EPN2020-RI

EUROPLANET2020 Research Infrastructure

H2020-INFRAIA-2014-2015

Grant agreement no: 654208

Deliverable D11.10
VO-GIS interface and potential application to space data archives

Due date of deliverable: 31/12/2018
Actual submission date: 19/12/2018

Start date of project: 01 September 2015 Duration: 48 months

Responsible WP Leader: Observatoire de Paris, Stephane Erard

Project funded by the European Union's Horizon 2020 research and innovation programme		
Dissemination level		
PU	Public	☐
PP	Restricted to other programme participants (including the Commission Service)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (excluding the Commission Services)	

Project Number	654208
Project Title	EPN2020 - RI
Project Duration	48 months: 01 September 2015 – 31 August 2019

Deliverable Number	D11.10
Contractual Delivery date	31/12/2018
Actual delivery date	19/12/2018
Title of Deliverable	VO-GIS interface and potential application to space data archives
Contributing Work package (s)	WP11
Dissemination level	PU
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Abstract: Services and tools developed within the VESPA JRA Task 4 (Planetary Surfaces) allowing interoperability across VO and GIS/mapping communities and data are described. Selected VESPA services providing OGC access to data available from external data services and projects are introduced. Libraries for accessing geospatial planetary data have been adapted and tools developed in order to bridge technical gaps. The use and role of both services, libraries and tools for current and future european planetary data archives are introduced

Table of Contents

List of figures

List of acronyms and abbreviations

Acronym	Explanation
CRISM	Compact Reconnaissance Imaging Spectrometer for Mars
FITS	Flexible Image Transport System
GDAL	Geospatial Data Abstraction Library
GIS	Geographic Information System
HiPS	Hierarchical Progressive Survey
IVOA	International Virtual Observatory Alliance
MLA	Mercury Laser Altimeter
OGC	Open Geospatial Consortium
OMEGA	Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité
OSIRIS	Optical, Spectroscopic, and Infrared Remote Imaging System
PANGAEA	Planetary ANalogue Geological and Astrobiological Exercise for Astronauts
PDS	Planetary Data System
QGIS	Quantum GIS
VO	Virtual Observatory
USGS	United States Geological Survey
WCS	World Coordinate System (note on possible confusion: also used as OGC Web Coverage Service)
WMS	Web Mapping Service

Introduction

The amount of available data is rapidly increasing for planetary investigations and planetary surface research continues to evolve from mostly visual assessment to more automated quantitative analysis. Both geologists and astronomers are involved in mapping planetary surfaces. Unfortunately, the technologies and data formats used by researchers from these two communities diverge as these related, but distinct domains evolve. Geologists, for their mapping and analysis needs, commonly use Geographic Information Systems (GIS). In general, GIS applications excel in data interoperability even though some have historically been anchored to Earth's spatial description. Astronomers, in contrast, use open and flexible formats and software for quantitative analysis of huge data sets.

In order to promote their activities, space data archives need tools to propose high level services of data mining and discovery, both human and machine-usable. Both communities are users of space data archives and their different needs must be addressed in a consistent way, without duplicating the development efforts.

In particular researchers involved in surface studies require:

- interoperability between distributed data and GIS protocols and software
- efficient quick-look tools for raw and processed data

In this document we stress how VESPA developments have addressed these needs, also through dedicated workshops, such as the VESPA Mapping workshop, under NA1 in 2017[1], and we provide case studies describing how they can be applied to space data archives. This is illustrated in Figure 1.

- We provide a collection of tools in order to connect EPN-TAP planetary surface services to Open Source GIS tools, so that GIS users can easily discover space archive data.
- We propose to homogenise data formats to those used in Astronomy applications, so that space archives could efficiently reuse tools already developed for space missions and large ground-based facilities.
- We provide metadata dictionaries to make the connection between the planetary VO and astronomical standards.

