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MarsSI: Martian surface data processing information system

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A B S T R A C T

MarsSI (Acronym for Mars System of Information, https://emars.univ-lyon1.fr/MarsSI/) is a web Geographic Information System application which helps managing and processing martian orbital data. The MarsSI facility is part of the web portal called PSUP (Planetary SUrface Portal) developed by the Observatories of Paris Sud (OSUPS) and Lyon (OSUL) to provide users with efficient and easy access to data products dedicated to the martian surface. The portal proposes 1) the management and processing of data thanks to MarsSI and 2) the visualization and merging of high level (imagery, spectral, and topographic) products and catalogs via a web-based user interface (MarsVisu). The portal PSUP as well as the facility MarsVisu is detailed in a companion paper (Poulet et al., 2018). The purpose of this paper is to describe the facility MarsSI. From this application, users are able to easily and rapidly select observations, process raw data via automatic pipelines, and get back final products which can be visualized under Geographic Information Systems. Moreover, MarsSI also contains an automatic stereo-restitution pipeline in order to produce Digital Terrain Models (DTM) on demand from HiRISE (High Resolution Imaging Science Experiment) or CTX (Context Camera) pair-images. This application is funded by the European Union's Seventh Framework Programme (FP7/2007–2013) (ERC project eMars, No. 280168) and has been developed in the scope of Mars, but the design is applicable to any other planetary body of the solar system.

1. Introduction

The last two decades have seen a growing number of space missions exploring the solar system with a very wide range of on board instruments recording very diverse types of data characterizing planetary surfaces. In particular, investigations of planetary surfaces thanks to orbital data required a large variety of remote sensing instruments. For Mars, for instance, the number of missions and instruments now requires a complex information system just to manage data the large volumes of data.

Efforts have been made by space agencies (NASA and ESA) to widely distribute and properly store the voluminous data acquired by the various missions. In particular, NASA creates the Planetary Data System (PDS) to store and distribute all scientific data from NASA planetary missions, astronomical observations, and laboratory measurements.[1]

More and more web-GIS (Geographic Information System) applications exist to visualize projected and already-processed data. For example, JMARS (Java Mission-planning and Analysis for Remote Sensing[2] allows users to visualize several layers of orbital data of Mars Surface (Christensen et al., 2009). MATISSE (Multi-purpose Advanced Tool for the Instruments of the Solar System Exploration) is a unique 3D visualization tool for the small bodies (Zinzi et al., 2016). ODE (Orbital Data Explorer) provides the selection of data to be downloaded from PDS under a GIS environment[3] for Mars, the Moon, Mercury and Venus. Google Mars and Moon allows the visualization of several martian or lunar data products.[4] PlanetServer provides access to calibrated lunar and martian multi and hyperspectral data (Marco Figuera et al., 2018). However, the applications above provide minimal, if any, on demand processing capabilities. Examples of planetary on-demand-processing services include THMPROC[5] and PILOT/POW (Bailen et al., 2017). THMPROC (THEMIS Image Processing Web Interface), a web based interface is designed to provide a simple method to process Mars Odyssey

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[1] https://pds.jpl.nasa.gov.
[2] https://jmars.asu.edu.
[3] http://ode.rsl.wustl.edu.
[4] http://earth.google.com.
[5] http://thmproc.mars.asu.edu/thmproc_help.html.

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THEMIS infrared instrument data (Christensen et al., 2004). The U.S. Geological Survey's (USGS) PILOT (Planetary Image Locator Tool) and POW (Map projection on the web) services provides visual map-selection of images for on-demand image calibration and map projection.

In general, individual instrument teams support the generation of software routines such that researchers worldwide can use their mission data, once they learn how to run the specific routines. Unfortunately, this means the same data can be reprocessed several times over, even within the same team.

With the objective of efficiently and easily providing access to martian data products, we have designed a distributed information system called MarsSI (Mars System of Information) to manage data from the four following martian orbiters: Mars Global Surveyor (MGS; Cunningham, 1996), Mars Odyssey (ODY; Saunders et al., 2004), Mars Express (MEX; Kolbe, 1999), and Mars Reconnaissance Orbiter (MRO; Graf et al., 2005). The application allows processing of orbital data on-demand. Once processed they are made available for other researchers to download that makes the concept of MarsSI unique;

MarsSI allows the user to select footprints of the desired dataset from a web-GIS interface and it downloads the corresponding original Experiment Data Record (EDR or raw) data to a storage server. Then the user can run remotely data-dependent automatic processes on our server from the EDR data and finally acquires “science-ready” data of the Mars surface. “Science-ready” means that the data are prepared and made available to be visualized under GIS or remote sensing software. An automatic stereo-restitution pipeline producing high resolution Digital Terrain Models (DTM) is also available. In the following sections, we present the architecture of the workflow and the functionalities of the application, then we detail the data proposed for processing and the DTM generation facility. Finally, we discuss the perspectives of this application for Mars first, and for other planetary bodies.

2. MarsSI design and functionalities

2.1. MarsSI global overview

MarsSI has been developed using Two Tracks Unified Process (2TUP) which is an iterative software development process, that starts with the study of the functional needs of the end users. This study, using a local team of planetary scientists, revealed they would benefit from an easy-to-use web-GIS application for selecting, downloading and processing large number of Mars remote sensing data. We choose a Java based project with the following open source projects: Geomajas[6] framework for the web-GIS application, Spring[7] framework for the server-side services and dialogs with the database, GeoServer[8] to publish images footprints, PostGIS[9] spatial add-on for PostGreSQL[10] relational database, and TORQUE[11] as resource manager for jobs scheduling.

