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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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 PDS4 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 ~~efficiently extract scientific information from~~ allow efficient scientific analysis of the data and to guarantee the reproducibility of the ~~scientific~~ results.

This paper proposes to use Flexible Image Transport System[1] (FITS) format [*Wells et al.*, 1981; *Pence et al.*, 2010] in planetary surface investigations, and describes how FITS metadata can easily be inserted in the PDS4[2] metadata distribution model. FITS is one of the

[1] https://fits.gsfc.nasa.gov/

[2] https://pds.nasa.gov/tools/standards-reference.shtml

standard formats implemented in the Virtual Observatory[3] (VO), therefore making obvious its connection to the Planetary Virtual Observatory 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.

~~This paper is organized as follows: 1. a brief description of FITS format; 2. a proposition for planetary surface metadata description in FITS; 3. dictionaries between FITS, PDS metadata description and EPN-TAP2.0 parameters; 4. some examples of planetary dataset in FITS; 5. current developments for making FITS more usable to handle data of planetary surfaces.~~

2 FITS Format in Planetary Surface Investigation

2.1 FITS Format

FITS is an open digital standard, created in the late 1970's for data acquisition, transfer and archiving of telescope data by astronomical observatories, where it has been used during the last thirty years. It had been ~~used~~ adopted for data exchange and archiving from several orbital telescopes and spatial missions. The International Astronomical Union approved FITS as the standard format for astronomical data[4]. Therefore, FITS is one of the standard formats implemented in the Virtual Observatory (VO). FITS data storage is compatible with the Planetary Data System (PDS) archiving specifications so that FITS files can be embedded in PDS datasets. Finally, it is supported by a large number of open libraries and software tools.

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 (MEF) 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 multi-detector imagery (e.g. from HiRISE [*McEwen et al.*, 2007]) or

[3] http://www.ivoa.net/astronomers/using_the_vo.html

[4] https://fits.gsfc.nasa.gov/iaufwg/history/IAU_1982_resolution_c1.html

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, e.g., Hayabusa AMICA and NIRS cameras[5], all Akatsuki cameras[6] (except the Lightning and Airglow Camera), and the Dawn Framing Camera[7] data. Some Rosetta data, from NAVCAM and OSIRIS cameras, are distributed in FITS format at the ESA Planetary Science Archive[8] (PSA). In addition, many PDS3 datasets in the Small Bodies Node are archived and distributed as FITS files with PDS3 labels. However, to be more efficiently used in planetary surface investigations, FITS metadata 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 VESPA[9] [*Erard et al.*, 2018] workpackage of the EuroplanetRI2020[10] project an extension to FITS metadata (GeoFITS) has been proposed[11], 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 is 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[12] (GDAL), released by the Open Source Geospatial Foundation. GDAL is essentially 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.

[5] http://darts.isas.jaxa.jp/planet/project/hayabusa/index.html
[6] http://darts.isas.jaxa.jp/planet/project/akatsuki/index.html
[7] https://sbn.psi.edu/pds/archive/dawn.html
[8] https://archives.esac.esa.int/psa
[9] http://europlanet-vespa.eu/
[10] http://www.europlanet-2020-ri.eu/
[11] https://voparis-confluence.obspm.fr/display/VES/GeoFITS:+Planetary+Data+FITS+format+and+metadata+convention
[12] http://www.gdal.org

FITS World Coordinate System representation[13] 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 and Greisen*, 2002; *Snyder*, 1987] as projection parameters (projection center or reference point) describe the difference between, e.g., 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 (CAR) 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 and Calabretta*, 2002].

Table 1 summarizes the FITS projection codes and their corresponding PDS4 projection names (see table A.1. in *Calabretta and 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 [*Greisen and Calabretta*, 2002; *Calabretta and Greisen*, 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 3D keywords will be proposed for FITS metadata, in order to standardize the conversion between angular and linear coordinates: alternate description

[13] http://fits.gsfc.nasa.gov/fits_wcs.html

Table 1. Projection names and codes ~~already~~ available in WCS FITS, suitable for planetary applications: the corresponding PDS4 terminology is provided.