[1] https://epn-vespa.github.io/mapping2017/

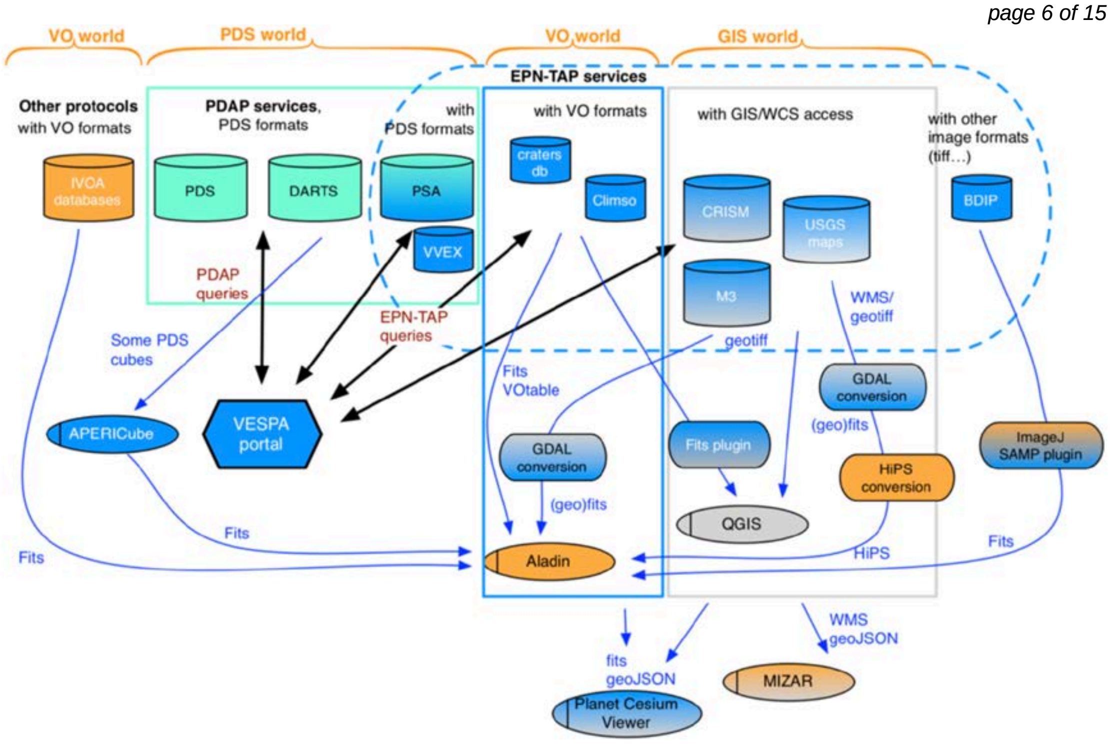

Figure 1: Overview of planetary archives, GIS and VO elements, interfaces and tools (see Erard et al., 2018). Orange: IVOA infrastructure; grey: GIS related elements; cyan: PDS/PSA data; blue: VESPA developments.

VO/GIS representative data services

VO software infrastructure has been enlarged in order to fulfill Planetary Science needs. Conversely data services implementing these VO standards benefit from these developments, too. A good amount of work has been dedicated to populate VO data services in the framework of VESPA. The data services listed below provide VO-enabled versions of pre-existing data sets related to planetary surfaces or terrestrial analogues, the original versions of which are not easily handled through efficient tools and interfaces. These services are available from the VO server at Jabobs University (epn1.epn-vespa.jacobs-university.de) and provide the basis for use cases to develop and test our GIS-VO interfaces. The first outcome of the VO interface is to provide the ability to search these datasets based on many parameters, either from the VESPA portal or from VO tools. Surface-related data must then be handled in specialised tools, according to the science user preferences: GIS on one hand, VO tools on the other hand.

Planetary surface data services

- USGS WMS
    - **VO-service name:** 'usgs_wms'. A selection of USGS planetary maps providing 55 WMS image mosaics (*Hare, T.M. et al., 2014*). Links are pre-formatted queries to web services at USGS.