The design of the facility is displayed in Fig. 1 showing MarsSI as a 3-tiered web application. The facility uses a local storage server coupled with a compute cluster to launch data processing scripts. The web-tier service is programmed with Google Web Toolkit (GWT) libraries[12] under Geomajas framework. The Spring framework communicates with the web-tier via Geomajas command pattern, and with the data-tier via Spring's Data Access Object (DAO) pattern. The data-tier is a PostgreSQL database and Mars data footprint's geometry and attributes are managed with PostGIS functionalities.

[6] http://www.geomajas.org.
[7] http://spring.io.
[8] http://geoserver.org.
[9] http://postgis.net.
[10] http://www.postgresql.org.
[11] http://www.adaptivecomputing.com/products/open-source/torque.
[12] http://www.gwtproject.org.

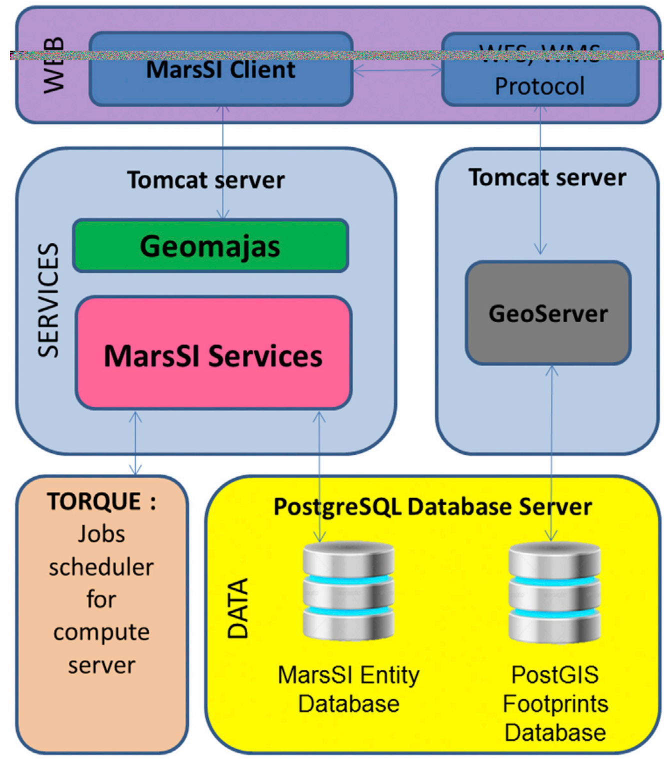

Fig. 1. Global architecture of MarsSI.

2.2. MarsSI welcome page

The MarsSI application is secured with Geomajas security plugin which shows a login window at the opening of the application Registered users can log-in, while new users are invited to create an account via a web form. Once registered, users are provided with a login and a password for both the MarsSI application and a personal FTP account (ftp://emars.univ-lyon1.fr/MarsSI/) from where the user will retrieve the processed data. The login page also links the online documentation of MarsSI including video tutorials.

MarsSI client program is inspired from Geomajas showcase and SmartGWT showcase websites[13]. It works with a “factory design pattern” that creates custom tabs. Thus it is easy to add new tabs in order to create additional functions.

The diagram in Fig. 2 shows that tabs, inserted into the MarsSI web page (Entrypoint), are created by a factory. This factory creates tabs that inherit from an abstract object containing global properties and user's data area, called a cart. This design allows that, when a user is identified, the set of tabs of the main page are filled with panels according the user's privilege. Basic users will have a map tab, a workspace tab and an about tab with the user manual and video tutorials. Admin users will have an administration tab in addition to basic user tabs.

2.3. Map tab

The aim of map panel is to search and select data based on their footprint locations. Once selected, the data can be added to the user's cart.

The layers available for display are listed (Fig. 3). They are published with Geoserver using either the Web Feature Services (WFS) or Web Map Services (WMS) interoperable specifications as defined by the Open

[13] http://apps.geomajas.org/geomajas-gwt-face-example/ and http://www.smartclient.com/smartgwt/showcase/#main.

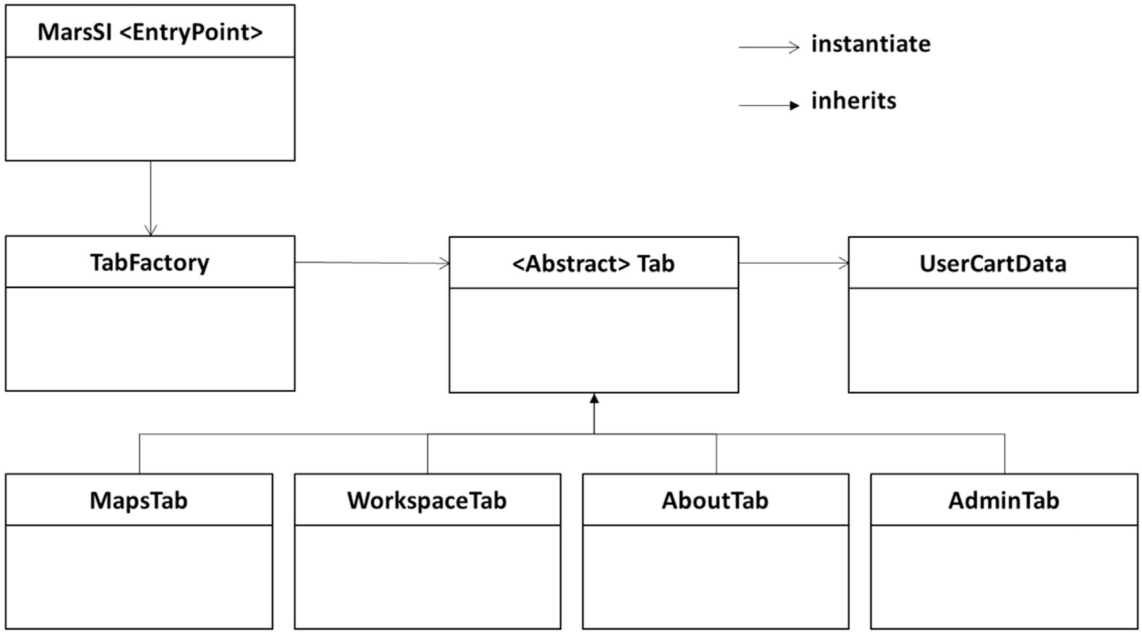

Fig. 2. UML (Unified Modeling Language) diagram to create MarsSI web tabs. The abstract tab contains global properties and user's cart data. Tabs that user can actually see contains specific properties and the global ones are obtained through inheritance.