FITS Name[a]	FITS code[a]	~~PDS~~ 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

[a]From *Calabretta and Greisen* [2002]

[b]From the PDS4 Data Dictionary ~~We cannot find correspondences in the WCS scheme for PDS4 Robinson, Van Den Grinten and Space Oblique Mercator: those three projections are not used for archival or analysis.~~

will still be important in our framework as standard libraries (e.g. wcslib[14] or astropy[15], *Astropy Collaboration et al.* [2013]) and some FITS visualization software (e.g. ds9[16]) already implement them, making linear coordinate tracking more efficient.

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 ~~(defaulted to 'ICRS')~~. Standard FITS defaults this keyword to `'ICRS'`. This is applicable to planetary data too as long as the planetary coordinate system parameters, i.e. 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 ~~(defaulted to 'J2000')~~. 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, e.g., 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, non-rotating, inertial). EPN-TAP provides ~~a~~ 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.

[14] http://www.atnf.csiro.au/people/mcalabre/WCS/wcslib/
[15] http://www.astropy.org/
[16] http://ds9.si.edu/

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 (1). For angular coordinates *Calabretta and Greisen* [2002] provides 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 and 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.
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). ~~In EPN-TAP they are connected to~~ They correspond to the *pixel_resolution_x* and `pixel_resolution_y` attributes in PDS4, to the `spatial_resolution` parameter in EPN-TAP .
11. CUNITn. Units of the coordinate system ~~, not mandatory, defaulted to degrees for angular coordinates and to meters (m) for linear ones~~. 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 WCSNAMEa 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.

Table 2. Codes to be used in CTYPE FITS keyword in order to identify the planetary body. Codes for planets are ~~assumed~~ implied in *Calabretta and Greisen* [2002]. We propose to add codes for classes of targets, more or less corresponding to PDS4 Target type attribute and to EPN-TAP target_class parameter.

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

[a]From *Calabretta and Greisen* [2002]

[b]Transneptunian (TNO) and Kuiper Belt (KBO) objects must be placed there

Table 3. Proposed keywords are related to 3D 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 semi-major 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 semi-minor 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 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.

[a]Note that IAU 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,C_RADIUS, must be set to the same value of the defined Mean Radius.

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[17]) 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 non-negative 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 non-negative integer.
3. `NAXISn`. It contains a non-negative 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[18]. 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).
5. `BSCALE`. It contains a floating point number representing the coefficient of the linear term in the scaling equation $physical\_value = BZERO + BSCALE \times array\_value$, 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 $physical\_value = BZERO + BSCALE \times array\_value$ For all classes containing Elements, PDS4 defines a `value_offset` attribute. Both FITS and PDS4 default this value to 0.

[17] https://fits.gsfc.nasa.gov/standard40/fits_standard40aa.pdf
[18] https://www.iau.org/publications/proceedings_rules/units/

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 UTC but other systems are accepted as long as they are specified in the ISO string[19]. 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 a 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 key-

[19] See table 30 in the Standard FITS document https://fits.gsfc.nasa.gov/standard40/fits_standard40aa.pdf

word. 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[20].

14. `OBJECT`. It contains a character string giving a name for the observed object[21]. 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[22] bibliographic identifier or the Digital Object Identifier[23] 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[24] format, as GeoTIFF make them GIS ready. Given 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 ~~some global maps from~~ a Mercury polar map from the USGS PDS Annex[25] and converted ~~them~~ it in FITS. The FITS image has been cropped in two smaller versions using

[20] https://naif.jpl.nasa.gov/pub/naif/toolkit_docs/FORTRAN/req/naif_ids.html#Spacecraft

[21] https://naif.jpl.nasa.gov/pub/naif/toolkit_docs/FORTRAN/req/naif_ids.html#Planets%20and%20Satellites

[22] http://adswww.harvard.edu/

[23] http://doi.org

[24] http://geotiff.osgeo.org/

[25] https://astrogeology.usgs.gov/search

the open source software SWarp[26] [*Bertin et al.*, 2002]: SWarp was able to automatically manage WCS planetary information. We used ds9 to display the ~~FITS image~~ three FITS images and were able to ~~visualize~~ correctly align them. Linear coordinates in meters are visualized (see figure 1, left side) as in QGIS, a popular open source GIS software, ~~but also in planetary latitude and longitude~~ thanks to the alternate coordinate description~~(see figure 1, left side)~~.