- CRISM
    - **VO-service name:** 'crism'. A set of 20722 hyperspectral coverages from the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) on-board the Mars Reconnaissance Orbiter mission (*Murchie, S. et al., 2007*). Each entry of the service table provides metadata describing a spectral cube and hyperlink to the PlanetServer version of the archive. PlanetServer provides a WCS service to a reformatted archive derived from the original one distributed by PDS (Marco Figueira, R. *et al*, 2018). A link to a preview image with adaptive resolution is also provided. Data provided by the service are not a 1:1 copy of the public archive from PDS, but a processed version based on the publicly available data reduction pipeline of CAT (CRISM-CAT), produced and maintained by the CRISM Team, available on the PDS Geosciences Node, but run independently before data ingestion on the service backend at JacobsUni.
- Moon Mineralogy Mapper
    - **VO-service name:** 'm3'. A set of 584 spectral cubes mapping the surface mineralogy of the Moon acquired by the M3 instrument on-board the Chandrayaan-1 mission (https://www.isro.gov.in/pslv-c11-chandrayaan-1). Similar to the VO-enabled 'CRISM' data service, the hyperlinks provide access to the PlanetServer version of the dataset (Marco Figueira, R. *et al*, 2018). Data provided by the service are not a 1:1 copy of the public archive from PDS, but a geometrically processed version based on the publicly available data.
- Mars Craters
    - **VO-service name:** 'mars_craters'. A VO version of the catalogue of Martian craters originally published by *S.J. Robbins & B.M. Hynek, 2012*, listing all craters down to ~1 km diameter, with morphologic and morphometric information for craters larger than 3 km. An exemplary visualisation of the data is represented in Figure 2.
- Mars Craters "Lagain"
    - **VO-service name:** 'mars_craters_lagain'. A revised and extended version of the *Robbins & Hynek* catalogue. False detections are corrected and ~ 185 extra craters are identified through a collaborative effort (*A. Lagain et al., submitted)*. This service will be publicly released when the paper is accepted.

Additionally, an external related service:

- HRSC from FU Berlin
    - HRSC (in preparation, external, from FU Berlin). Access to individual level4 HRSC imagery is provided by FU Berlin. An exemplary visualisation of mosaicked data is represented in Figure 3 (see Walter et al., 2018)

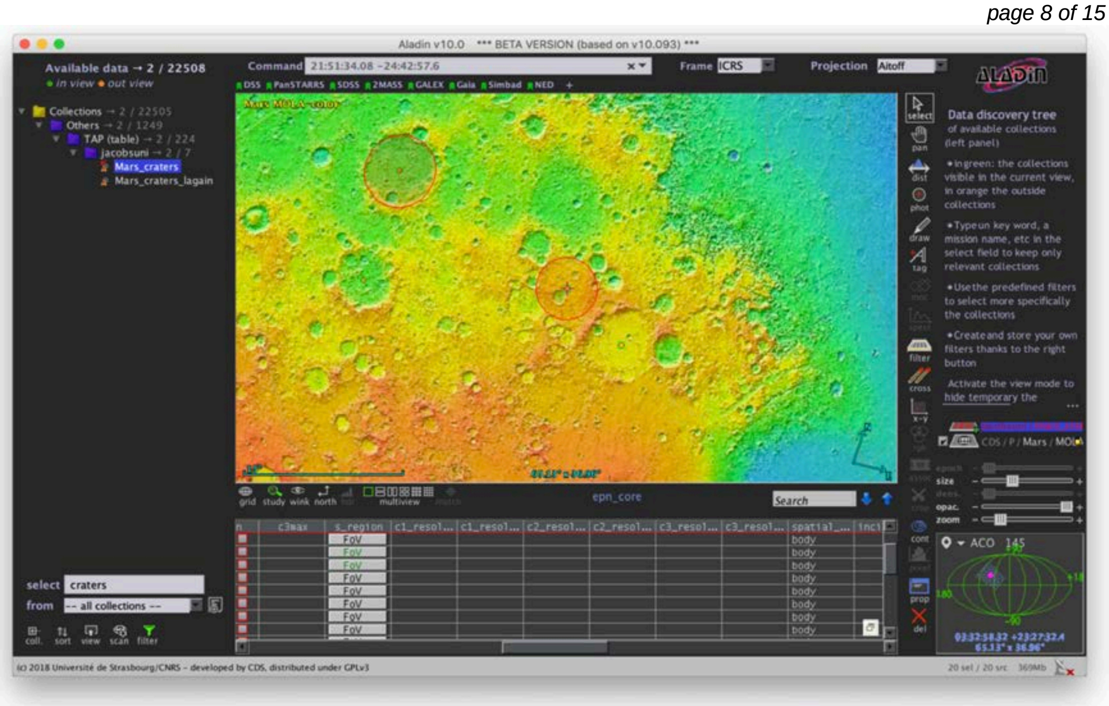

Figure 2: Visualisation of the Robbins Mars crater database footprints in Aladin 10 beta, with support for Solar System bodies. This sample query loads only the top 40 craters with a diameter of more than 300 km (i.e. "SELECT TOP 40 * FROM mars_craters.epn_core WHERE diameter > 300").