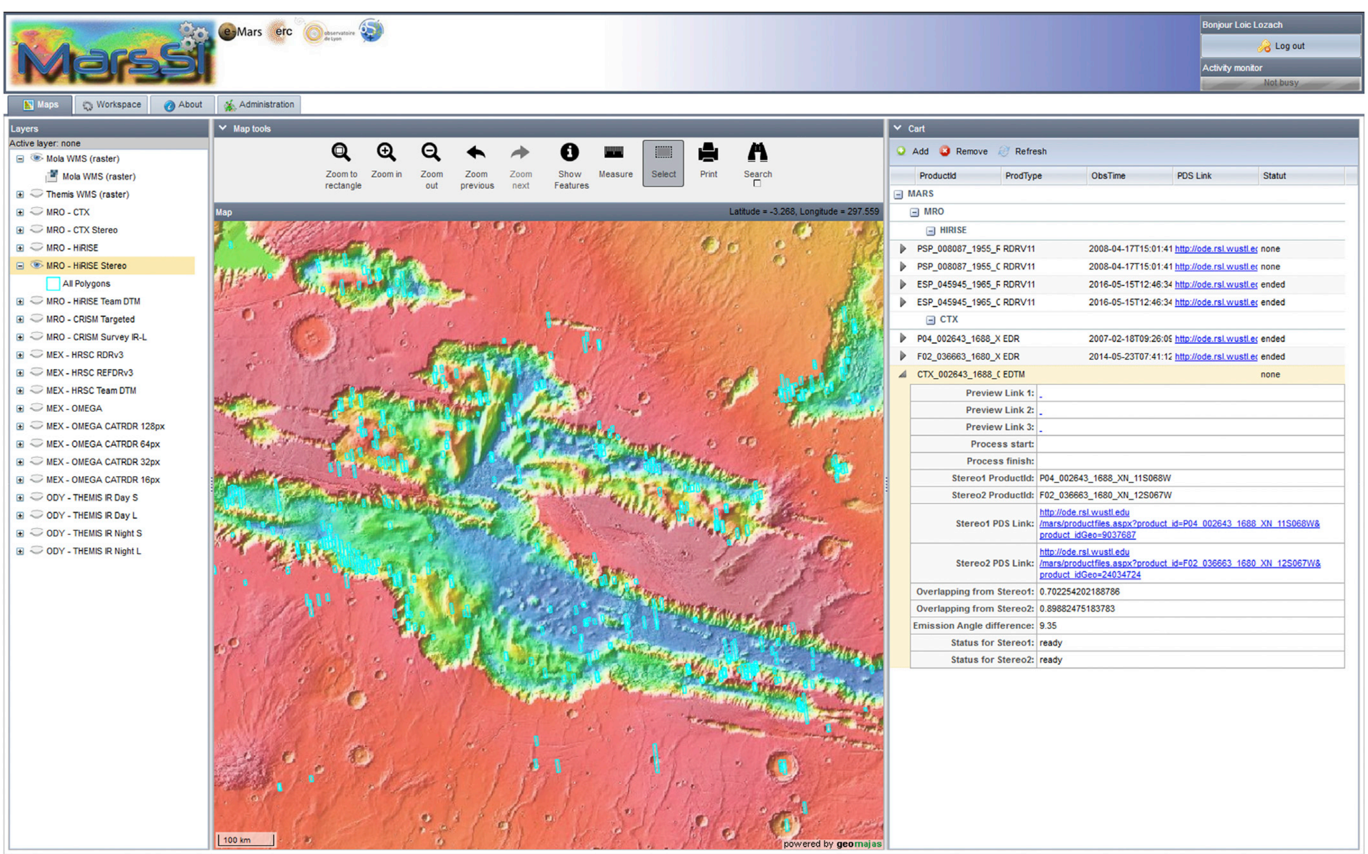

Fig. 3. MarsSI's maps tab. User can here search and select footprints with a web GIS interface and add those to his cart.

Geospatial Consortium (OGC). For background context of the map, two raster images are available for display: MOLA (Mars Orbiter Laser Altimeter) global mosaic (Smith et al., 2001) and THEMIS (thermal emission imaging system) day time infrared global mosaic (Edwards et al., 2011). For data selection, several data layers are available for display: CTX (Context Camera; Malin et al., 2007), HiRISE (High Resolution Imaging Experiment; McEwen et al., 2007) and CRISM data (Compact Reconnaissance Imaging Spectrometer for Mars; Murchie et al., 2007) from the MRO mission; HRSC (High Resolution Stereo Camera; Neukum et al., 2004a,b) and OMEGA (Observatoire pour la Minéralogie,

