



PlanetServer: Innovative approaches for the online analysis of hyperspectral satellite data from Mars

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Abstract

PlanetServer is a WebGIS system, currently under development, enabling the online analysis of Compact Reconnaissance Imaging Spectrometer (CRISM) hyperspectral data from Mars. It is part of the EarthServer project which builds infrastructure for online access and analysis of huge Earth Science datasets. Core functionality consists of the rasdaman Array Database Management System (DBMS) for storage, and the Open Geospatial Consortium (OGC) Web Coverage Processing Service (WCPS) for data querying. Various WCPS queries have been designed to access spatial and spectral subsets of the CRISM data. The client WebGIS, consisting mainly of the OpenLayers javascript library, uses these queries to enable online spatial and spectral analysis. Currently the PlanetServer demonstration consists of two CRISM Full Resolution Target (FRT) observations, surrounding the NASA Curiosity rover landing site. A detailed analysis of one of these observations is performed in the Case Study section. The current PlanetServer functionality is described step by step, and is tested by focusing on detecting mineralogical evidence described in earlier Gale crater studies. Both the PlanetServer methodology and its possible use for mineralogical studies will be further discussed. Future work includes batch ingestion of CRISM data and further development of the WebGIS and analysis tools.

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1. Introduction

Advances in computer power and internet speed as well as developments in web standards and browser technology currently make, for the first time, online visualization, processing and analysis of large geoscience datasets possible. Google Earth Engine for example uses cloud computing to enable analysis of 40 years of Landsat satellite data (Regalado, 2010). Zhao et al. (2012a,b) describe the emergence of a 'Geoprocessing Web', a "framework of interoperable geoprocessing tools, allowing geoscientific collaboration". Such an infrastructure would save scientists time-consuming and expensive processing steps on their

own computer. Scientists would get online access to high-level scientific data products.

In this paper the first results are presented of a contribution to the Geoprocessing Web, transposed to Planetary science: PlanetServer (www.planetserver.eu), an online visualization and analysis service for planetary data (Oosthoek et al., 2013). PlanetServer, developed at Jacobs University Bremen, is part of EarthServer project (www.earthserver.eu) which is creating an on-demand online access and analysis infrastructure for massive (10^3 TB) Earth Science data. PlanetServer is one of six so-called EarthServer Lighthouse Applications, each of which is situated in one particular Earth Science domain (climate, ocean, geology, cryosphere, and airborne) and Planetary science, respectively. The common underlying data management platform is the rasdaman Array Database Management System (DBMS) (Baumann,

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1994, 2009a) which allows for SQL-style declarative queries on massive multi-dimensional array (“raster”) data. Interfaces conformant to Open Geospatial Consortium (OGC, www.opengeospatial.org) web standards allow clients to access data via standard HTTP requests, ranging from simple subsetting to complex analytics. Rasdaman is further detailed in Section 2.3.

The work presented here focuses on the online analysis of Compact Reconnaissance Imaging Spectrometer (CRISM) hyperspectral data from Mars. The CRISM imager on board the NASA Mars Reconnaissance Orbiter (MRO, launched in 2005) is a visible to infrared imaging spectrometer, collecting data over 544 channels from 362 to 3920 nm at a 6.55 nm spectral and 18 m spatial resolution at best (Murchie et al., 2007, 2009). More than 20 TB of CRISM targeted and nadir observations are freely available on the NASA Planetary Data System (PDS) archive as of Spring 2013.

PlanetServer uses the OGC Web Coverage Processing Service (WCPS) standard (Baumann, 2009b) which allows for submitting on-demand filtering and processing queries in a high-level, declarative query language similar to databases, but on multi-dimensional arrays. This provides, for example, access to (subsets of) the bands and spectra of a given CRISM dataset in the rasdaman database and therefore enables online spatial and spectral analyses.

For testing purposes two CRISM Full Resolution Target (FRT) observations were added to rasdaman covering Gale crater, Mars, the NASA MSL rover Curiosity landing site (Fig. 1). Also various imagery and topography data from Gale crater were added, such as the MRO High Resolution Imaging Science Experiment (HiRISE) and Context camera (CTX) data (McEwen et al., 2007; Malin et al., 2007), and the Mars Express High Resolution Stereo Camera (HRSC) data (Neukum et al., 2004).

The aim of this paper is to show how WCPS can be used in a new and innovative way to analyze complex data, such as hyperspectral satellite data, in an online environment. Future applications are therefore not limited to CRISM or data from Mars.

In Section 2, the concepts and components are presented which establish the basis of PlanetServer. Section 3 describes the current use of PlanetServer with the example of a Gale crater Case Study. The approach taken is discussed in Section 4, and Section 5 concludes the paper.

2. Concepts and components

2.1. Introduction

The current PlanetServer hardware is a 12-core machine with 128 GB RAM and several tens of TB available storage. The machine is running CENT OS and Apache Tomcat 6 and the open source rasdaman community version 8.3 has been installed. The migration to a production environment is planned for early September 2013. This will include batch ingestion of CRISM data. Various components and

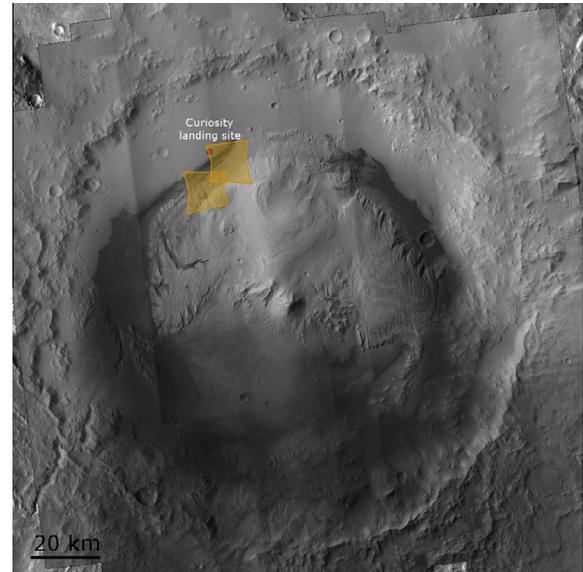


Fig. 1. The NASA MSL Curiosity rover landing site within the 154 km in diameter Gale crater on a CTX mosaic (see acknowledgements). The coverage ‘footprints’ for the two CRISM data used in this demonstration are shown in orange. The CRISM data directly covering the MSL landing site (FRT0000C51807S (VNIR) and FRT0000C51807L (IR) (see Table 1)) is used in the Case Study. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

processing steps are involved in setting, running and utilizing PlanetServer.

2.2. OGC coverage standards

The term coverage is defined as the digital representation of a phenomenon varying over space/time (ISO, 2005). An interoperable definition of a coverage is the OGC Unified Coverage Model (UCM) defined in the GML 3.2.1 Application Schema – Coverages standard (Baumann, 2012). Gridded data, which PlanetServer uses, is a specific coverage class. The subclass *RectifiedGridCoverage* represents regular grids, i.e., raster data, whereas *ReferenceableGridCoverage* allows for irregular grids.