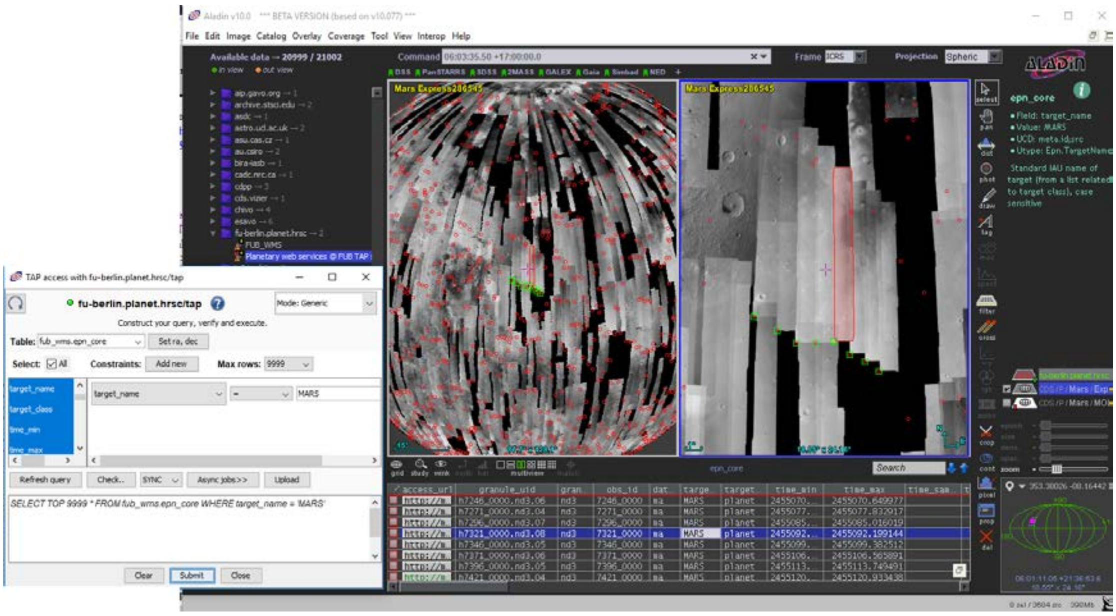

Figure 3: Visualisation of MARS HRSC images mosaicked within Aladin 10 beta, from an EPN-TAP server developed at FU Berlin.

Field analogue data services

- <u>Pangaea-x 2017</u>
    - **VO-service name:** 'pangaea-x ': contains 944 images of drone-based photogrammetric survey raw data from ESA PANGAEA-X 2017 planetary analogue campaign collected in November 2017 (*Unnithan, V. Pio Rossi, A., and Jaehrig, T., 2017*).

An example of use of the Pangaea-X 2017 data through the VO framework is presented in Figure 4. Here the data published through the VO service at the Jacobs University is accessed in real-time using Aladin (*Bonnarel, F. et al., 2000*). The file format of raw data is JPEG, including internal metadata (in EXIF tags) on the center location of each image, which has been used to extract and compute metadata needed to populate the relevant service table. Refined georeferenciation will make it possible to easily mosaic many images from a given data set. This service is used to prototype data services derived from other field study activities, such as those from the Europlanet-2020 TAs.