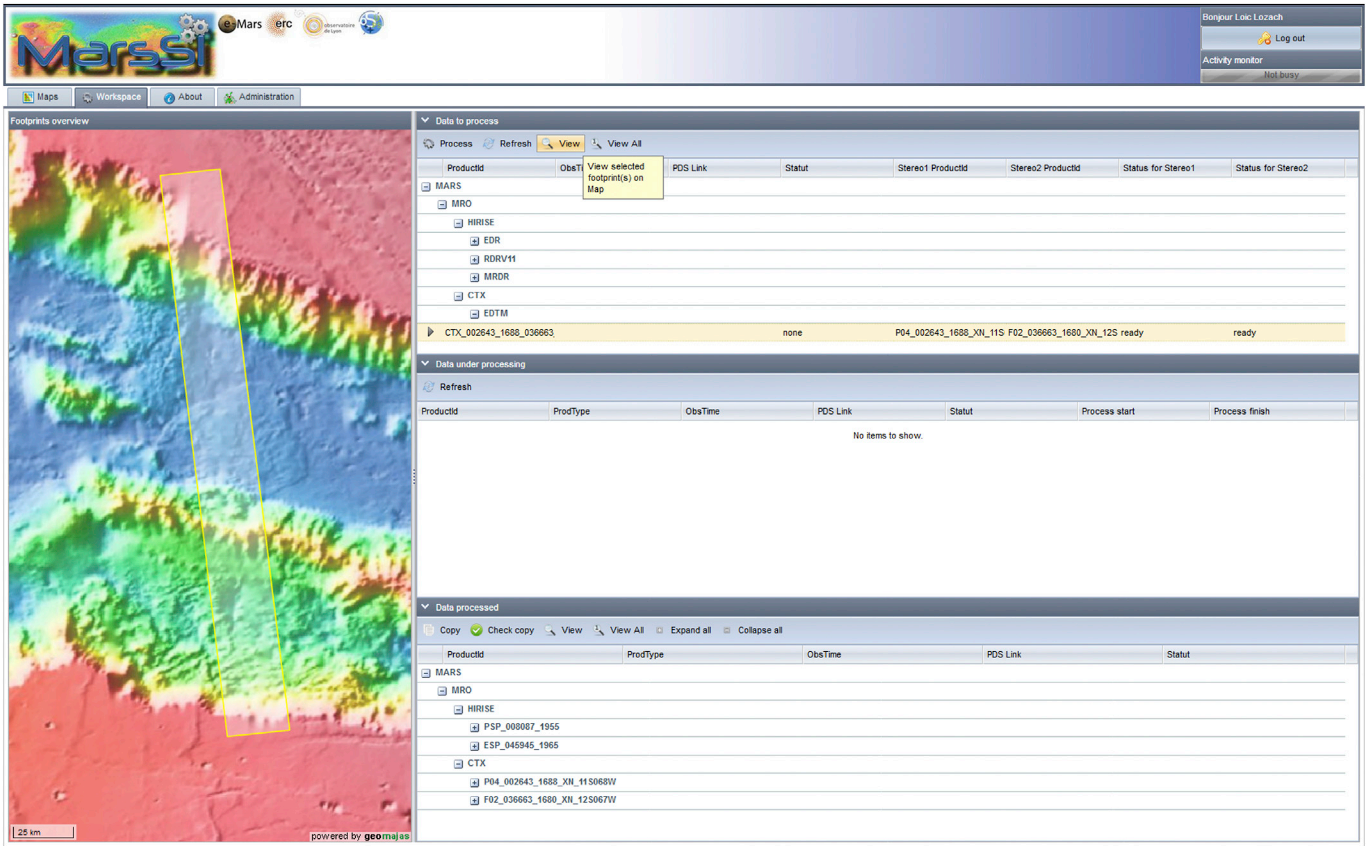

Fig. 4. MarsSI's workspace tab. User can here process and copy data.

l'Eau, les Glaces et l'Activité; Bibring et al., 2004) from MEX mission and THEMIS (Christensen et al., 2004) from the ODY mission. The footprints of possible DTM from CTX and HIRISE stereo-pair coverage are also available for display.

The map view (Fig. 3) allows to visualize the Mars surface and to view data footprints location and attributes. The ribbon at the top of this map view offers the common GIS tools (zoom, identifying, measurement, selection and search). Search tools allow requests based on data attributes, user's drawn polygons or a combination of both.

The cart view (Fig. 3) allows users to add the data selected on the map or to actually remove data from their cart. In this window, several attributes of each added data are displayed, such as the link to the EDR (or raw) data products hosted by the ODE PDS server[14].

2.4. Workspace tab

The aim of the workspace panel (Fig. 4) is to launch processing pipelines of the data selected by the user and access those processed data via copying datasets to the user's personal ftp account. There is an overview map showing the footprints from the user's cart. The user can also make a selection of data from his cart to be displayed by clicking the "view" button (Fig. 4). This functionality allows an easier management of the data when there is dense overlaps. The workspace displays 3 tables corresponding to the available workflows available from MarsSI (Fig. 4). The first one, "Data to process", shows data in the user's cart that can be processed with MarsSI's pipelines. To start a processing job, the data must first be selected and then simply pressing the "Process" button. When a processing pipeline is running, the associated record appears in the second table "Under processing". Finally, when the process is completed, the record appears in the third table "Data processed". Automatically, when available for further processing, an entry again is added the "Data to process" table. To access the processed data, the user selects the processed data under the "Data processed" table and clicks the "copy" button. They can check its availability for download with the "check copy" button which will show the number of datasets that are still being copied to the user's personal FTP account. When all datasets have been copied, the user can connect to their FTP account ftp://emars.univ-lyon1.fr/MarsSI/) and download data to their personal computer with the same login and password than for MarsSI application access.

2.5. Administrator panel

When a user is identified as Administrator, the administrator tab is available. Its aim is to monitor users accounts. When a new user requests an account via the contact page, the administrator receives an email with the contact information and can add this new user to the system. He can also modify or delete a user's account. Further developments will allow the administrator to restart failed processes, view statistics of MarsSI's usage and make automatic updates of footprints.

3. MarsSI technical description

3.1. Client – server communication

All interactions between client and server (Fig. 6) like adding, removing or processing, are held by the Geomajas custom command pattern. This custom command pattern is handled in Geomajas through the command dispatcher and security manager modules (Fig. 5). Communication between client and server are carried by command request and command response which encapsulate Data Transfer Object (DTO). DTO is a java pattern that allows access to an object both from

14 http://ode.rsl.wustl.edu/mars/.