The Web Coverage Service (WCS)¹ defines a service interface for accessing coverages offered by a server. The WCS Core defines simple subsetting: trimming yields a smaller coverage with the same number of dimensions as the original coverage, whereas slicing reduces dimensionality (e.g., when extracting an x/y slice from an $x/y/t$ timeseries). WCS extension standards establish further functionality, such as a variety of format encodings, or CRS reprojection. The Web Coverage Processing Service (WCPS)², finally, defines a raster query language on coverages allowing spatio-temporal analytics on multi-dimensional, hyperspectral raster data. In Section 3 various WCPS queries used for CRISM data analysis will be discussed.

¹ <http://www.opengeospatial.org/standards/wcs>.

² <http://www.opengeospatial.org/standards/wcps>.

2.3. The rasdaman array database management system

Traditional database management systems (DBMSs) do not support large, multi-dimensional arrays. Consequently, these data are served through custom-made ad hoc servers which support arrays, but, on the other hand, lack database features such as query languages, query optimization and parallelization, and access-efficient storage architectures. An Array DBMS (Baumann, 2009a), on the other hand, offers the classical database advantages on n-D arrays. The system that has pioneered this category is rasdaman, which stands for “raster data manager” (Baumann, 1994). The rasdaman data model consists of strongly typed arrays that can have any number of dimensions with individually fixed or variable lower and upper bounds per dimension. Any C/C++ type (except pointers) can be defined, in a C-style syntax, as cell (“pixel”, “voxel”) type. Arrays are introduced as new column (i.e., attribute) types in standard relational tables. The rasdaman query language, rasql, offers declarative array selection and processing by extending ISO SQL with multi-dimensional operators (Baumann, 2012). The architecture is based on transparent array partitioning, called tiling, along which both the storage and processing engine are architected. Geographic and temporal coordinate system support (Campalani et al., 2013) is added by the PetaScope component (Aiordăchioaie and Baumann, 2010) which implements the relevant OGC standards, encompassing WMS, WCS, WCPS, and WPS.

2.4. Planetary Coordinate Reference System support

Enabling support for planetary Coordinate Reference Systems (CRS) in a (Web)GIS is a work in evolution. Hare et al. (2006) proposed to allow for non-EPSS namespaces for planetary bodies. For Mars the current official CRS is defined by the International Astronomical Union (IAU) in 2000 (Seidelmann et al., 2002). Hare et al. (2006) therefore proposed IAU2000 as the namespace for Mars.

IAU2000 defines Mars as an ellipse with a 3,396,190 m equatorial and a 3,376,200 m polar radius. The latitude is defined relative to the center of Mars (planetocentric). Terrestrial coordinate systems however (e.g. WGS84) commonly define the latitude relative to the surface (planetographic). See Fig. 2 for an explanation of planetocentric vs. planetographic. This causes the IAU2000 definition not to be fully supported by many GIS clients. Therefore a Mars geographic CRS with a 3,396,190 m sphere is used (Hare et al., 2005).

EarthServer researchers have established a naming scheme for CRSs (Misev et al., 2012; Baumann et al., 2012) which allows for creating new CRSs by combining existing ones, based on the standard URI identifier syntax adopted by OGC. For example, spatial and temporal CRSs can be combined providing support for $x/y/t$ image time-series. SECORE (Semantic Resolver for Coordinate Reference Systems) is a Java servlet acting as a resolver for such

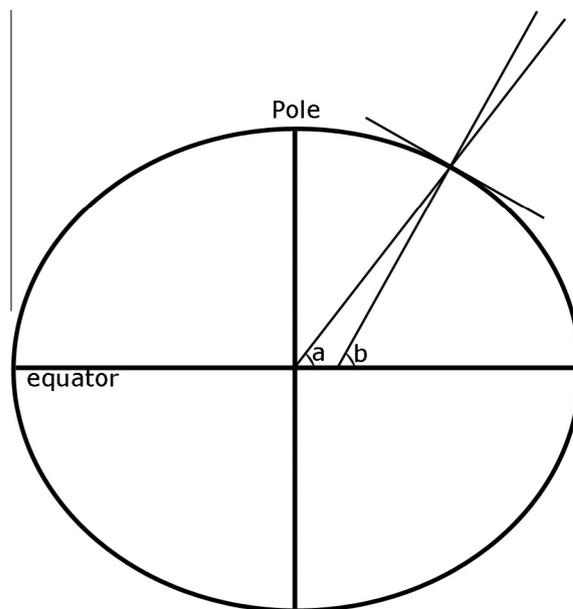


Fig. 2. Planetocentric latitude (a) vs. planetographic latitude (b).

URIs, delivering the complete CRS definition for a URI sent. At the moment, CRS definitions are returned in GML, but other syntax variants are under consideration, such as WKT. SECORE is open-source and part of rasdaman, available from www.rasdaman.org. SECORE is currently undergoing a beta test phase by OGC.

For PlanetServer, the PS (PlanetServer) namespace has been defined. The following GML URL defines the 3,396,190 m sphere geographic CRS and is currently used by PetaScope for WCS and WCPS requests:

<http://kahlua.eecs.jacobs-university.de:8080/def/crs/PS/0/1>

Future plans include proposing the family of Planetary CRSs to be hosted by OGC; in this case, the identifier URI might read:

<http://www.opengis.net/def/crs/PS/0/1>

GIS clients and cartographic libraries currently do not support a URI-oriented CRS schema. PetaScope, therefore, additionally supports “AUTH:CODE” for CRS identification, such as “EPSG:4326” for WGS84.

2.5. CRISM data selection and processing

CRISM is a push-broom spectral imager collecting images of a portion of the Martian surface at 544 different wavelengths (Murchie et al., 2007, 2009). The Full Resolution Target (FRT) CRISM data, currently the focus of this study, consist of high resolution (18 m/pixel) hyperspectral observations of a 10×10 km scene. FRT data are part of the CRISM Targeted Reduced Data Record (TRDR)

Table 1

The two CRISM datasets covering Gale crater (see Fig. 1) currently available through PlanetServer. The FRT nomenclature is: FRTaaaaaaa_bb_ccdde_ffff where aaaaaaa is a 8-digit hexadecimal Observation ID, bb the image number within the observation (Hex, 07 for the central swath), cc either RA (radiance) or IF (radiance divided by the solar flux scaled to Mars' solar distance), ddd the macro used to process the data, e either S (VNIR) or L (IR) and ffff the version. The rasdaman collection name is a shortened version of the CRISM ProductId with the following nomenclature: FRTaaaaaaabbe.

Type	CRISM ProductId	Rasdaman collection name
VNIR	FRT0000C518_07_IF165S_TRR3	FRT0000C51807S
IR	FRT0000C518_07_IF165L_TRR3	FRT0000C51807L
VNIR	FRT0000B6F1_07_IF165S_TRR3	FRT0000B6F107S
IR	FRT0000B6F1_07_IF165L_TRR3	FRT0000B6F107L

which contains I/F calibrated data (the radiance divided by the solar flux, scaled to the Mars' solar distance). The CRISM TRDR includes data from both CRISM detectors, in the Visible and Near InfraRed domain (VNIR, S-detector, 107 bands) and in the InfraRed domain (IR, L-detector, 438 bands), provided as separate files. For each VNIR and IR observations, 10 short scans are acquired before and after the main image or central swath, providing an emission phase function (EPF) for future atmospheric studies. However only the central swath is used to retrieve the surface properties and will be used hereafter. Each TRDR file is associated with a corresponding Derived Data Record (DDR) file, which contain information relative to the geometry (latitude, longitude, incidence, emission and phase angles) and physical properties (e.g.

elevation, thermal inertia) of the scene, and is necessary to process the observation.