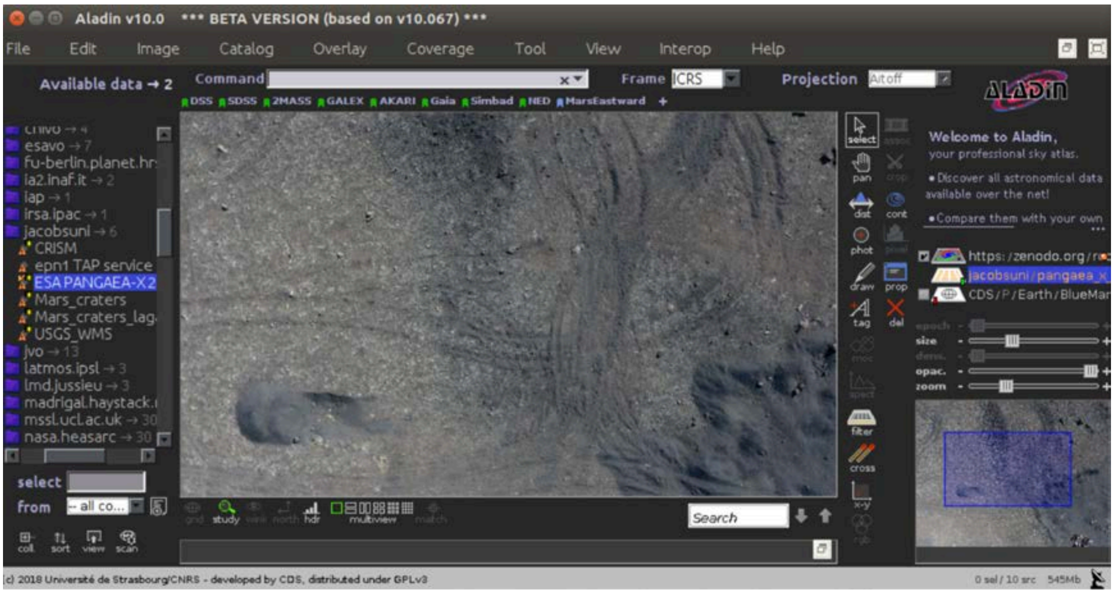

Figure 4: Visualisation of exemplary planetary analogue data on the Aladin VO visualisation tool (raw drone-based aerial imagery) collected within the ESA Pangaea-X 2017 campaign, stored as data on Zenodo/Openaire (Unnithan et al, 2017) and made discoverable via VESPA

FITS for Planetary Sciences

FITS is an open digital standard, created in the late 1970s for data acquisition, transfer, and archiving of telescope data by astronomical observatories, where it has been used during the last 30 years. It had been adopted for data exchange and archiving from several orbital telescopes and space missions. The International Astronomical Union (IAU) approved FITS as the standard format for astronomical data (https://fits.gsfc.nasa.gov/iaufwg/history/IAU_1982_resolution_c1.html). Therefore, FITS is one of the standard formats implemented in the VO. FITS data storage is compatible with the PDS archiving specifications so that FITS files can be embedded in PDS data sets (Marmo et al., 2018).

FITS can already be used as standard formatting for most data products commonly used in planetary surface investigations. In particular, the Multi-Extension FITS schema proposes an easy way to store inhomogeneous digital information (reflectance, calibration data, vector, table data, etc.) in the same file, each with corresponding metadata, or hyperspectral cubes with geometry information e.g., from OMEGA (Bibring et al. 2005) or CRISM

(Murchie et al. 2007) instruments. FITS has been already chosen to distribute data from, for example, Hayabusa AMICA and NIRS cameras (http://darts.isas.jaxa.jp/planet/project/hayabusa/index.html), all Akatsuki cameras (http://darts.isas.jaxa.jp/planet/project/akatsuki/index.html; except the Lightning and Airglow Camera), and the Dawn Framing Camera (https://sbn.psi.edu/pds/archive/dawn.html) data. Some Rosetta data, from the NAVCAM and OSIRIS cameras, are distributed in FITS format at the ESA Planetary Science Archive (http://psa.esa.int). In addition, many PDS3 data sets in the Small Bodies Node are archived and distributed as FITS files with PDS3 labels.

However, solar system imagery data have been traditionally described using terrestrial-based geospatial descriptions and remote sensing formats. This is particularly true for planetary surface investigations. Engineers and cartographers working in the first space missions were more familiar with Earth observation techniques and standards than with the astronomy ones. Furthermore, the standardisation of the spatial references in FITS dates back to the 2000s, when planetary surface research habits had already been installed. In small bodies investigations, where astronomers and planetary scientists have worked together for a long time, FITS format is already more popular.

To be more efficiently used in planetary surface investigations, FITS metadata needed be thoroughly mapped to planetary geospatial concepts, then to be extended in order to take into account the size and orientation of the reference body as standardised by the IAU Working Group on Cartographic Coordinates and Rotational Elements (WGCCRE).

