FITS Format for Planetary Surfaces: Definitions, Applications, and Best Practices

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Key Points:
- We present an extension of FITS metadata for planetary surface investigations
- A FITS description for planetary data aims to simplify sharing data across the astronomy and planetary domains
- An open FITS portrayal will promote interoperability from raw data formatting to final visualization

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FITS Format for Planetary Surfaces: Definitions, Applications, and Best Practices

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Abstract Planetary science encompasses a broad number of research fields and brings together several research communities (geologists, astronomers, physicists, geochemists, etc.). Planetary missions produce an impressively growing amount of diverse data requiring an evolution from a mostly manual-based visual analysis to a more automated and quantitative analysis. Interoperability, openness of data formats, and shared processing techniques are a necessity to efficiently extract scientific information from the data and to guarantee the reproducibility of the scientific results. Unfortunately, the technologies and data formats used by researchers for planetary surface studies and the field of astronomy diverged as these related, but almost completely isolated, domains evolved. In this paper we will describe how a small addition to the Flexible Image Transport System (FITS) standard, widely used in the astronomy investigations, will allow FITS to be more easily used in planetary surface investigations. We will also show how FITS metadata can easily be transformed in the Planetary Data System version 4 metadata archival model and lastly provide example implementations. More than imposing a formal data model, a FITS description for planetary data aims to simplify sharing data across the planetary and astronomy domains and promoting interoperability from raw data formatting to final visualization.

1. Introduction

Planetary science encompasses a broad number of research fields and brings together several research communities (geologists, astronomers, physicists, geochemists, etc.). Planetary missions produce an impressively growing amount of diverse data requiring an evolution from a mostly manual-based visual analysis to a more automated and quantitative analysis. Interoperability, openness of data formats, and shared processing techniques are a necessity to allow efficient scientific analysis of the data and to guarantee the reproducibility of the results.

This paper proposes to use Flexible Image Transport System (FITS; https://fits.gsfc.nasa.gov/) format (Pence et al., 2010; Wells et al., 1981) in planetary surface investigations and describes how FITS metadata can easily be inserted in the Planetary Data System (PDS) version 4 (https://pds.nasa.gov/tools/standards-reference.shtml) metadata distribution model. FITS is one of the standard formats implemented in the Virtual Observatory (VO; http://www.ivoa.net/astronomers/using_the_vo.html), therefore making obvious its connection to the Planetary VO initiative and the planetary Table Access Protocol (EPN-TAP; Erard et al., 2014). FITS format is open, flexible, and largely implemented in open and efficient processing tools allowing to handle large amounts of raster data. The goal of this approach is to make easier data mining and reprocessing in planetary surface investigations, promoting general software based on those standards. The option to use FITS within the planetary surface domain can help to homogenize methods from raw formatting to visualization, while allowing for optimized data processing across the planetary and astronomy domains.

2. FITS Format in Planetary Surface Investigation

2.1. FITS Format

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 spatial 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.

FITS format is supported by a large number of open libraries and software tools, developed in numerous languages. The reference C and Fortran library, CFITSIO (https://heasarc.gsfc.nasa.gov/docs/software/fitsio/fitsio.html), is maintained by the NASA's High Energy Astrophysics Science Archive Research Center, and it comes with a number of interfaces for other languages (C++, C#, Perl, Python, MatLab, etc.). Independent libraries are available, for example, in JAVA, go, Python, R, IDL, and many other languages (a nonexhaustive list is available at https://fits.gsfc.nasa.gov/fits_libraries.html). Software tools for visualization and analysis make use of those libraries or implement their own, having different levels of maturity and option completeness (see https://fits.gsfc.nasa.gov/fits_viewer.html).

FITS is already capable of being used as a 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, as well as multidetector imagery (e.g., from HiRISE, McEwen et al., 2007) or hyperspectral cubes with geometry information (e.g., from CRISM, Murchie et al., 2007, or OMEGA, Bibring et al., 2005, 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 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 spatial missions were more familiar with Earth observation techniques and standards than the astronomy one. Furthermore, the standardization 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 longer, FITS format is already more popular.

With the impressive increasing of raster data from planetary missions, the efficient automatization of data processing is an issue. Metadata, historically optimized for archiving, are not always ready for efficient processing. FITS metadata schema can be a solution to this problem.

To be more efficiently used in planetary surface investigations, FITS metadata must be thoroughly mapped to planetary geospatial concepts. Then, they must be extended in order to take into account the size of the reference body and orientation as standardized by the IAU Working Group on Cartographic Coordinates and Rotational Elements (WGCCRE). This group reports triennially (Archinal et al., 2011) on the preferred rotation rate, spin axis, prime meridian, and reference surface for planets and satellites ensuring that cartographic endeavors are effectively comparable. In the framework of the Virtual European Solar and Planetary Access (VESPA; http://europlanet-vespa.eu/; Erard et al., 2018) workpackage of the EuroplanetRI2020 (http://www.europlanet-2020-ri.eu/) project an extension to FITS metadata (GeoFITS) has been proposed (https://voparis-confluence.obspm.fr/display/VES/GeoFITS:+Planetary+Data+FITS+format+and+metadata+convention), taking into account the WGCCRE recommendations.