CRISM data are stored on the PDS website and can be identified by location through the Orbital Data Explorer (ODE) tools (Wang et al., 2011). Two CRISM VNIR and IR FRT observations covering Gale crater were downloaded with their corresponding DDR, and added to rasdaman (Table 1).

The downloaded CRISM FRT observations were subsequently processed using the CRISM Analysis Tool (CAT) for ENVI (Murchie et al., 2009). This involves (1) photometric, (2) atmospheric correction (only for IR) and (3) map projection of the data. The atmospheric effects are removed using a ratio of a CRISM scene of Olympus Mons, scaled to the same column density of CO₂. The atmospheric transmission reference is automatically chosen as an optimum wavelength shift volcano scan, using the McGuire 2-wavelength for the scaling (McGuire et al., 2009). Using the GDAL library, the data was further converted to multiband GeoTIFF, using a Mars geographic Coordinate Reference System with a 3,396,190 m sphere:

```
proj4 code: "+proj = longlat + a = 3396190 + b = 3396190 + no_defs"
```

2.6. Data ingest

Before ingestion, a rasdaman data type for the CRISM data needs to be defined. A type definition was made for the 107 bands CRISM VNIR and 438 bands CRISM IR

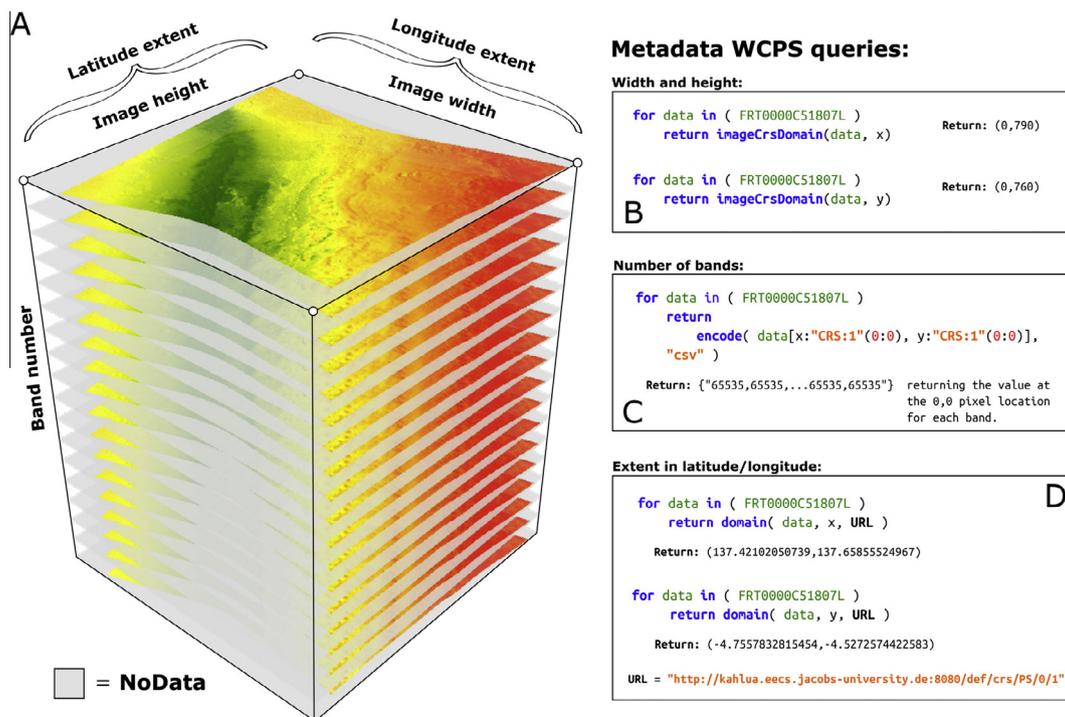


Fig. 3. Illustration of the CRISM data cube metadata (left) and WCPS queries to extract CRISM metadata (right). The NoData value for CRISM data is 65,535.

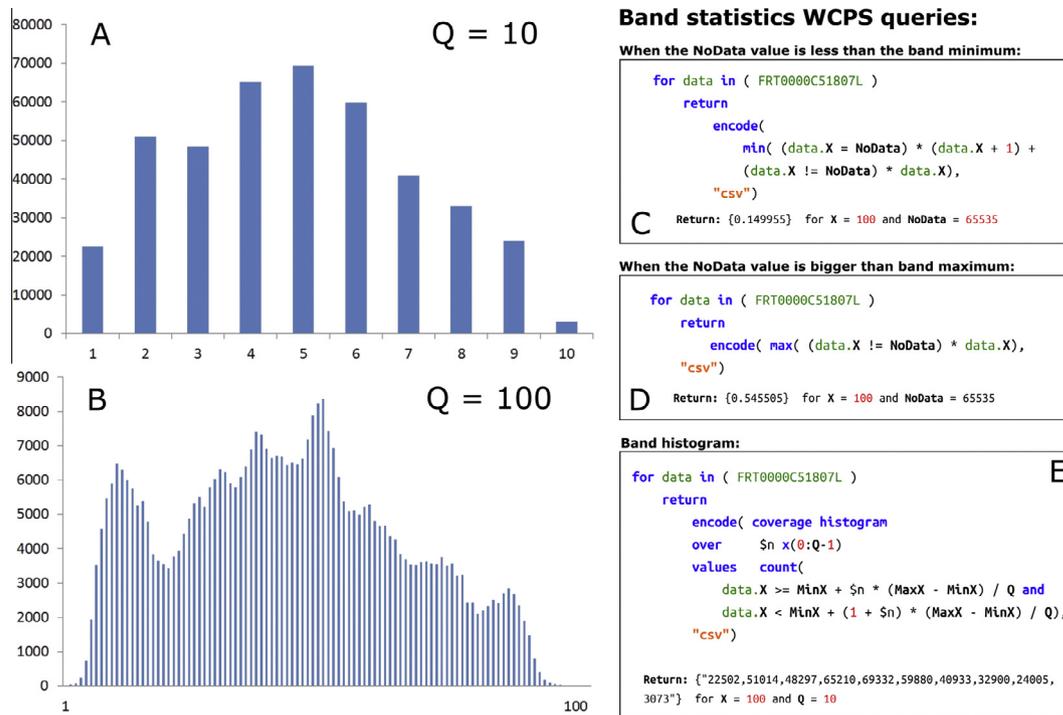


Fig. 4. WCPS queries to calculate the minimum, maximum and histogram. Two example histograms are shown using 10 and 100 bins for *data.100*.

data. For the CRISM VNIR data the definition looks as follows:

```

struct CRISM_VNIRPixel {float band1,band2,...,
band107;}
typedef marray < CRISM_VNIRPixel,2 > CRISM_
VNIRImage;
  
```

This type definition first defines the “pixel type” by establishing the amount of bands and the value type for each band. For CRISM the value type is floating point. In the second line, a raster type is created (using the keyword “marray” for “multi-dimensional array”) which is specified as being 2D, with completely open bounds in all directions; this way, the server will allow for coverages at any coordinate and with an extent that can grow dynamically. A python script was created which uses GDAL to read an input raster, creating the data type definition.