We have proposed a metadata profile (GeoFITS: Planetary Data FITS format and metadata convention, Marmo et al 2018) for fitting planetary data into FITS and correspondent mappings from typical planetary data structures (e.g. PDS, EPN-TAP). We plan to submit a Request for Comment at the IVOA and the IPDA in 2019.

Space data archives often host imagery from Astronomical and Planetary missions. Using FITS for planetary data will allow to reuse tools already developed for astrophysics space missions, and will guarantee interoperability from raw data formatting to final visualisation, especially for quick look options (Figure 5).

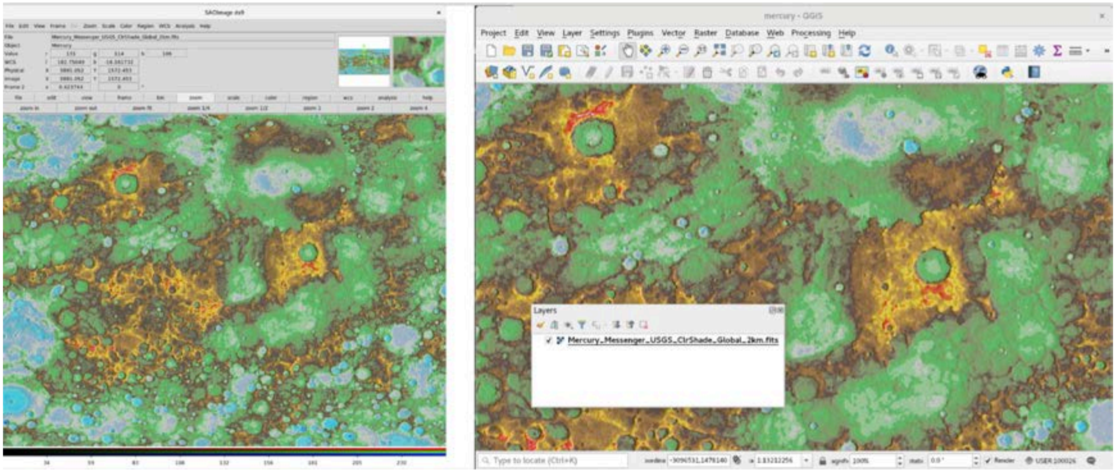

Figure 5: Example of global topographic data (from Mercury Messenger MLA gridded topography) encoded in GeoFITS format. Left: visualised with ds9 (in RGB mode). Right: visualised in QGIS (linked against the GeoFITS compatible GDAL version).

PDS and PSA archiving standards have reservations about the GeoTiff format, one of the preferred raster format in GIS applications; such images can only be accommodated in the (optional) EXTRA directory of space archives. The implementation of GeoFITS in the GDAL library (see https://github.com/epn-vespa/gdal) solves this problem: GeoFITS files can be converted to GeoTiff format upon import in QGIS, which makes them directly readable in a GIS environment. GeoTiff and GeoFITS then become indistinguishable from the GIS point of view, and the need to include additional GeoTiff versions in the archives disappears. A docker version of QGIS compiled against our GDAL implementation is available on github https://github.com/epn-vespa/gdal-fits-docker.

VO interface to GIS

1) QGIS plugins

The geospatial data listed above are distributed in VESPA via a dedicated German Astronomical Virtual Observatory Data Center Helper Suite (GAVO DaCHS) server, and several services exposing existing Open Geospatial Consortium (OGC) compliant planetary services were published to VESPA providing a variety of geospatial data types: vector data, spectral cube rasters, as well as OGC Web Map Service of planetary maps (Figure 6). Tutorials are available on the VESPA GitHub organisation tutorial repository in particular on https://github.com/epn-vespa/tutorials/blob/master/surfaces/vo_qgis_plugin/

We have developed plugins for QGIS (https://github.com/epn-vespa/VO_QGIS_plugin) to retrieve and visualise these geospatial data via the SAMP protocol which connects VO applications (Minin et al., submitted).

- The VESPA plugin allows for running the SAMP hub and SAMP Client from within QGIS. It accepts VOTables sent from other applications, provided they contain an "s_region" parameter correctly formatted, and saves these as SpatiaLite in temporary folder. It then loads these as polygon feature layers into QGIS.