2.2. Planetary Surface Proposed Convention

To facilitate surface investigations, data taken of a planetary surface should be radiometrically calibrated and orthorectified (when topographic data are available) into a well-known map projection as required by Geographical Information Systems (GIS) applications. In general, GIS applications excel in planetary data set integration and interoperability even though some have historically been anchored to Earth's spatial description. Often, robust interoperability in GIS applications is achieved by using the Geospatial Data Abstraction Library (GDAL; http://www.gdal.org), released by the Open Source Geospatial Foundation. GDAL is essentially

10.1029/2018EA000388

Table 1
Projection Names and Codes Available in World Coordinate System FITS, Suitable for Planetary Applications: the Corresponding PDS4 Terminology is Provided

FITS Name[a]	FITS code[a]	PDS4 name[b]
Zenithal Equidistant	ARC	Azimuthal Equidistant
Zenithal Perspective	AZP	General Vertical Near-sided Projection
Plate Carre	CAR	Equirectangular, Miller Cylindrical
Equidistant Conic	COD	Equidistant Conic
Conic Equal-Area	COE	Albers Conical Equal Area
Conic Ortomorphic	COO	Lambert Conformal Conic
Mercator	MER	Mercator, Oblique Mercator, Transverse Mercator
Polyconic	PCO	Polyconic
Sanson-Flamsteed	SFL	Sinusoidal
Ortographic	SIN	Orthographic
Stereographic	STG	Stereographic, Polar Stereographic
Gnomonic	TAN	Gnomonic
Zenithal Equal-Area	ZEA	Lambert Azimuthal Equal Area

Note. FITS = Flexible Image Transport System; PDS4 = Planetary Data System (version 4).
[a]From Calabretta and Greisen (2002). [b]From the PDS4 Data Dictionary.

a format translation library written in C++ for geospatial raster and vector data and, fortunately, it also offers basic support for the FITS format, however missing a FITS metadata dictionary.

FITS World Coordinate System (WCS) representation (http://fits.gsfc.nasa.gov/fits_wcs.html) is the standard way to describe spatial dependencies in FITS metadata. WCS simplifies the spatial coordinate description with respect to historical terrestrial references. For instance, there is no need for oblique projection definitions (Calabretta & Greisen, 2002; Snyder, 1987) as projection parameters (projection center or reference point) describe the difference between, for example, the Mercator and Oblique Mercator or Simple Cylindrical and Equirectangular map projections. This simplification is effective when a spherical local approximation is applied on planetary imagery. This is particularly the case with growing image resolutions and increasing computing capabilities: spherical projections with a local radius definition are easier to reproject from one system to another than from or to a global spheroidal datum. As an example, the HiRISE team has chosen to distribute HiRISE projected products using Equirectangular projection on a local surface, approximated by the sphere with radius equivalent to the local Mars spheroid radius.

In addition, WCS resolves the ambiguity between east-positive and west-positive longitude systems, as the pixel conversion in world coordinates is set by an oriented matrix. If needed, FITS does offer the possibility to fully describe the projected coordinate system using several alternative WCS definitions (meters, degrees, east and west longitude, etc.; Greisen & Calabretta, 2002).

Table 1 summarizes the FITS projection codes and their corresponding PDS4 projection names (see Table A.1. in Calabretta & Greisen, 2002, for details).

Once reprojected in one of the standard projections listed in Table 1, planetary images or maps can be described using the WCS scheme (Calabretta & Greisen, 2002; Greisen & Calabretta, 2002). In WCS context pixels are first translated in an intermediate pixel coordinate system via linear transformations, then mapped on the grid specified by the `CTYPE` keyword, containing the projection code and the coordinate system. The coordinate system must be defined with respect to a specific inertial reference frame. Multiple coordinate system descriptions are allowed in the same header: this is a valuable property for planetary surface imagery, as angular ("deg") and linear ("m") description of the surface are often needed at the same time. Further, below 3-D keywords will be proposed for FITS metadata, in order to standardize the conversion between angular and linear coordinates: alternate description will still be important in our framework as standard libraries (e.g., wcslib [http://www.atnf.csiro.au/people/mcalabre/WCS/wcslib/] or astropy [http://www.astropy.org/], Astropy Collaboration et al., 2013) and some FITS visualization software (e.g., ds9 [http://ds9.si.edu/]) already implement them, making linear coordinate tracking more efficient.

Table 2
Codes to be Used in CTYPE Flexible Image Transport System Keyword in Order to Identify the Planetary Body

Body	CTYPE[a]
Moon	SE
Mercury	ME
Venus	VE
Mars	MA
Jupiter	JU
Saturn	SA
Uranus	UR
Neptune	NE
Satellites (other than the Moon)	ST
Asteroids[b]	AS
Dwarf Planets	DW
Comets	CO

Note. Codes for planets are implied in Calabretta and Greisen (2002). We propose to add codes for classes of targets, more or less corresponding to Planetary Data System version 4 Target type attribute and to EuroPlaNet Table Access Protocol target_class parameter.
[a]From Calabretta and Greisen (2002). [b]Transneptunian (TNO) and Kuiper Belt (KBO) objects must be placed there.