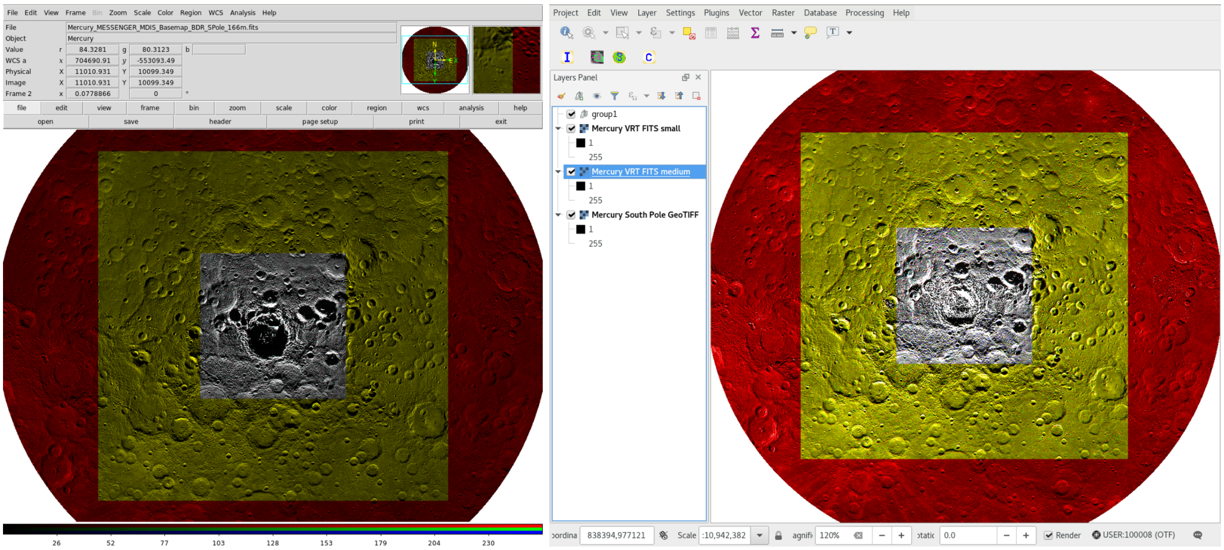

Figure 1. left: Mercury South Pole FITS ~~image~~ images displayed in ds9, alternate coordinates in meters are displayed; right: GeoTIFF raster (displayed in ~~yellow~~red) and the two virtual ~~header~~ haeders linked to ~~the~~ FITS ~~raster~~ rasters (displayed in ~~red~~green and blue); the ~~two~~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

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[27] files simply describe the internal structure of a FITS image, but also the map projection and body size in a standardized "well known text" (WKT) 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).

[26] https://www.astromatic.net/software/swarp

[27] http://www.gdal.org/gdal_vrttut.html

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, E. W. 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[28], available in all major linux distribution.

As an example of non projected 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-PSA ~~and PDS archives~~[*Besse et al.*, 2018] . Their structure is described in the OMEGA Experiment Archive Interface Control Document[29].

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 (BIL) to Band Sequential (BSQ) in order to make them easily understandable when visualized using standard FITS viewer (as ds9 in figure 2)[30].