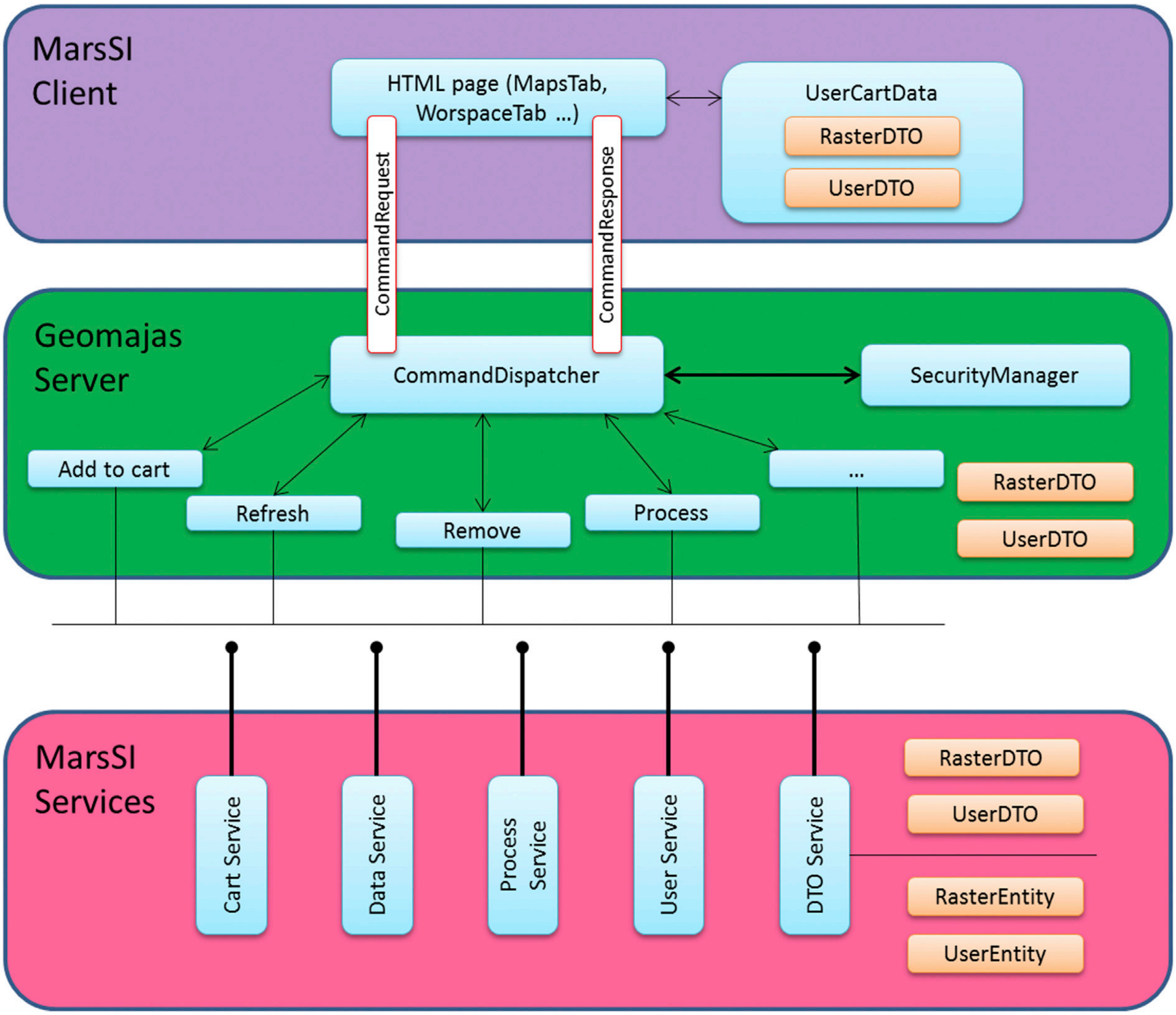

Fig. 5. Custom commands design. Client communicate with server thanks to command request and response that encapsulate Data Transfer Object (DTO). A command defined in Geomajas server uses MarsSI services interfaces to transform DTO in database entities and perform the command functionality.

client or server side.

When a user clicks on a command button, a command request is sent to the command dispatcher. A DTO is created from user's cart or selection, and then encapsulated in the command request. First, the command dispatcher checks user's authority for this command with the security manager and then run the command. Each command has access to MarsSI services interfaces which will transform DTO into database entities and perform the functionality associated with the command. Those services will return DTO to the command dispatcher which will send back a command response with the DTO encapsulated.

3.2. MarsSI server side

The applicative architecture of MarsSI server that translates the functional needs of a user into 3 parts: a service layer, a data layer and a processing layer (Fig. 6).

3.2.1. Service layer

The service layer provides the interfaces to access methods to fulfill the functional needs. Five main services are available:

1. DTO Service – this service transforms backend entities used in the database into Data Transfer Objects that are sent to client and back.
2. User Service – this service manages the user's account and checks the user's authority. It also provides a bridge to configure the Geomajas security manager.
3. Cart Service – this service manages the user's cart with methods for refreshing, adding and removing data.
4. Data Service – this service manages data products including data set integrity. It creates dataset and fills it with the default raster. It also creates the next level of raster when a process is finished.
5. Process Service – this service rules process creation and execution. It uses a java ProcessBuilder Class to launch TORQUE ‘s job on the operating system. It also handles the copy on user's FTP account.

In order to obtain modularity, i.e. easily adding new instruments, those services use a factory design pattern to access DataTools interface (Fig. 7).

This interface implements an abstract object providing methods that are shared by all instruments (i.e. CTX, OMEGA, THEMIS…). Then each instrument inherits from this abstract object and specific methods are performed based on the instrument and the processing level of the data.