2.2.1. FITS WCS Keywords and Their Recommended Use in Planetary Surface Context

In this section WCS FITS keywords are inserted in the planetary surface context. When possible, corresponding PDS4 and EPN-TAP definitions are added for archiving and distribution standardization purposes.

1. RADESYS. Name of the inertial reference frame with respect to which the coordinate system is defined. Standard FITS defaults this keyword to `ICRS`. This is applicable to planetary data too as long as the planetary coordinate system parameters, that is, the rotational elements, are defined with respect to `ICRS`. This is the case starting from the 2003 WGCCRE report (Seidelmann et al., 2005). Before the 1982 WGCCRE report (Davies et al., 1983) the inertial system was `FK4`, after it was `FK5`.
2. EQUINOX. The value field contains the equinox in years for the celestial coordinate system in which positions are expressed. Standard FITS defaults this keyword to `J2000`. This is applicable to planetary data starting from the 1982 WGCCRE report (Davies et al., 1983). Before 1982 the standard equinox was `B1950`.
3. WCSAXES. Number of axes in the WCS description. The value of WCSAXES may exceed the number of raster pixel axes. WCSAXES is, for example, generally set to 2 in two-dimensional rasters, it could be set to 3 if an additional time or filter dependency is added to the coordinate description.
4. WCSNAME. Name of world coordinate descriptions (e.g., body-fixed rotating—ocentric—ographic, nonrotating, inertial). EPN-TAP provides similar information through the `spatial_coordinate_description` parameter.
5. CRPIXn. Location of a reference point along axis *n*, in units of the axis index. The reference point value do not need to lie within the actual data array.
6. CTYPEn. Name of the coordinate represented by axis *n*, in "4–3" form: the first four characters specify the coordinate type, the fifth character is a "-" and the remaining three characters specify an algorithm code for computing the world coordinate value (see Table 1). For angular coordinates Calabretta and Greisen (2002) provide the form xLN xLT or yzLN yzLT, where x or yz correspond to the target body. We propose to standardize those codes as listed in Table 2. For projected coordinates in meters we propose a similar scheme: xPX as Projected X, xPY as Projected Y, or yzPX and yzPY. Alternative representation of WCS are already possible in FITS to describe images in degrees and in meters (Greisen & Calabretta, 2002). The name of the alternative axis will be specified using the alternative CNAMEn keyword.
7. CRVALn. Value of the coordinate specified by the CTYPEn keyword at the reference point CRPIXn.
8. CDi_j. The *ij* linear transformation matrix (rotation, skewness, scaling) defining the intermediate world coordinates.

Table 3
Proposed Keywords are Related to 3-D Surface Shape, not Available in Astronomical Celestial Standards

Keyword	Type	Status	Definition
WGCCRECS	String	Reserved	Value field contains a string referring to the WGCCRE report or document defining the coordinate system describing the data. (DOI)
A_RADIUS[a]	Real	Mandatory	Value field contains the semimajor axis of the ellipsoid that defines the approximate shape of a target body used in projection. "A" is usually in the equatorial plane. Always in meters.
B_RADIUS[a]	Real	Mandatory	Value field contains the value of the intermediate axis of the ellipsoid that defines the approximate shape of a target body used in projection. "B" is usually in the equatorial plane. Always in meters.
C_RADIUS[a]	Real	Mandatory	Value field contains the value of the semiminor axis of the ellipsoid that defines the approximate shape of a target body used in projection. "C" is normal to the plane defined by "A" and "B." Always in meters.
OGCCODE	String	Reserved, optional	Value field contains a string describing the standard Open Geospatial Consortium (OGC) code (if any) from Hare et al. (2006) corresponding to the shape and projection used in the image. This keyword will assure compatibility with standard GIS softwares.

Note. GIS = Geographical Information Systems.
[a]Note that International Astronomical Union Working Group defines a mean radius for each Solar System body. When this Mean Radius is used in projection definition, the three keywords A_RADIUS, B_RADIUS, and C_RADIUS, must be set to the same value of the defined Mean Radius.

9. PCi_j. The *ij* linear transformation matrix (rotation, skewness) defining the intermediate pixel coordinates (to be used with CDELT keywords).
10. CDELTn. The coordinate increment along axis *n* (scaling component of the linear transformation matrix PCi_j). They correspond to the `pixel_resolution_x` and `pixel_resolution_y` attributes in PDS4 and to the `spatial_resolution` parameter in EPN-TAP.
11. CUNITn. Units of the coordinate system. This is a not mandatory keyword: when not present FITS standard assumes its value as degrees, the most common description in astronomical sky images. The same can be assumed for planetary surfaces: when linear coordinates are used SI units must be used (meters, m).
12. CNAMEn. The description of a particular coordinate for an axis in a particular WCS (up to 68 characters), while the WCSNAMEn keyword names the particular WCS as a whole. Its default value will be blank.