This definition was added to rasdaman using the ‘rasdl’ tool. For ingestion into rasdaman the ‘rasimport’ tool was used. Rasimport is part of the rasgeo package. Its command variables are the input file, the desired rasdaman collection name and the type definition of the data. Table 1 shows the chosen CRISM nomenclature for the rasdaman collection names.

2.7. PlanetServer client

The current PlanetServer client includes tools to analyze processed CRISM data. It relies heavily on OpenLayers for its WebGIS capabilities. OpenLayers WMS support is used

for the visualization of background visual imagery. WCPS derived PNG imagery was added to their correct location on the OpenLayers map using the Image Overlay functionality of OpenLayers.

A Console window was added where users can interact with the CRISM data on the server using various javascript functions. These functions contain predefined WCPS queries and will be described in detail in Section 3. This interactive environment enables the user to perform spatial and spectral calculations.

3. Case study

3.1. Introduction

A Case Study was undertaken involving online spatial and spectral analysis of CRISM observations using PlanetServer. The rasdaman database on PlanetServer currently contains two CRISM VNIR and two IR datasets, which cover Gale crater, Mars, where the NASA MSL Curiosity rover landed (see Fig. 1 and Table 1). The IR FRT CRISM product FRT0000C518_07_IF165L_TRR3 (ingested into rasdaman as collection name FRT0000c51807L) directly covers the MSL landing site and is used for this Case Study.

Gale crater, 154 km in diameter, is located along the Martian dichotomy border. The crater contains a 5.2 km high central mound that is interpreted as a pile of sedimentary material, surrounded by dark dune fields (Thomson et al., 2011). Previous mineralogical studies have shown that the dark aeolian material is enriched in mafic minerals such as olivine and pyroxene (Silvestro et al., 2013), whereas the

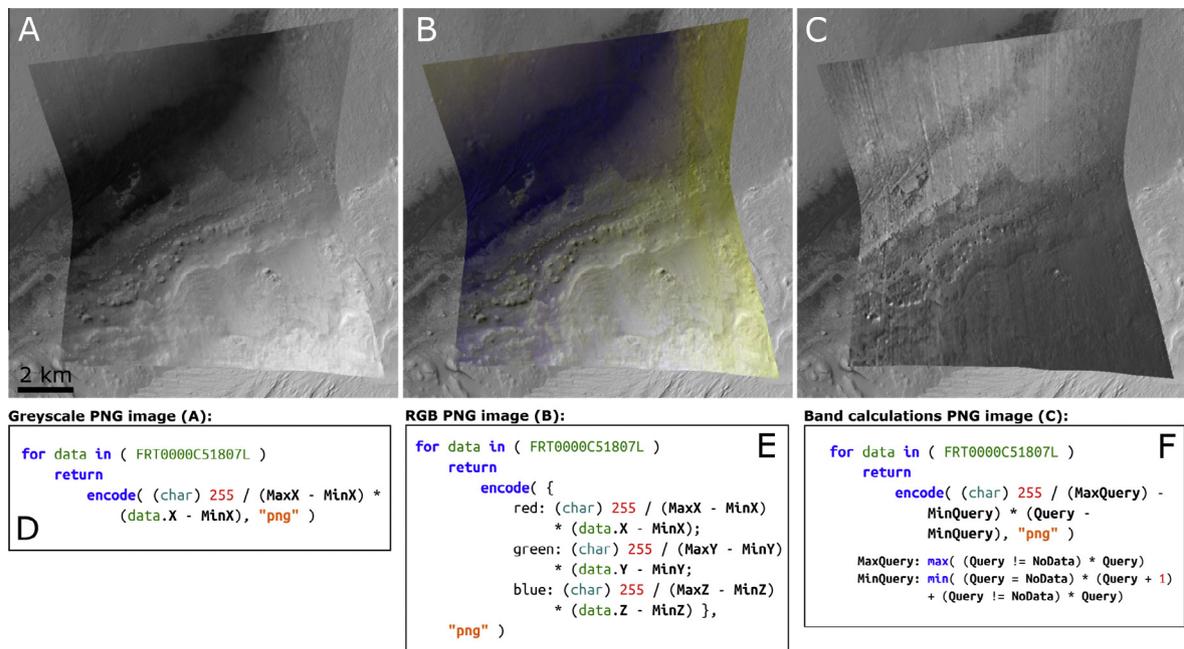


Fig. 5. WCPS derived PNG images and accompanying WCPS queries. The background for each image is a CTX mosaic of Gale Crater (Malin et al., 2007). (A) A greyscale PNG image of *data.100*. The MinX and MaxX values mentioned in the accompanying WCPS query need to be calculated using the queries described in Fig. 4. (B) A PNG color image of Red: *data.100*, Green: *data.200* and Blue: *data.300*. (C) A greyscale PNG image of *data.100/data.200*. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

central mound shows hydrated mineral signatures (Milliken et al., 2010). Both phyllosilicates and sulfates have been detected, leading to the idea that a major mineralogical (and likely climatic) transition was possibly recorded in this 3.8–3.6 Gy old environment (Milliken et al., 2010). These observations motivated NASA to choose Gale crater as the final landing site for MSL. This section will explain how to derive mineralogical information from the CRISM observations available in PlanetServer, using WCPS. The results will subsequently be compared with the published literature. Generally, WCPS queries use a *forClause* to define the input data and a *returnClause* to define which information is returned:

```

for data in (FRT0000c51807L)
return encode (data.0, "csv")

```

If the collection is multiband, as is the case with CRISM data, the first band can be derived by using *data.0*. In the example above, the values of the first band are encoded as comma-separated-values (CSV).

PlanetServer places the WCPS image results inside the map. Therefore, as a first step, metadata needs to be determined (Section 3.2). Band statistics are needed to investigate band quality and to determine the minimum and maximum values (Section 3.3). Various spatial and spectral calculations are described in Sections 3.4 and 3.5. Section 3.6 describes the current OpenLayers WebGIS functionality.

3.2. Determining metadata

Loading a CRISM dataset in the PlanetServer client uses WCPS queries to determine the dimensions of the

requested dataset (Fig. 3). The width, height and areal extent of a rasdaman coverage can be derived using the WCPS *imageCrsDomain* and *domain* elements, respectively. It is currently not possible to directly derive a value representing the band number. Therefore a WCPS query was made which returns an array of all the band values at the origin (0,0) pixel location. The length of the CSV array subsequently represents the number of bands.

The image width, image height and geographical extent are used to place a WCPS derived PNG image at its correct location in the PlanetServer OpenLayers background map. This allows for hyperspectral data analysis in a WebGIS environment.

3.3. Band statistics

Simple statistics of a specific band can be determined by calculating a histogram. The PlanetServer client console window allows for the creation of histograms using the following javascript function:

```
WCPS> histogram(query, bins)
```

Fig. 4 shows the histogram results for running *histogram("data.100", 10)* and *histogram("data.100", 100)*.