3.2.2. Data layer

The data layer reflects the database entity model (Fig. 8) and performs CRUD access (Create-Read-Update-Delete) on the database via the Data Access Object (DAO) pattern. For each database table, there is a

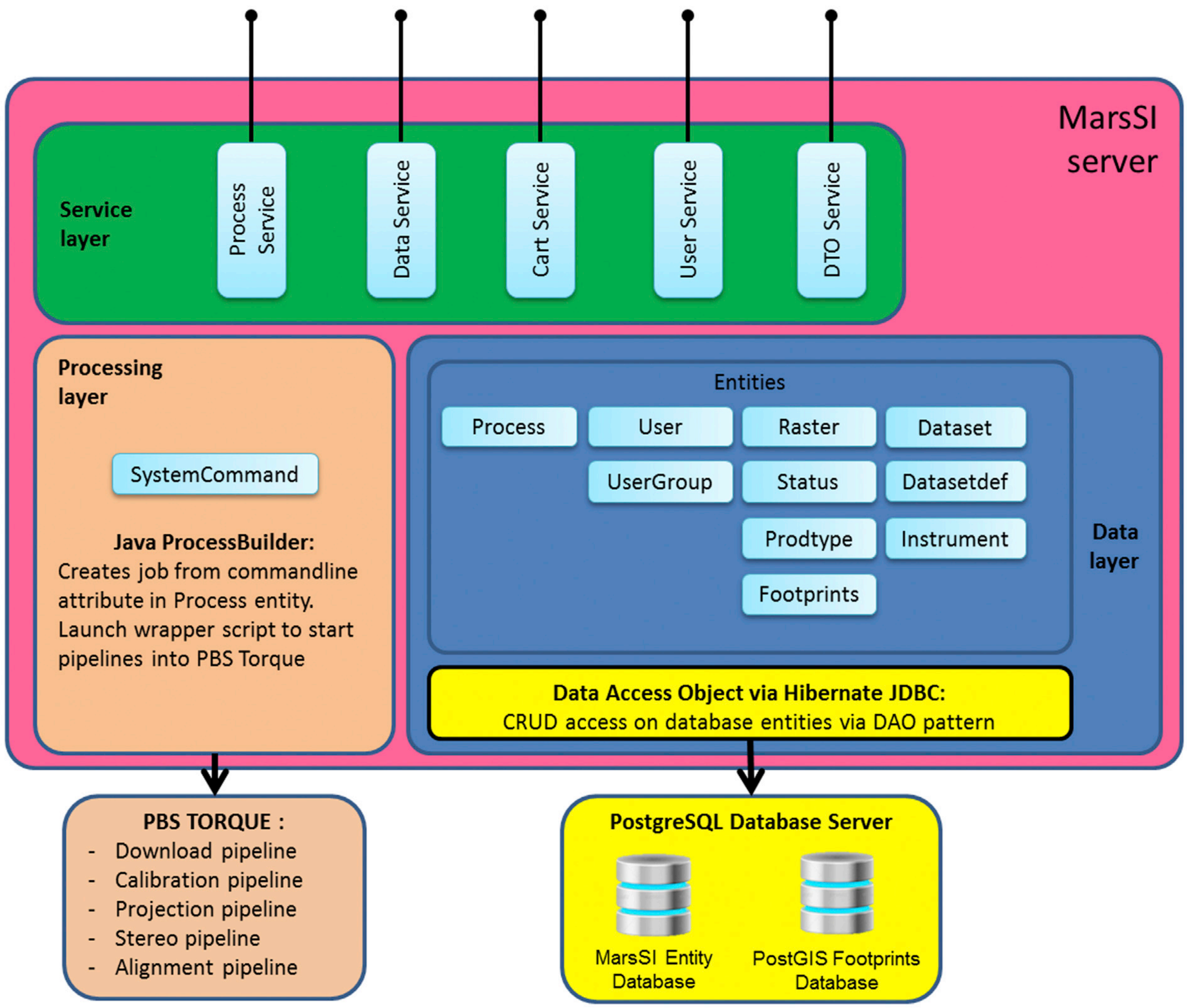

Fig. 6. MarsSI server architecture. Service layer fulfills the functional needs of the user. Data layer reflects the database entity model and handles communication (Create-Read-Update-Delete access on database manage by Data Access Object). The processing layer sends jobs over the TORQUE application.

corresponding java entity class and DAO class. Connection to the database is held by Spring Hibernate libraries.

The entity model presented (Fig. 8) shows how entities behave between each other in the database. A raster is an image that can be obtained by a download from the PDS server (based raster) or a MarsSI process (derived raster). It has 1 dataset, 1 product type, 1 process, 1 status and many temporary rasters. A dataset contains the base raster and its derived rasters. It has 1 instrument, many rasters and many users. A process creates a next product type raster from creation's raster. It has 1 output raster and 1 user. A user has many datasets (corresponding to his cart), many processes and 1 usergroup. Datasetdef defines the next product type for a determined instrument. It also defines if a processing level is authorized for a usergroup.

The data, which fill the database, are first taken from the footprints tables. Those tables are stand-alone and built from the footprints shapefiles created by the NASA PDS and referencing a remote access to the data. Shapefiles are converted into tables in the PostGIS database and a java entity class is created for each table corresponding to one imagery instrument.

In order to ease the addition of new data and their access, a factory design pattern is also used (Fig. 9). With the footprint factory, a footprint interface or a stereo-footprint interface can be added. Those implement a footprint abstract object and a stereo-footprint abstract object. The footprint object gathers all the attributes of a footprint (e.g., target, mission, instrument, product id, product type, product URL) and a stereo-footprint abstract object gathers specific attributes of a stereo-footprint (e.g., first stereo-pair product id, second stereo-pair product id, overlapping, emission's angle deviation). Then, thanks to inheritance, new instrument can be added by just adding a java class with nothing in it but the inheritance.