Nevertheless, WCS does not record information about the body shape and orientation and reference surface. Table 3 summarize the keywords we propose to add to FITS metadata description.

2.2.2. Correspondence Between Reserved FITS Keywords and PDS4 Standard Reference

The correspondence between mandatory and reserved FITS keywords, as defined in the last version of the FITS standard document (https://fits.gsfc.nasa.gov/standard40/fits_standard40aa.pdf) and PDS4 attributes, is described here.

1. `BITPIX`. It specifies the number of bits that represent a data value in the associated data array. PDS4 uses the attribute `data_type`: corresponding values depend on the associated object class.
2. `NAXIS`. It contains a nonnegative integer representing the number of axes in the associated data array. A value of zero signifies that no data follow the header. PDS4 uses `axes`, always defined as a nonnegative integer.
3. `NAXISn`. It contains a nonnegative integer representing the number of elements along axis `n` of a data array. The `elements` attribute of the PDS4 `Axis_Array` class provides the count of the number of elements along an array.
4. `BUNIT`. It contains a string, describing the physical units in which the quantities in the array are expressed. The units of all FITS header keyword values should conform with the recommendations in the IAU Style Manual (https://www.iau.org/publications/proceedings_rules/units/). For angular measurements given as floating-point values, degrees are the recommended units (with the units, if specified, given as "deg"). PDS4 specifies in the class Element (of a vector, array, or any other class containing Elements), a `unit_id` (unit abbreviation) and a `unit` (unit long name).

10.1029/2018EA000388

5. BSCALE. It contains a floating-point number representing the coefficient of the linear term in the scaling equation *physical_value = BZERO + BSCALE × array_value*, the ratio of physical value to array value at zero offset. For all classes containing Elements, PDS4 defines a scaling_factor attribute. Both FITS and PDS4 default this value to 1.
6. BZERO. It contains a floating-point number representing the constant term in the scaling equation *physical_value = BZERO + BSCALE × array_value* For all classes containing Elements, PDS4 defines a value_offset attribute. Both FITS and PDS4 default this value to 0.
7. BLANK. This keyword must be used only with integer data. It contains an integer that specifies the value that is used to represent pixels that have an undefined physical value. On floating-point data the IEEE NaN must be used to represent undefined values. It is comparable with the invalid_constant or missing_constant in PDS4 Special Constants class.
8. DATAMAX. It always contains a floating-point number, giving the maximum valid physical value represented by the array, excluding any IEEE special values. PDS4 defines a valid_maximum attribute in the Special Constants class having this same meaning.
9. DATAMIN. It always contains a floating-point number, giving the minimum valid physical value represented by the array, excluding any IEEE special values. PDS4 defines a valid_minimum attribute in the Special Constants class having this same meaning.
10. DATE. It contains the date on which the file was created, provided as ISO 8601 string. PDS4 provides a creation_date_time attribute defining date and time of product creation.
11. DATE-OBS. It contains the date of the observation, provided as ISO 8601 string. The value shall be assumed to refer to the start of the observation, unless another interpretation is clearly explained in the comment field. It is assumed to be expressed in Universal Time (UTC) but other systems are accepted as long as they are specified in the ISO string(See Table 30 in the Standard FITS document, https://fits.gsfc.nasa.gov/standard40/fits_standard40aa.pdf). PDS4 provides a Time_Coordinates class with attributes start_date_time and stop_date_time providing start and stop date and time appropriate to the product being labeled, always in UTC. The time_min and time_max fields are mandatory in the EPN-TAP scheme, they must always be formatted in UTC as an ISO string (planned in EPN-TAP v2.1).
12. INSTRUME. It contains a character string identifying the instrument used to acquire the data. PDS4 provides an Instrument class which attribute Name ideally corresponds to this FITS keyword. EPN-TAP provides with an instrument_name parameter.
13. TELESCOP. It contains a character string identifying the telescope used to acquire the data. The PDS4 Instrument_Host class provides the description of the physical object mounting the instrument. Its Name attribute should correspond to the FITS keyword. PDS4 also provides for the definition of a Telescope class, in case of ground-based observations. In the EPN-TAP scheme this is introduced by the instrument_host_name parameter (https://naif.jpl.nasa.gov/pub/naif/toolkit_docs/FORTRAN/req/naif_ids.html#Spacecraft).
14. OBJECT. It contains a character string giving a name for the observed object (https://naif.jpl.nasa.gov/pub/naif/toolkit_docs/FORTRAN/req/naif_ids.html\#Planets%20and%20Satellites). The PDS4 Target class contains the name attribute corresponding to this FITS keyword. EPN-TAP standard also provides with a target_name parameter. Notice that PDS4 and EPN-TAP also ask for a target_type attribute, which must be specified from an enumerated list.
15. ORIGIN. It contains string identifying the organization or institution responsible for creating the FITS file. No clear correspondence for this reserved FITS keyword is available in PDS4. This is because PDS4 is focused on referencing the authors of the data collection and its metadata curation, not the data producer itself. Yet the content of the ORIGIN keyword can be inserted in a PDS4 comment.
16. REFERENC. It contains a character string citing the bibliographic reference where the data are first described. It is recommended that either the Astrophysics Data System bibliographic databases (http://adswww.harvard.edu/) bibliographic identifier or the Digital Object Identifier (http://doi.org; DOI) be used. PDS4 External_Reference class and EPN-TAP bib_reference have exactly the same meaning and use than the FITS keyword.