All the javascript console window functions work with either *"data.100"* or *"band101"* as syntax; *"band101"* is automatically converted to *"data.100"*. Fig. 4 details the WCPS queries needed to calculate a histogram. First the minimum and maximum values of the query are requested. The WCPS language specification of the open source rasdaman community version currently does not exclude NoData values

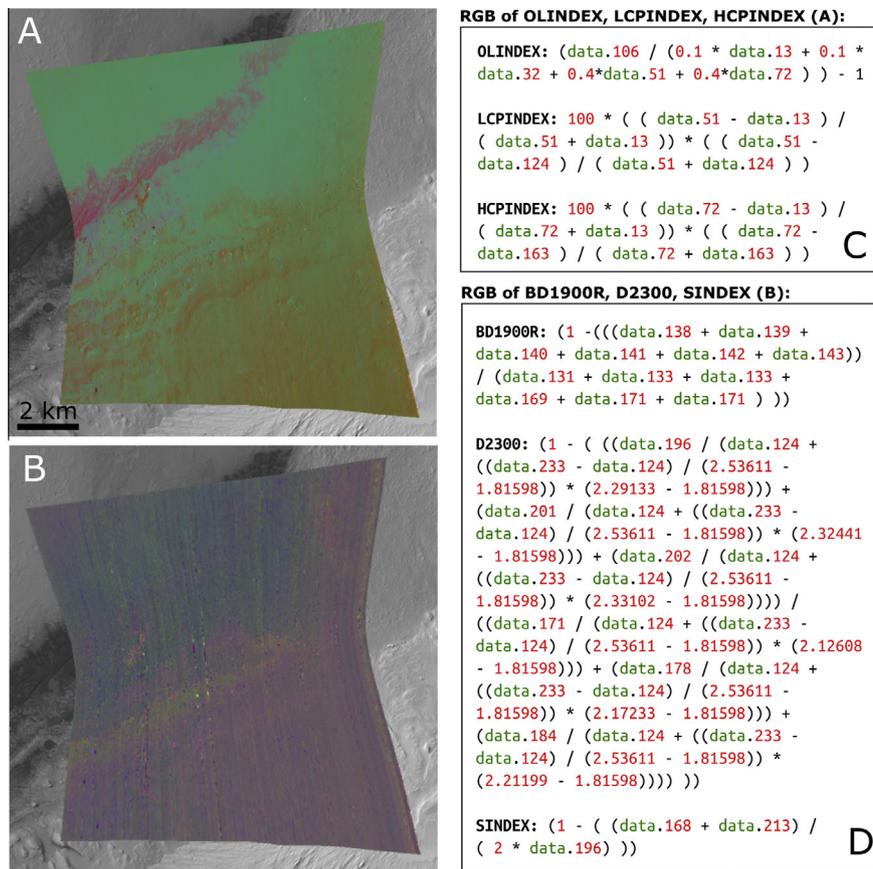


Fig. 6. Examples of CRISM CAT summary parameters converted to WCPS, (A) A PNG color image of the CRISM RGB combination *rgbimage(olindex, lcpindex, hcindex)*. Olivine-rich areas appear in red (dark dune field), pyroxene-rich areas in cyan. It should be noted that the central mound (lower portion of the image) appear in orange as these parameters can also sensitive to the presence of hydrated minerals. (B) The WCPS queries for OLINDEX, LCPINDEX and HCPINDEX. (C) A PNG color image of the CRISM RGB combination *rgbimage(bd1900r, d2300, sindex)*. The SINDEXT parameter in this example is of poor quality, but it should be noted that this RGB image allows for distinguishing between three main mineralogical units: a clay-rich one (1.9 μm band + 2.3 μm drop) in yellow (lower portion of the central mound), a sulfate-rich one in red (1.9 μm band) to purple (1.9 μm band + 2.4 μm drop) (bottom of the mound + upper section), a non-hydrated one in greenish (noise)/black (floor of the canyon). Associated spectra, which were used to confirm the mineralogy, are shown in Fig. 7. (D) The WCPS queries for BD1900R, D2300 and SINDEXT. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(65,535 for CRISM data). This causes interference when requesting the minimum and maximum values. The WCPS queries shown in Fig. 4 therefore use a workaround.

3.4. Spatial calculations

Rasdaman supports the output of imagery using the PNG format. The CRISM data is 32-bit floating point, so the original values need to be converted to Byte [0:255]. The PlanetServer client console window allows for the use of the following javascript functions to calculate and display greyscale and RGB images on the OpenLayers map:

```

WCPS> image(query)
WCPS> rgbimage(redquery, greenquery, bluequery)

```

Fig. 5 shows three screenshots of the resulting map after running *image("data.100")*, *rgbimage("data.100","data.200","data.300")*, and the band calculation of dividing band

101 over band 201, *image(data.100/data.200)*. Fig. 5D–F show the respective WCPS queries used.

The WCPS syntax allows for more advanced band calculations. As an example, the olivine index (OLINDEX), low-calcium pyroxene index (LCPINDEX) and high-calcium pyroxene index (HCPINDEX) CRISM CAT summary parameters (Pelkey et al., 2007) were translated into WCPS (Fig. 6A and C). These indexes are the results of math performed on a subset of CRISM bands, to spatially highlight the presence of certain minerals. They can be used within the *image()* and *rgbimage()* functions to create images:

```
WCPS> rgbimage(olindex, lcpindex, hcindex)
```

The map result of the OLINDEX, LCPINDEX, and HCPINDEX RGB combination is shown in Fig. 6A. This combination is used to capture the Martian surface diversity (Pelkey et al., 2007) as these combinations can distinguish between different mafic minerals based on their

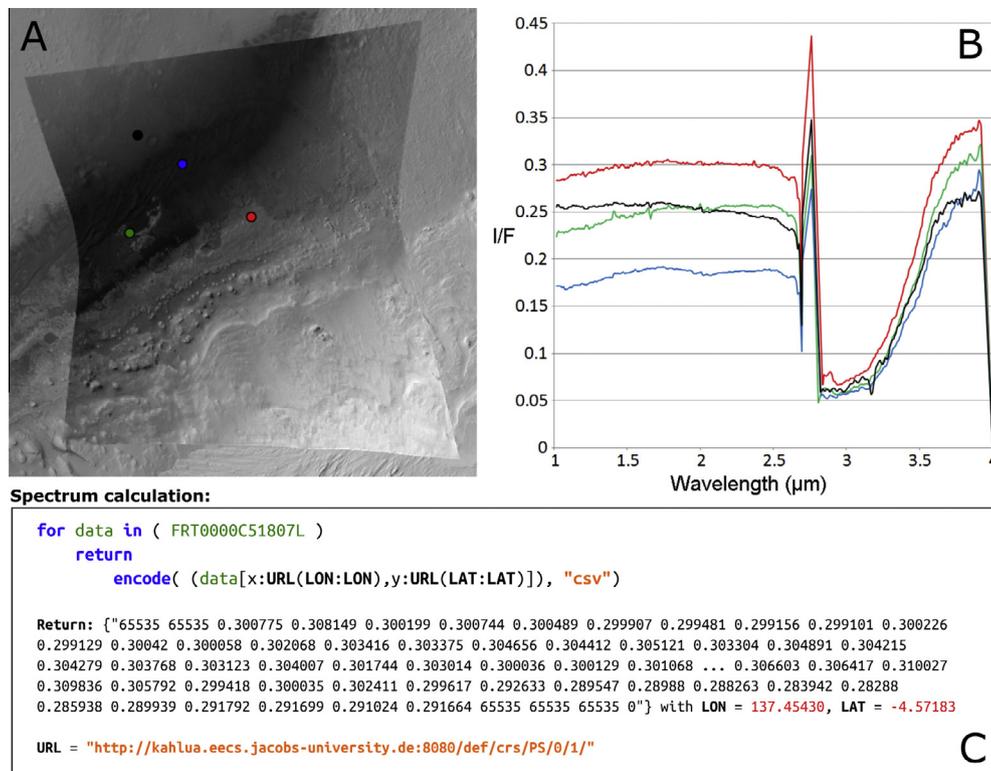


Fig. 7. (A) PlanetServer screenshot showing the location of the four spectra in Fig. 7B: (137.54065, −4.63009), (137.47816, −4.63833), (137.50528, −4.60300) and (137.48228, −4.58813). (B) CRISM raw spectra. (C) WCPS query to extract a spectrum at a certain location. The returned array of values is only partly shown as it consists of 438 values.

absorptions at specific wavelengths (around 1 μm for the olivine, 2 μm for both pyroxenes).