[28] http://www.atnf.csiro.au/people/mcalabre/WCS/wcslib/

[29] ftp://psa.esac.esa.int/pub/mirror/MARS-EXPRESS/OMEGA/MEX-M-OMEGA-2-EDR-FLIGHT-V1.0/DOCUMENT/EAICD_OMEGA.PDF

[30] 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

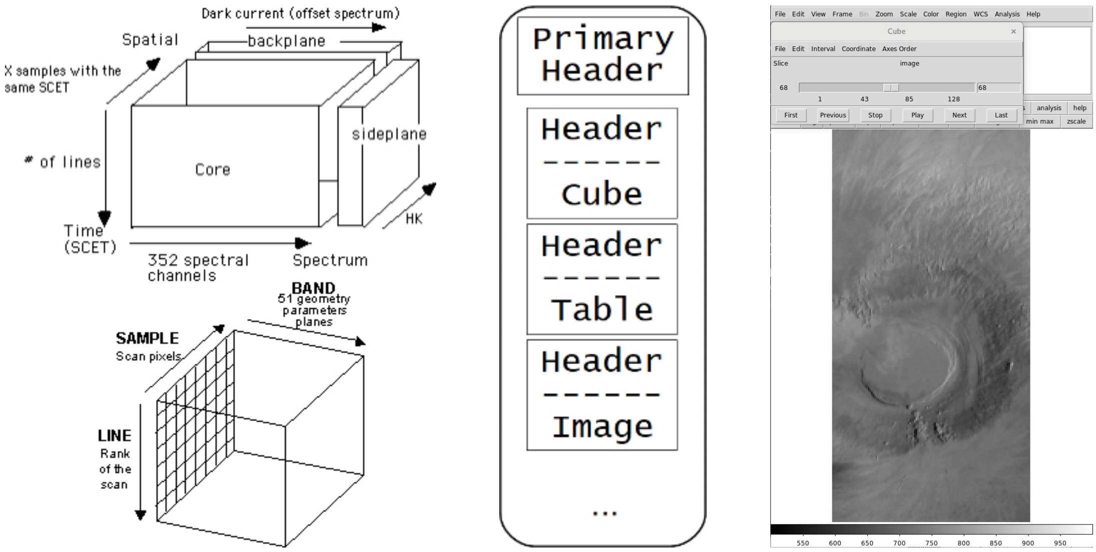

Figure 2. left: OMEGA data structure (from OMEGA EAICD), science data and geometry description are distributed in different files; center: FITS Multi Digital Object scheme; as an example, we stored the spectral data in the first cube extension, the coordinate look-up table in the second extension, and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

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[31] 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:

[31] http://akatsuki.isas.jaxa.jp/en/

tabular representation avoids to store unnecessary data. In that case, coordinate indexes are necessary to identify which pixels contains the spatial information[32].

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

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[33]. 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 to VO and GIS tool integration will be to directly implement metadata translation into GDAL C++ library.

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. The complete implementation of FITS metadata in GDAL library is in progress. Once implemented in GDAL, FITS will officially become a supported format by QGIS.

In addition to that, a QGIS plugin has been developed[34] ~~[*Minin et al.*, 2018, in preparation]~~ [*Minin et al.*, 2018] in order to download and display files exposed via EPN-TAP servers.

[32] 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

[33] https://github.com/epn-vespa/fits2vrt

[34] https://github.com/epn-vespa/VO_QGIS_plugin

3.3 MATISSE

MATISSE[35] (Multi-purpose 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 (SSDC-ASI) to access, visualize and analyze data from solar system exploration missions. Currently, ~~it~~ MATISSE provides access to public data from five different targets (i.e., Mercury, Venus, Mars, the dwarf planet Ceres and the asteroid Vesta)~~using both data stored on SSDC local storage or by querying remote dataset, such as VESPA, Planet Server and NASA JPL and can be integrated with other datasets thanks to its modular structure. One of th~~. MATISSE 2D outputs ~~is~~ are formatted as FITS, ~~projected by interpolating the original observations to a grid regularly spaced in planetocentric coordinates (i. e., latitude and longitude). We used the~~ in equirectangular projection and in planetocentric coordinates. The planetary FITS standard described in this work ~~in~~ 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[36], whose output is a VRT virtual GDAL 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) ~~we are planning to make use of~~ JS9 ~~as~~ will be the standard reader for the 2D online output of the tool, thus allowing users to perform advanced analysis in both 2D and 3D directly inside a web-based environment.