2.3. Examples and Best Practices

2.3.1. Visualization of Global and Projected Maps

High level products are meant to be used for visual inspection or GIS analysis. They are distributed as projected rasters, often in GeoTIFF (http://geotiff.osgeo.org/) format, as GeoTIFF make them GIS ready. Given

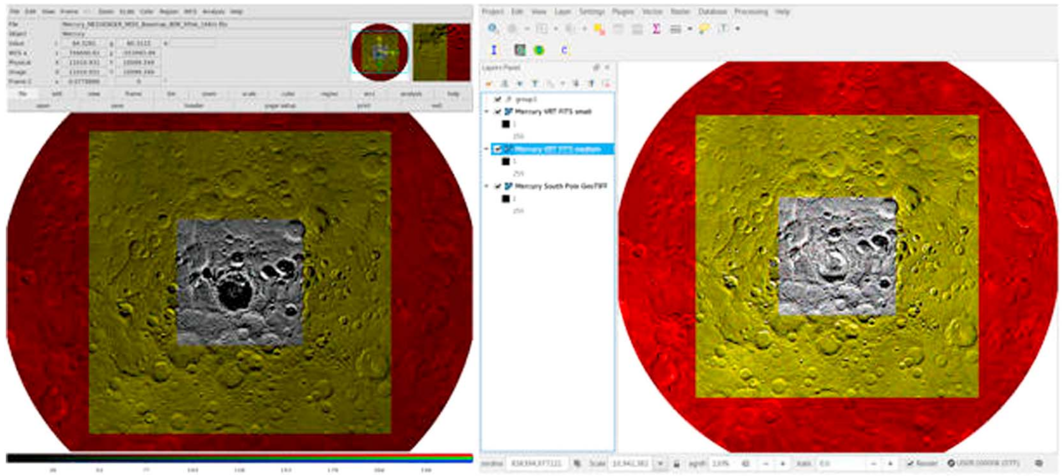

Figure 1. (left) Mercury South Pole FITS images displayed in ds9, alternate coordinates in meters are displayed; (right) GeoTIFF raster (displayed in red) and the two virtual headers linked to FITS rasters (displayed in green and blue); the three layers are perfectly superposed. Mercury image credits: MESSENGER Team, Arizona State University, Johns Hopkins Applied Physics Laboratory, Carnegie Science.

some new keywords introduced in FITS and WCS definitions adapted to planetary surface, FITS and GeoTIFF are completely interchangeable. As an example we have downloaded a Mercury polar map from the United States Geological Survey PDS Annex (https://astrogeology.usgs.gov/search) and converted it in FITS. The FITS image has been cropped in two smaller versions using the open source software SWarp (https://www.astromatic.net/software/swarp; Bertin et al., 2002): SWarp was able to automatically manage WCS planetary information. We used ds9 to display the three FITS images and were able to correctly align them. Linear coordinates in meters are visualized (see Figure 1, left side) as in QGIS, a popular open source GIS software, thanks to the alternate coordinate description.

Assuming projected products are distributed in FITS format, a quick method to add GIS support for FITS images is to use a GDAL-supported detached header. GDAL Virtual Header (http://www.gdal.org/gdal_vrttut.html) files simply describe the internal structure of a FITS image, but also the map projection and body size in a standardized "well-known text" projection string. As a result, the FITS raster loaded into QGIS thanks to its corresponding GDAL Virtual Header is indistinguishable from the GeoTIFF layer (see Figure 1, right side).

In order to load FITS files in GIS software, it is recommended to have body radii and linear coordinates filled in. Information about invalid values (NoData values) and minimum and maximum values are useful to correctly display the image dynamics.

2.3.2. OMEGA Spectra and Geometry Data

As stressed above, having planetary data distributed in FITS at any processing level is a way to avoid multiple conversions in the processing chain and to simplify reprocessing. In planetary science spatial information is first provided for specific points over the detector (the four corners of the detector, the center of each pixel, one or more pixel corners, etc.). To support in FITS metadata such look-up table coordinate representation the `TAB` algorithm has been defined in Greisen et al. (2006). In the `TAB` algorithm, coordinates are listed in a coordinate array, an indexing vector can be used to address coordinate array elements. Coordinates can then be sampled more or less coarsely depending on the behavior of the spatial reconstruction. Also, when the field is only partially covered by the planetary surface, coordinate array dimensions can be significantly reduced. TAB projection is implemented in the Calabretta WCSLIB (http://www.atnf.csiro.au/people/mcalabre/WCS/wcslib/), available in all major linux distribution.