In the case of Gale crater, which is a sedimentary environment (e.g. Wray, 2012 and Ref. therein), spectral parameters of hydrated minerals are also useful. However, as absorption features in hydrated minerals tend to be thinner and smaller in amplitude than in mafic minerals, the resulting map is noisier. The CAT summary parameters that are commonly used to identify the presence of hydrated minerals (BD1900R, a 1.9 μm absorption band), Fe/Mg-rich clays (D2300, a 2.3 μm absorption band) and most sulfates (SINDEX, 2.4 μm drop in reflectance) were also added to PlanetServer. An RGB combination of those can be obtained by:

```
WCPS> rgbimage(bd1900r, d2300, sindex)
```

Fig. 6B shows the resulting map, and Fig. 6D the accompanying WCPS band calculations.

Both RGB combination maps (Fig. 6A and B) give good insights into the possible occurrence of certain minerals in the scene; they allow for defining mineralogically distinct units, but they are not true mineralogical maps (Pelkey et al., 2007). A supplementary spectral analysis is required to confirm the presence of a given mineral (cf. next section).

A ‘Save for GIS’ option is available in the console window. When selected, spatial calculations using image() and/

or rgbimage() are, instead of being displayed in the OpenLayers map, exported as a PNG image and accompanying PGW worldfile. The worldfile provides the georeference information allowing the PNG image to be displayed in off-line GIS software.

3.5. Spectral calculations

A spectrum, e.g. all the reflectance values at different wavelengths for a given location, can be extracted through WCPS (Fig. 7C). The quality of the spectrum depends on the quality of the solar and atmospheric signal-removal algorithm and the instrument background noise, leaving the surface signal after correction (see Section 2.5). The spectrum gives information about the mineralogy of the scene, based on its global shape (continuum) and set of absorptions. Fig. 7A and B show the PlanetServer spectrum results for four different pixels. The red, green and³ blue colored spectra locations in Fig. 7A were chosen to capture the mineralogical diversity of the scene (clay-rich, sulfate-rich, mafic-rich, respectively), with the help of the RGB combinations of summary parameters from Fig. 6A and B.

It is also possible to use PlanetServer to derive a spectral ratio of two locations (Fig. 8A). This process is commonly

³ For interpretation of color in Fig. 7, the reader is referred to the web version of this article.

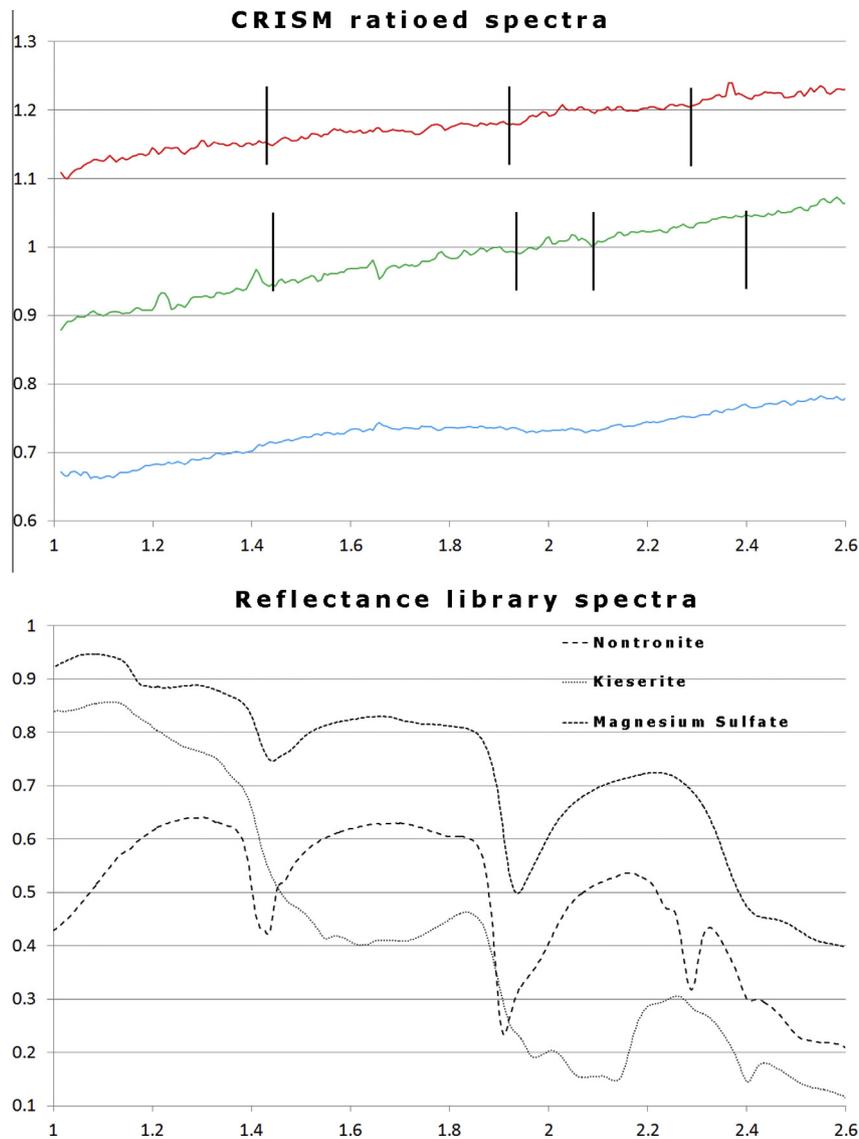


Fig. 8. (A) CRISM ratioed spectra of the locations given in Fig. 7. The fourth raw spectrum (black spectrum) in Fig. 7B, taken on the crater floor, was taken as a common denominator. The ratio technique allows for suppression of the atmospheric residue and enhancing spectral features. The vertical lines indicate the location of the key absorptions. The first spectrum (red) shows absorption bands at 1.92 and 2.29 μm , which are diagnostic of Fe-rich clays, such as nontronite. The occurrence of weak additional features at 2.21 μm indicates a likely contamination by Al-clays such as montmorillonite (not shown here). The second spectrum (green) has major absorption features at 1.43, 1.95 μm and a slight drop at 2.4 μm , characterizing polyhydrated sulfates. Additional bands at 2.1 and 2.2 μm suggest the presence of monohydrated sulfates and Al-clays as well. The third spectrum (blue) has wide absorptions around 1 and 2 μm which are similar to the ones observed in mafic minerals such as pyroxene (not shown). The increase in reflectance from 1 to 1.6 μm and the relative depth of the 1 μm band compared to the 2 μm one is indicating of the presence of olivine as well. (B) CAT library spectra of hydrated minerals are given for comparison: nontronite (sample CBJB26), kieserite (F1CC15) Mg-rich polyhydrated sulfates (799F366). The spectral library of mafic minerals (e.g., pyroxene, olivine) is not shown as it has not been implemented to PlanetServer yet. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