Another purpose of the data layer is to feed Geoserver with footprints from the PostGIS add-on for the PostgreSQL database. GeoServer publishes, via a WFS protocol, the footprints that are visible on the map in Geomajas web GIS interface. Thus, to perform an update on the footprints, only the PostGIS database needs to be modified.

Geoserver also publishes raster data (MOLA and THEMIS global mosaics). The MOLA mosaic is at 128 pixels per degree resolution and is tiled in images of $30^\circ \times 30^\circ$ each. The THEMIS mosaic is at 512 pixels per degree resolution and is tiled in images of $60^\circ \times 30^\circ$ each. The spatial reference used is the Geographic Coordinates System defined by the International Astronomical Union, informally called Mars2000 (Seidelmann et al., 2002).

3.2.3. Processing layer

The processing layer performs the processing on images and manages their status. It is divided in 2 main components (Fig. 10), one internal with the creation of an operating system command launched outside the java environment, and one external with TORQUE, a resource manager that distributes jobs over the compute cluster.

When a process entity is created by a user, a script is generated (via

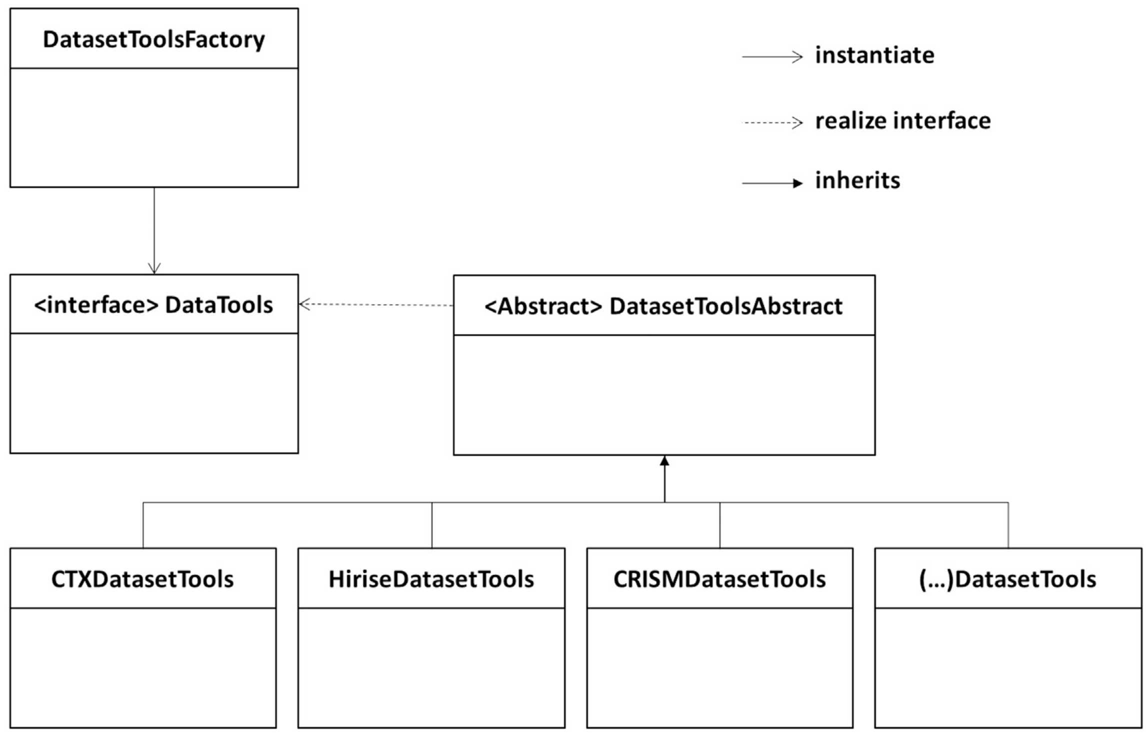

Fig. 7. –UML diagram for accessing data tools. In order to obtain the right tool for the right instrument, services use a factory that will link the right instrument's tools to the interface. The abstract object gathers common properties to all instruments.