3.4 Aladin

Aladin is both a sky atlas and a portal to access data~~–~~, mainly images and catalogues~~–~~, available through the VO. ~~It~~ Aladin is able to load FITS files and to display images taking into account various WCS projections. ~~Like DS9, Aladin is popular and broadly used in the part of the astronomical community manipulating images.~~ So far it is also the reference generator and visualizer of Hierarchical Progressive Survey (HiPS). HiPS[37] is a recommendation endorsed by the International Virtual Observatory Alliance (IVOA). It describes how to access to 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

[35] https://tools.asdc.asi.it/matisse.jsp
[36] https://github.com/epn-vespa/fits2vrt
[37] http://www.ivoa.net/documents/HiPS/

FITS files. Aladin[38] [*Bonnarel et al.*, 2000] and its HiPS generator have been updated to support planetary conventions (see Figure 3).

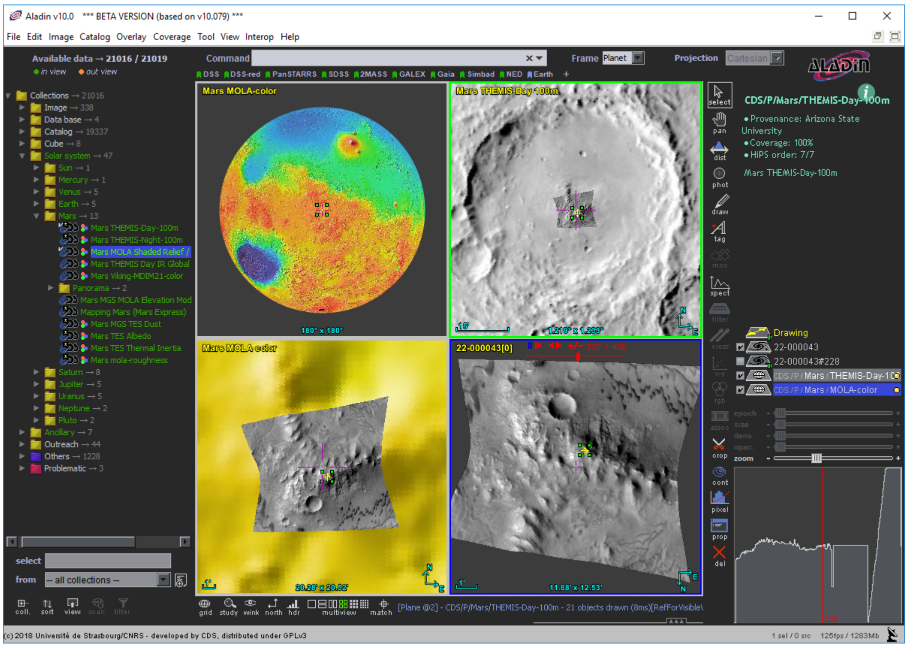

Figure 3. Visualization of several level of detail on Mars with Aladin: from the global topographic map, as a HiPS layer, to a high resolution CRISM spectral cube in FITS format. All spectral analysis tools useful for astronomical spectra are then available for planetary data.

In the future, Aladin will be able to recognize the FITS keywords defined in the present paper (see Tab. 1 and 2). ~~For example, it will be able to take into account a planet's radii to compute distances on the surface of the body.~~ Finally, among the WCS projections listed in Tab. 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. ~~We expect all projections to be available in a forthcoming release.~~

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.

[38] http://aladin.u-strasbg.fr/

~~We are aware that FITS is today subject of questioning in astronomical applications~~ We understand that some believe FITS has grown too old for newer astronomical applications [*Thomas et al.*, 2015]. We are not convinced that one format can solve all the issues faced from long-term archiving to on-line streaming. ~~Planetary science research community has used a large variety of format customizing specific software. We want to stress here that using FITS could be an efficient compromise, reducing custom data format conversions during the processing chain and allowing easy conversion for final products following the needed application.~~ 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 ~~as~~ is an open and flexible data and metadata exchange and archiving format, ~~could be inserted~~ its use in the PDS4 data model scheme ~~in order to address~~ would solve the issue of ~~more~~ complex metadata and data relationships ~~.~~ separating data processing and the data archiving processes.

~~In order to improve interoperability and knowledge sharing between astronomy and planetary science, we will soon finalize the~~ 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.

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