used to suppress residual artifacts and enhance signatures in a given spectrum (by dividing it with a spectrum of a neutral area, or comparing the spectra of two areas of interest). As an example, the red, green and blue colored spectra were ratioed using the black spectrum shown in Fig. 7A and B. This spectrum is located on the crater floor, and has a very weak mafic signature, which might affect the resulting spectrum continuum, but will not influence the hydrated mineral absorption bands. The atmospheric cor-

rection residue, around 2 μm , is mostly removed by dividing the raw spectra over this nearly 'neutral' spectrum, allowing for the identification of minerals through their remaining absorption bands. The ratio results are shown in Fig. 8A.

All user generated spectra are accessible through the PlanetServer client console window. The maximum amount of spectra in the diagram window is currently 10. A spectrum and its location can be retrieved using:

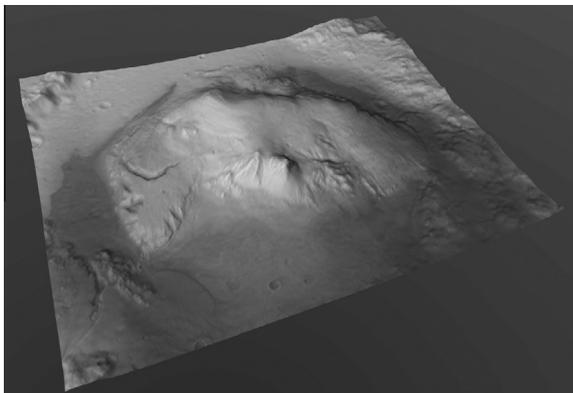


Fig. 9. Screenshot of 3D window showing a High Resolution Stereo Camera (HRSC) nadir mosaic of Gale crater draped over an HRSC DTM (see acknowledgements). The X3DOM javascript library is used for the 3D capability (Behr et al., 2009).

WCPS> $s(x)$ (x is the location number, depending on which location was clicked first)

WCPS> $p(x)$

Spectral calculations can subsequently be performed using the *spectrum()* function:

WCPS> $spectrum(s(x)/s(y))$

WCPS> $spectrum(s(x) * s(y))$

The result is shown in the diagram window. The mathematical functions available to javascript can be used, such as *Math.cos()* and *Math.sin()*:

WCPS> $spectrum(Math.cos(s(x))/s(y))$

A ratioed spectra can be compared with reference spectra, taken from the CRISM spectral library (Murchie et al., 2007). The CRISM sulfates and phyllosilicates spectral library can be accessed through the diagram window by (1) selecting the library from a list, (2) clicking 'Load' to load the library, (3) selecting the library spectrum, and (4) clicking 'Load' again to load the library spectrum in the diagram. The best match for the Fe-rich clay and sulfate-rich spectral ratios (red and green spectra, Fig. 8A), based on the exact position of their absorption features, are shown in Fig. 8B. All spectra can be saved and exported as .CSV files by clicking the save button in the diagram window.

3.6. WebGIS capability

PlanetServer uses PetaScope and the WMS protocol to add CTX, HiRISE and HRSC visual imagery datasets available in rasdaman to the OpenLayers map. The CRISM data can therefore be compared with overlapping visual imagery data. This enables geological mapping to be

performed, as the landforms and deposits associated with a mineralogical signature of interest can be observed and further characterized with visible imagery.

Currently PlanetServer contains an additional elevation data analysis demonstration. Here elevation values are based on HRSC data and can be determined as point values or as cross section lines. The demonstration also includes an online 3D viewer, which uses X3DOM (Behr et al., 2009) and enables the draping of visual imagery over an elevation data model (Fig. 9). The data is retrieved from the server through WCS and WCPS.

4. Discussion

Generally, scientists interested in investigating surface mineralogy using hyperspectral data need to use two different types of software: (1) *ENVI*, or similar software, to perform spatial and spectral analysis and (2) GIS software such as *ArcGIS* to use the ENVI-derived mineral map products together with other datasets as input for geological (e.g. mineralogical, geomorphological, structural) mapping. The data, after being downloaded, are first analyzed in ENVI as unprojected, non-GIS-ready data. It, therefore, needs to be map-projected and converted before it can be further analyzed in a GIS. Alternative or concurrent use of those software packages proves to be time consuming. With PlanetServer, on the other hand, the hyperspectral data do not need to be downloaded, are available pre-processed, and therefore, are immediately ready for analysis in a WebGIS environment. In this section the PlanetServer methodology described in Section 3 will be compared with the ENVI-GIS workflow described above. Moreover, the current limitations of PlanetServer and the planned solutions will be discussed.

In the Case Study section, it was shown that PlanetServer can be used to survey the mineralogy of an area with CRISM in a simple and time-effective way. CRISM summary parameters enabled us to scan the scene for distinct mineralogical units. By quickly analyzing the spectra of the scene manually, clay, sulfate and mafic-rich spectra were retrieved, as published in the existing literature. Moreover, mixtures and contamination by Al-clays were observed, as suggested by the comparison with reference library spectra (Fig. 8). The layers which bear the mineralogical signature were directly observed on the corresponding HiRISE and CTX observations. The exact same steps could have been undertaken with ENVI, but processing the observation and calculating each summary parameter would have required more time and work. The CRISM observation would then have to be saved in an appropriate format and projection, to be later incorporated with HiRISE and other imagery datasets into a GIS.

Still, the current PlanetServer client, combining hyperspectral analysis and WebGIS functionality, is in development and lacks many features and tools available in the

ENVI-GIS workflow. PlanetServer, for example, currently only contains a set of CAT summary products and library spectra which are especially appropriate for Gale crater, focusing on detecting clay, sulfate, and mafic minerals. Hence, more CAT summary products will be converted from IDL into WCPS. Moreover, the ability will be included for scientists to do their own band depth calculations by manually selecting the absorption feature ‘shoulders’ and ‘valley’ in the spectrum diagram. The option to adjust the stretch parameters of the WCPS-derived PNG image will be added, allowing the user to only show positive values or values larger than 0.01 (lower than this 1% threshold the band values are not considered significant). The possibility to interactively stretch the values will be investigated. More libraries will be added, including the USGS spectral library (Clark et al., 2007). The spectral libraries will be integrated, enabling scientists to overlay CRISM spectra and library spectra in the spectrum diagram for visual comparison.