As an example of nonprojected planetary data we have converted in FITS format some data acquired by the imaging spectrometer OMEGA on-board of Mars Express. OMEGA unprojected and uncalibrated data (level1b) are distributed by ESA Planetary Science Archive (Besse et al., 2018). Their structure is described in the OMEGA Experiment Archive Interface Control Document (ftp://psa.esac.esa.int/pub/mirror/MARS-EXPRESS/OMEGA/MEX-M-OMEGA-2-EDR-FLIGHT-V1.0/DOCUMENT/EAICD_OMEGA.PDF).

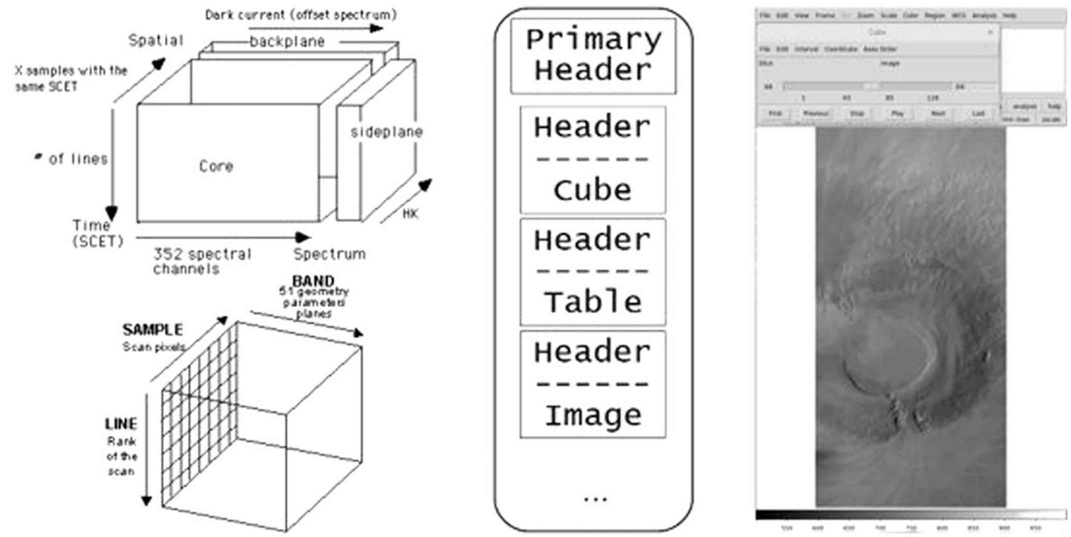

Figure 2. (left) OMEGA data structure (from OMEGA EAICD), science data, and geometry description are distributed in different files; (center) Flexible Image Transport System Multi Digital Object scheme; as an example, we stored the spectral data in the first cube extension, the coordinate look-up table in the second extension, and other geometry parameters (incidence and emission angle, etc.) as images in the following extensions; (right) Band Sequential cube visualization with ds9.

OMEGA rasters are equally sampled all over the field: we use them to exemplify TAB description without indexing. In addition, as geometrical description depends on the observation filter, this allows us to distribute a file for each filter, containing science and geometry data. The spectral cubes have been converted from Band Interleaved per Line to Band Sequential in order to make them easily understandable when visualized using standard FITS viewer (as ds9 in Figure 2; the output result can be downloaded at the address https://github.com/cmarmo/convertofits/releases/download/v1.0-beta/orb0413_1.IR1.fits.gz together with the python script used for conversion https://github.com/cmarmo/convertofits/blob/master/omega2fits.py).

The `wcsware` tool (available in the `wcslib-utils` package in Fedora distribution, in the `wcslib-tools` in Debian) had been run on the output file, validating the WCS structure and checking the ability to convert to (`wcsware -w`) and from (`wcsware -x`) pixel and planetary surface coordinates.

2.3.3. Akatsuki Imaging Data

The Venus Climate Orbiter Akatsuki(http://akatsuki.isas.jaxa.jp/en/) is a JAXA spacecraft dedicated to the study of the Venus atmosphere. Akatsuki imaging data are already distributed in FITS format. Geometry information is distributed in two different cubes of data, containing, respectively, values at the center of the pixel and at the lower left corner of the pixel. Tabular coordinate representation allows us to gather geometry in one table together with the described raster. In addition to that, in Akatsuki images Venus is sometime far from completely filling the field: tabular representation avoids to store unnecessary data. In that case, coordinate indexes are necessary to identify which pixels contains the spatial information (The output result can be downloaded at the address https://github.com/cmarmo/convertofits/releases/download/v1.0-beta/ir1_20160415_070351_097_l2b_v10_out.fit.gz together with the python script used for conversion https://github.com/cmarmo/convertofits/blob/master/akatsukil2b.py).

Again, we used `wcsware` to validate the WCS structure and to test pixel to world/world to pixel coordinate conversion. Even though TAB projection is not fully implemented in FITS visualization tools, this representation has the advantage to store the detector geometrical information together with physical quantities measured by the detector itself in a standardized way.

