by using R and QGIS: Setting out of a land expropriation zone. *Geonauka*, 2(2), 12–18.
- Pirotti, F., Brovelli, M. A., Prestifilippo, G., Zamboni, G., Kilsedar, C. E., Piragnolo, M., & Hogan, P. (2017). An open source virtual globe rendering engine for 3D applications: NASA world wind, Open Geospatial Data. *Software and Standards*, 2(1), 4. <https://doi.org/10.1186/s40965-017-0016-5>
- QGIS Development Team (2016). QGIS Geographic Information System, Open Source Geospatial Foundation.
- Quinn, P. J., Barnes, D. G., Csabai, I., Cui, C., Genova, F., Hanisch, B., et al. (2004). The international virtual observatory alliance: Recent technical developments and the road ahead. In P. J. Quinn & A. Bridger (Eds.), *Optimizing scientific return for astronomy through information technologies* (vol. 5493, pp. 137–146). Glasgow, UK: International Society for Optics and Photonics. <https://doi.org/10.1117/12.551247>
- Robbins, S. J., & Hynek, B. M. (2012). A new global database of Mars impact craters 1 km: 1. Database creation, properties, and parameters. *Journal of Geophysical Research*, 117, e05004. <https://doi.org/10.1029/2011JE003966>
- Robitaille, T. P., Tollerud, E. J., Greenfield, P., Droettboom, M., Bray, E., Aldcroft, T., et al. (2013). Astropy: A community Python package for astronomy. *Astronomy & Astrophysics*, 558, A33.
- Rossi, A. P., Unnithan, V., Torrese, P., Borrmann, D., Nuechter, A., Lauterbach, H., et al. (2018). Augmented field geology and geophysics for planetary analogues, EGU General Assembly Conference Abstracts, EGU General Assembly Conference Abstracts, vol. 20.
- Rots, A. (2009). Stc-s: Space-time coordinate (STC) metadata linear string implementation version 1.30.
- Schubert, E., Zimek, A., & Kriegel, H.-P. (2013). Geodetic distance queries on r-trees for indexing geographic data. In *SSTD 2013, Proceedings, 13th International Symposium in Spatial and Temporal Databases: vol. 8098, Springer, Munich, Germany, August 21–23, 2013*, pp. 146.
- Song, X. F., Rui, X. P., Wei, H. O. U., & Tan, H. Q. (2008). An OGC standard-oriented architecture for distributed coal mine map services. *Journal of China University of Mining and Technology*, 18(3), 381–385. [https://doi.org/10.1016/S1006-1266\(08\)60080-2](https://doi.org/10.1016/S1006-1266(08)60080-2)
- Taylor, M. B. (2005). TOPCAT STIL: Starlink Table/VO Table Processing Software. In P. Shopbell, M. Britton, & R. Ebert (Eds.), *Astronomical data analysis software and systems XIV* (Vol. 347, pp. 29). Pasadena, CA: Astronomical Society of the Pacific Conference Series.
- Taylor, M., Boch, T., Fitzpatrick, M., Allan, A., Paoro, L., Taylor, J., et al. (2009). Samp-simple application messaging protocol version 1.3, ArXiv e-prints arXiv:1110.
- Unnithan, V., Pio, R. A., & Jaehrig, T. (2017). Drone-based photogrammetric survey raw data from esa PANGAEA-X 2017 planetary analogue campaign—Data collected on 2017-11-19, data were collected in the framework of the ESA PANGAEA-X testing campaign held in November 2017: we acknowledge ESA for organising the campaign and providing scientific and logistic assistance on site. The authors would like also to thank the Geopark of Lanzarote, the touristic center of Cueva de Los Verdes, the Cabildo of Lanzarote, the National Park of Timanfaya and the IGEO-CSIC-UCM for providing the necessary permits, <https://doi.org/10.5281/zenodo.1095400>
- Vastel, C., Bottinelli, S., Caux, E., Glorian, J.-M., & Boiziot, M. (2015). CASSIS: A tool to visualize and analyse instrumental and synthetic spectra. In F. Martins, S. Boissier, V. Buat, L. Cambrésy, & P. Petit (Eds.), *SF2A-2015: Proceedings of the Annual meeting of the French Society of Astronomy and Astrophysics* (pp. 313–316). Toulouse, France: Société Française d'Astronomie et d'Astrophysique (SF2A).
- Walter, S. H. G., Muller, J.-P., Sidiropoulos, P., Tao, Y., Gwinner, K., Putri, A. R. D., et al. (2018). The web-based interactive Mars analysis and research system for HRSC and the iMars project. *Earth and Space Science*, 5, 308–323. <https://doi.org/10.1029/2018EA000389>