- The GAVOImage plugin uses the "thumbnail_url" and a few other EPN-TAP2.0 standard parameters to load a thumbnail image onto the canvas, also georeferencing it over the polygon. This has been tested on CRISM service. In combination with WMS layers distributed on the same server, this provides a handy tool for the exploration of planetary surface data.

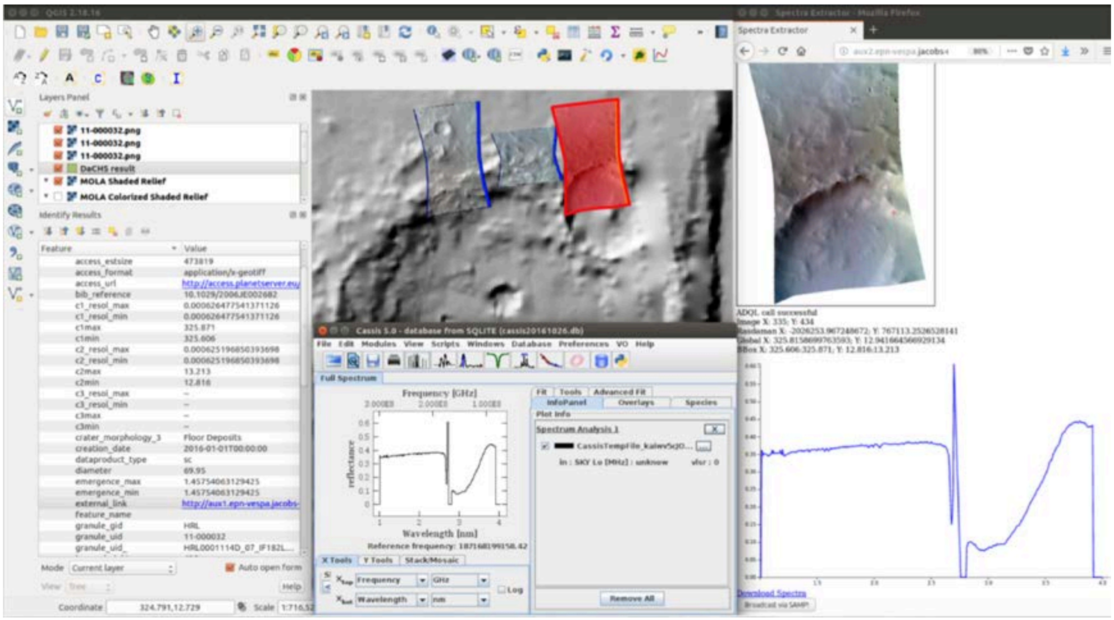

Figure 6: integration of WMS layers and local spectral analysis in QGIS, thanks to the VO_QGIS_plugin.

2) Aladin and HiPS

[Aladin](#) has nowadays the capability of mosaicking planetary imagery (Figure 3)

Moreover, [Aladin](#) and its [HiPS](#) (Hierarchical Progressive Survey, a recommendation endorsed by the International Virtual Observatory Alliance) generator have been updated to support planetary conventions. Aladin is both a sky atlas and a portal to access data, it is able to load FITS files and to display images taking into account various WCS projections (*Bonnarel, F. et al., 2000*). So far Aladin is also the reference generator and visualiser of HiPS tiling allowing to access sky survey data stored at various spatial resolutions, offering a progressive view of possibly very large datasets. HiPS are usually generated from a collection of WCS tagged FITS files (Figure 7).

The Web version of Aladin ([Aladin Lite](#)) is used as graphical interface by [ESO](#) and [ESA Science](#) archives (Baines D. et al 2016, http://dx.doi.org/10.1088/1538-3873/129/972/028001). Use cases on the use of the web-based version of Aladin for Mars landing site visualisation exist (http://aladin.u-strasbg.fr/AladinLite/doc/API/examples/mars-visualisation/)

Thanks to FITS planetary metadata dictionary, global planetary maps have been integrated in the Aladin HiPS server and they are available for efficient discovery via standard VO tools. At the moment 55 maps from the global mosaics from USGS are available.