3. Interoperable Software Developments

In section 2.2 the mapping between planetary metadata concepts and FITS metadata description has been addressed. In order to impulse the use of FITS in planetary sciences this section will provide some example efforts of implementation of the proposed mapping. On remote sensing side, our goal is to get FITS into habits of geospatial developers, improving GDAL and QGIS compatibility with FITS. On the other side, planetary

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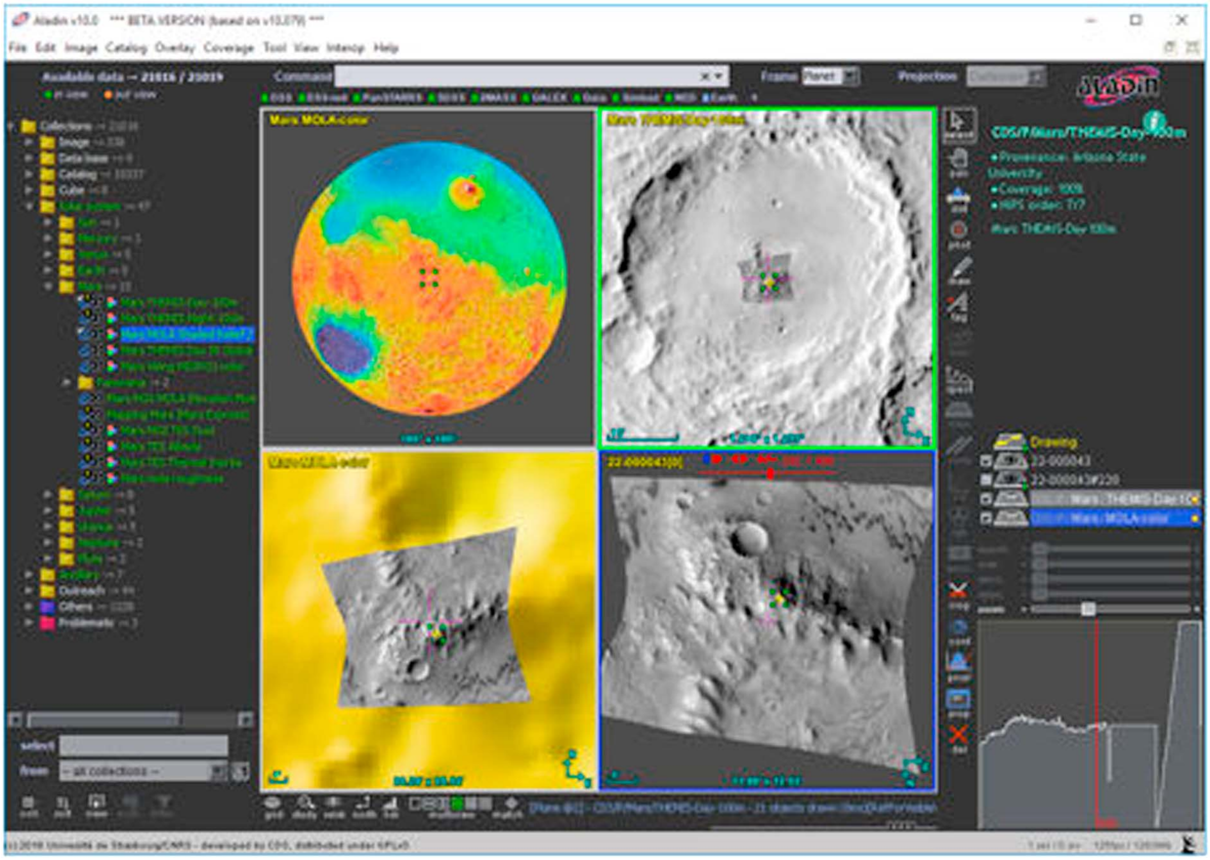

Figure 3. Visualization of several level of detail on Mars with Aladin: from the global topographic map, as a Hierarchical Progressive Survey layer, to a high resolution Compact Reconnaissance Imaging Spectrometer for Mars spectral cube in Flexible Image Transport System format. All spectral analysis tools useful for astronomical spectra are then available for planetary data.

astronomers will benefit of a FITS efficient description of their data, once the new keywords fully implemented in their traditional tools. We provide here two examples chosen within the Europlanet VESPA collaboration.

3.1. FITS and GDAL

Basic conversion from and to FITS is already supported by GDAL. However, dictionaries for precisely translate geospatial metadata are not implemented yet. The conversions described in section 2.3.1 have been performed using python scripts available from the VESPA github repository (https://github.com/epn-vespa/fits2vrt). Those python developments benefit from the rich and well-maintained Astropy and GDAL python APIs. They will be implemented in planetary VO services with the goal to bridge between GIS and VO services. The next step will be to directly implement metadata translation into the GDAL library. This work is already in progress, and new developments are available from the VESPA github repository (https://github.com/epn-vespa/gdal).

3.2. FITS and QGIS

QGIS is a largely used open source geospatial analysis software. It is using GDAL for layer import: QGIS is then already capable to display FITS files, making use of a Virtual GDAL header, as described above. Once implemented in GDAL, FITS will officially become a supported format by QGIS.

In addition to that, a QGIS plugin has been developed (https://github.com/epn-vespa/VO_QGIS_plugin;) in order to download and display files exposed via EPN-TAP servers.