Within the ENVI-GIS workflow, the functionality of deriving information within overlapping point, line and polygon features is supported. PlanetServer, on the other hand, currently only supports point and line features. A single pixel spectrum value, for example, will be returned, through WCPS, after a user click in the OpenLayers map. This value, however, is more prone to contain noise. The option to calculate average spectra for 3×3 and 5×5 binned pixels, available under ENVI, will therefore be added. This will make use of the *kernel* element of WCPS. Line features are currently supported within the PlanetServer elevation data analysis demonstration. Here, an HRSC elevation cross section line can be extracted through WCPS. The WCPS query language, however, does not support deriving information within an overlapping line directly. The line is therefore divided into 100 points and each elevation value is extracted using a WCPS query similar to Fig. 7C. Handling 100 WCPS queries takes time and therefore the ability to use WCPS to extract information overlapping a line will be further investigated. Moreover, both the elevation data analysis and CRISM hyperspectral analysis demonstrations will be integrated enabling the joint analysis of elevation and hyperspectral data in the same environment.

WCPS currently also does not support deriving information within irregular polygon features. Using ENVI, however, a user can create a Region of Interest (ROI) by manually drawing a polygon, or importing a shapefile from ArcGIS. The average spectrum within this ROI can then be determined. Within ArcGIS, the polygon could mark the irregular boundary of a geological feature visible in high resolution visual imagery, overlapping the hyperspectral data. For this to work the user needs to continuously interact with ArcGIS and ENVI. The integration of the hyperspectral analysis tools within a WebGIS, on the other hand, would allow for the drawing of polygons using various overlapping visual imagery datasets and deriving of mean spectra on-the-fly. As WCPS supports extracting rect-

angular subsets of data, therefore, as a first step, a tool will be added where the average spectrum of a user-drawn rectangle on the map can be calculated. The final step, the ability to extract information within an irregular user-generated polygon, will exploit a rasdaman feature called ‘in-situ database’. Through this technique, rasdaman can process queries on data which remain in their file and are only registered by the database server, as opposed to the standard procedure of copying data during the ingestion process. The sequence starts with the user drawing a polygon in the OpenLayers map. The polygon information is then sent to the server. On the server side, the polygon is converted to a raster and registered as an in situ data source. Following this, a WCPS query will use this temporary raster to return the average value within the masked area.

An important processing step of CRISM data (and hyperspectral data in general) is the atmospheric correction technique. For the CRISM data in PlanetServer, the volcano-scan atmospheric correction method was used (see Section 2.5). However, CRISM analysis results corrected using the emission phase function have recently been published (Dobrea et al., 2011), and implementation of this more advanced atmospheric correction method will be investigated. Compared to the ENVI-GIS workflow, one limitation of PlanetServer is that the user cannot yet easily try out different atmospheric correction methods. A possible solution is upgrading to the Map-projected Targeted Reduced Data Record (MTRDR) CRISM data, when made available by the instrument team. MTRDR CRISM data will be combined VNIR and IR products that have been photometrically and atmospherically corrected. They can, therefore, immediately be ingested into rasdaman without further CAT processing. Until MTRDR is available, the VNIR and IR products will be combined through javascript within the PlanetServer client. A separate issue is the fact that the VNIR and IR are spatially offset by a couple of pixels, as the CRISM instrument consists of two separate detectors (S and L). A possible solution would be to allow for users to manually and interactively georeference the data, as is possible using ArcGIS. Overlapping high-resolution imagery in the OpenLayers map, such as HiRISE and CTX, could then be used as a reference.

On the server side, the additional rasdaman features currently under investigation are GeoTIFF export, null value handling, on-the-fly CRS transformations (e.g. to display equirectangular projected data as part of a polar stereographic background map), and compressed data storage. Advanced issues include addition of irregular grids so that non map-projected CRISM data can be offered as well (requiring the aforementioned reprojection capability). Furthermore, point cloud support is needed to host Mars Orbiter Laser Altimeter (MOLA) Precision Experiment Data Records elevation values (Neumann et al., 2003). On the client side, the PlanetServer X3DOM (Behr et al., 2009) implementations will for now remain in separate windows, but this 3D capability hints at a full online 3D GIS environment, which PlanetServer could evolve into in the near future. And

finally, data search capabilities and user registration will be added. The former will possibly make use of the PDS Unified Planetary Coordinates database (Akins et al., 2009). The latter will allow for a user to load and save queries, PNG imagery as well as point, line, and polygon features.

An obvious constraint of PlanetServer compared to the ENVI-GIS workflow is the currently still limited amount of data, focusing on Gale crater. Therefore, for PlanetServer to become of general use, it is planned to batch-ingest a variety of Mars datasets into rasdaman. In addition to the 18 m/pixel CRISM Full Resolution Target (FRT), other Targeted Reduced Data Records (TRDR) products (36 m/pixel Half Resolution Long (HRL) and Half Resolution Short (HRS)) will be added. CRISM Multispectral Reduced Data Records (MRDR) products (100 m/pixel Multispectral windows (MSW) and 200 m/pixel Multispectral survey (MSP)), which are multispectral (72 bands) observations taken when the instrument points at nadir, will also be included. Besides CRISM data, HiRISE (McEwen et al., 2007), CTX (Malin et al., 2007), and HRSC visual imagery and elevation data (Neukum et al., 2004) will be added to PlanetServer, enabling geological mapping. And where possible, other WMS and WCS Mars data sources available online will be used. Finally, derived products and datasets available from other missions and experiments, such as OMEGA (Observatoire pour le Mineralogie, l'Eau, les Glaces et l'Activite, Bibring et al., 2004) on board European Space Agency (ESA) Mars Express, will be considered and potentially added to complement the datasets already available in terms of spatial extent, scale, and resolution. Due to the limit of tens of TB of storage, ingestion will focus on regions of interest, provided by the PlanetServer Team. Also feedback from the Mars geoscience community will be collected.

The main focus of PlanetServer is currently the planet Mars, integrating access to CRISM hyperspectral data and Mars visual imagery datasets within a WebGIS. WCPS, however, can also be used to analyze other hyperspectral data such as the terrestrial EO1 Hyperion (Pearlman et al., 2001) and the Lunar Chandrayaan M3 data (Pieters et al., 2009). Other data types such as ground penetrating radar data from the SHallow RADar (SHARAD) (Seu et al., 2007) on board the NASA Mars Reconnaissance Orbiter could be added. The system is therefore flexible and can be adapted for various needs, not only for the planetary community, as the EarthServer project already shows. PlanetServer, within the 'Geoprocessing Web', is a first step in moving away from offline data analysis. It will have the potential to enable collaborative research, as scientists from different institutions and locations can analyze the same data 'in the cloud'. Therefore adding further collaborative features will be considered. PlanetServer has also potential, being currently evaluated, for cost-effective teaching, education and outreach applications. The community targeted could also be broadened by using PlanetServer for online education purposes within Coursera (www.coursera.org, Severance, 2012) or similar services.

5. Conclusion

PlanetServer is currently at demonstration stage showing how WCPS can be used to analyze and visualize CRISM data online. However, it is rapidly evolving and the final "production" PlanetServer will offer an advanced WebGIS environment with integrated spatial and spectral analytics. It will give access to global Mars visual and hyperspectral imagery and elevation datasets.

To conclude, the rasdaman Array DBMS with its OGC WCPS query language facility used in PlanetServer enables online analysis of hyperspectral CRISM data in a WebGIS environment, whereas until now the data had to be analyzed offline and manually imported into a GIS. This technology therefore has the potential to be a key part of an advanced WebGIS environment. Inputs from the Planetary Science community and individual researchers are welcome contacting the authors using the contact form on <http://planetserver.eu>.

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