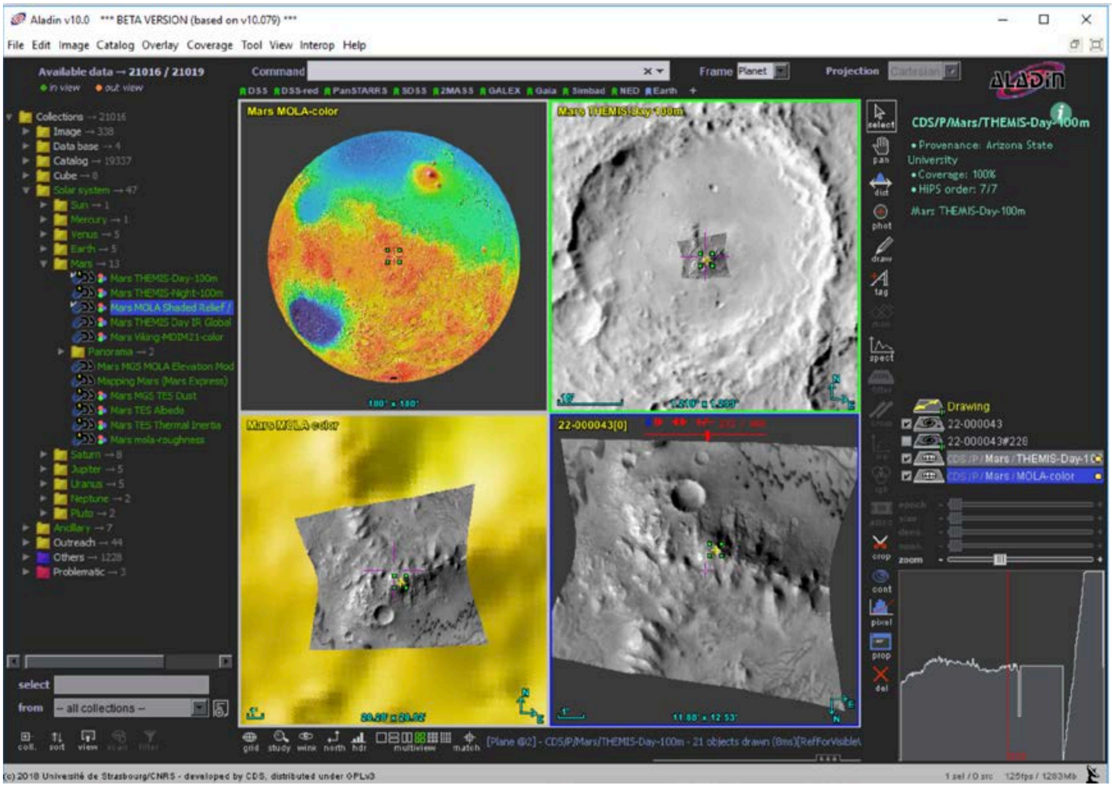

Figure 7: Several levels of detail on Mars with Aladin: from the global topographic map, a HiPS layer, down to the high resolution CRISM spectral cube in FITS format. All spectral analysis tools useful for astronomical spectra are then available for planetary data (as visualised in the right bottom spectral thumbnail).

These developments show that space agencies can now host high level data products in OGC compatible formats and then expose them via a standard machine-readable EPN-TAP layer, preserving GIS interoperability.

Conclusions and perspective

Format, service and tool-based developments within VESPA JRA (WP11) Surface Task resulted in increased interoperability across geospatial surface mapping and planetary Virtual Observatory data discovery and access. The current plugins will be further developed with external resources as well as possible follow-up projects and activities.

Additional support for the VESPA-driven GeoFITS developments onto standard GDAL-based software packages such as QGIS will be pursued beyond the current implementations, such as the above mentioned docker solution. VO-enabling other popular mapping tools used by the community would be also valuable additions to be considered for future developments, such as JMars and its variations, e.g. JMoon. Contacts in this direction will be focus of future efforts.

Moreover, adding direct support for VO data access to existing frameworks for web-based globe visualisation (such as WorldWind and Cesium) direct support for VO data access is considered. Also, the integration of OGC catalogue services with VO services would be of interest to deepen and broaden further the interoperability across GIS/VO worlds. Existing and future data services, both from institutional data providers and space agencies/archives will benefit from current and expanded functionalities for direct or on-demand file conversions (e.g. GeoTiff - GeoFITS) and cross-tool support.

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