3.3. MATISSE

MATISSE (https://tools.ssdc.asi.it/matisse.jsp; Multipurpose Advanced Tool for the Instruments for the Solar System Exploration; Zinzi et al., 2016) is the webtool designed by the Space Science Data Center of the Italian Space Agency to access, visualize, and analyze data from solar system exploration missions. Currently, MATISSE provides access to public data from five different targets (i.e., Mercury, Venus, Mars, the dwarf planet Ceres, and the asteroid Vesta). MATISSE 2-D outputs are formatted as FITS, in equirectangular projection and in planetocentric coordinates. The planetary FITS standard described in this work has been implemented in MATISSE in order to make the output file compliant with most FITS readers, especially DS9 and JS9. The files generated by MATISSE could be also opened with standard GIS software (e.g., QGIS, ArcGIS) after being provided as input of the fits2vrt Python library (https://github.com/epn-vespa/fits2vrt), whose output is a `.vrt` GDAL Virtual Header pointing to the FITS file with the appropriate projection. Thanks to this approach, in the next major release of MATISSE (v2.0, planned to be online by the end of 2018) JS9 will be the standard reader for the 2-D online output of the tool, thus allowing users to perform advanced analysis in both 2-D and 3-D directly inside a web-based environment.

3.4. Aladin

Aladin is both a sky atlas and a portal to access data, mainly images and catalogs, available through the VO. Aladin is able to load FITS files and to display images taking into account various WCS projections. So far it is also the reference generator and visualizer of Hierarchical Progressive Survey (HiPS). HiPS (http://www.ivoa.net/documents/HiPS/) is a recommendation endorsed by the International Virtual Observatory Alliance. It describes how to access to sky survey data stored at various spatial resolutions, offering a progressive view of possibly very large data sets. HiPS are usually generated from a collection of WCS tagged FITS files. Aladin (http://aladin.u-strasbg.fr/; Bonnarel et al., 2000) and its HiPS generator have been updated to support planetary conventions (see Figure 3).

In the future, Aladin will be able to recognize the FITS keywords defined in the present paper (see Tables 1 and 2). Finally, among the WCS projections listed in Table 1, several of them are barely used in extrasolar astronomy and are not supported in Aladin yet. An effort has been started to revamp and update the code of projections in Aladin.

4. Discussion and Perspectives

An extension to the FITS standard has been proposed to encompass planetary surface data description. Planetary surface investigation is lacking open and general software for massive data processing and can benefit from astronomy experience in this field.

We understand that some believe FITS has grown too old for newer astronomical applications (e.g., Thomas et al., 2015). We are also not convinced that one format can solve all the issues faced from long-term archiving to online streaming. But we want to stress that using FITS can be an efficient compromise. FITS can become the format that allows the astronomy and the planetary science research communities to more easily share data across domains, allowing for reduced data format conversions during processing and easy conversion for final archival products.

FITS is an open and flexible data and metadata exchange and archiving format, its use in the PDS4 data model scheme would solve the issue of complex metadata and data relationships separating data processing and the data archiving processes.

The integration of FITS specifications in the GDAL library will be finalized soon. In the framework of the VESPA project a review of the available and planned mission data archives is ongoing in order to evaluate their insertion in the planetary VO structure with a possible on-demand conversion in FITS format.

Acronyms

AMICA	Asteroid Multi-band Imaging Camera
BIL	Band Interleaved per Line
BSQ	Band SeQuential
CRISM	Compact Reconnaissance Imaging Spectrometer for Mars
DOI	Digital Object Identifier
EAICD	Experiment Archive Interface Control Document
EPN-TAP	EuroPlaNet Table Access Protocol
ESA	European Space Agency
FITS	Flexible Image Transport System
GDAL	Geospatial Data Abstraction Library

GeoTIFF	Geographical Tagged Image File Format
GIS	Geographical Information Systems
HiPS	Hierarchical Progressive Survey
HiRISE	High Resolution Imaging Science Experiment
IAU	International Astronomical Union
IEEE	Institute of Electrical and Electronics Engineers
IVOA	International Virtual Observatory Alliance
ISO	International Organization for Standardization
JAXA	Japan Aerospace Exploration Agency
MATISSE	Multipurpose Advanced Tool for the Instruments for the Solar System Exploration
MEF	Multi-Extension FITS
NAVCAM	NAVigation CAMera
NIRS	Near-Infrared Spectrometer
OGC	Open Geospatial Consortium
OMEGA	Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité
OSIRIS	Optical, Spectroscopic, and Infrared Remote Imaging System
PDS	Planetary Data System
PDS3	Planetary Data System (version 3)
PDS4	Planetary Data System (version 4)
PSA	Planetary Space Archive
SSDC-ASI	Space Science Data Center of the Italian Space Agency
USGS	United States Geological Survey
UTC	Universal Time Coordinated
VESPA	Virtual European Solar and Planetary Access
VO	Virtual Observatory
WCS	World Coordinate System
WGCCRE	Working Group on Cartographic Coordinates and Rotational Elements
WKT	Well-Known Text

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