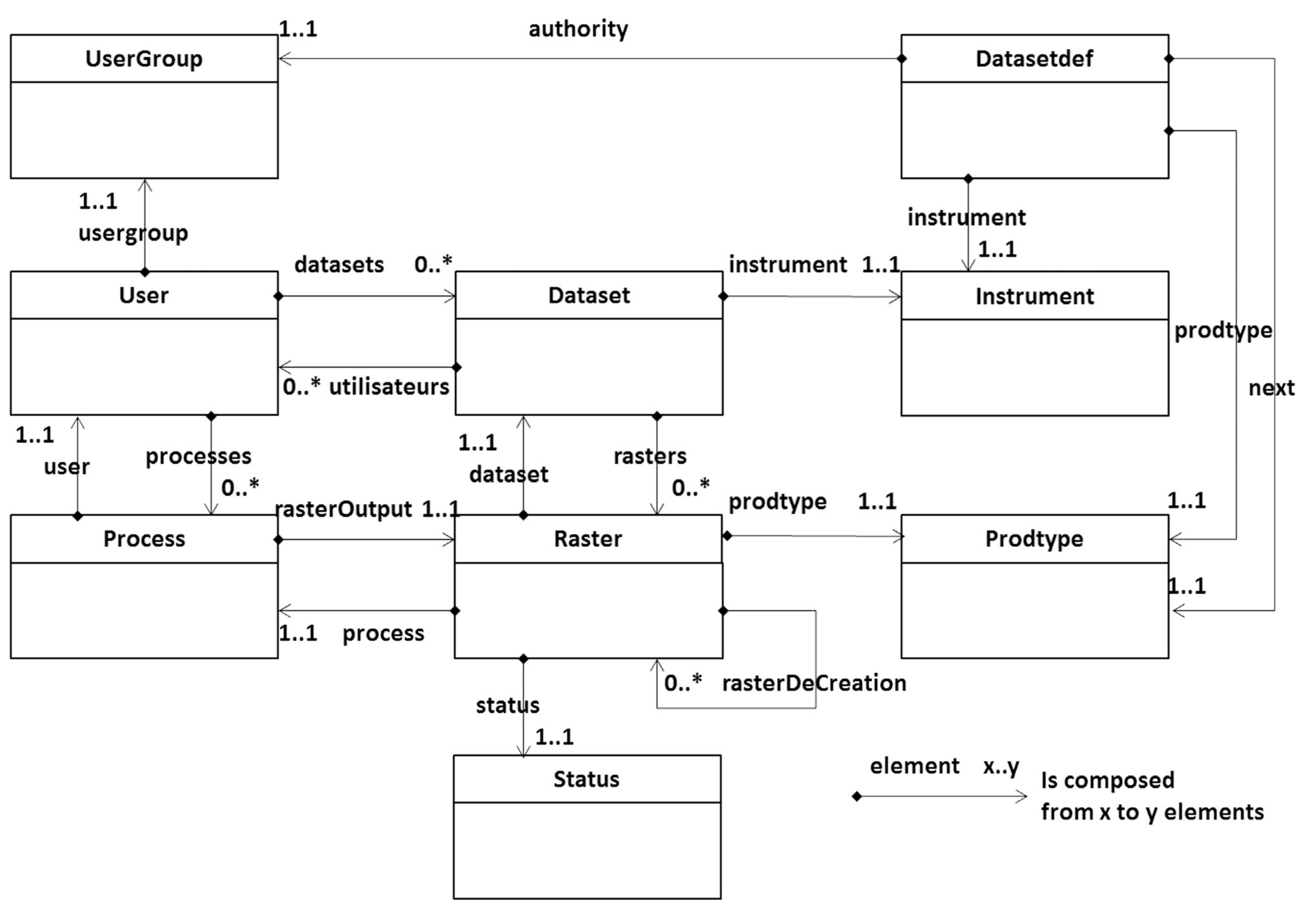

Fig. 8. Database entity model. It reflects the behavior between entities in the MarsSI's database.

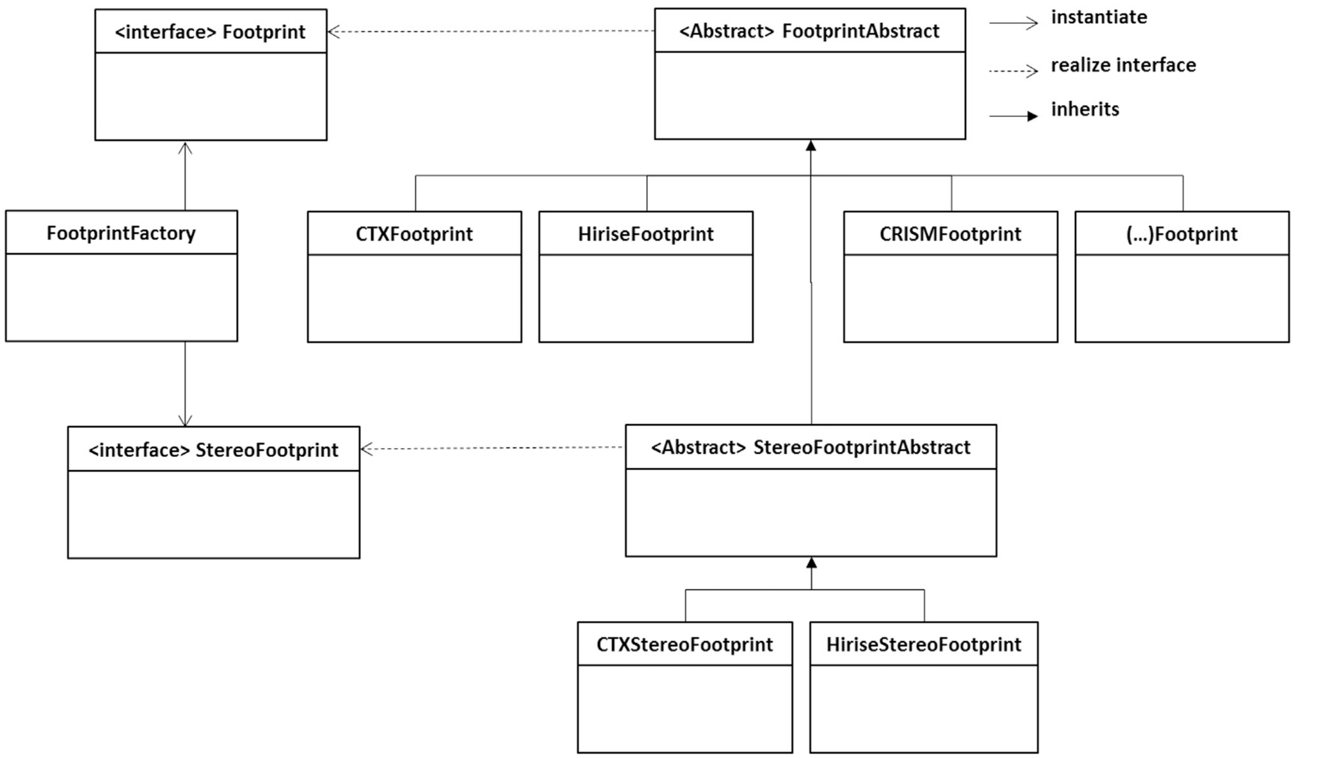

Fig. 9. UML diagram for accessing footprints. From footprint's factory we can access footprint or stereo-footprint interfaces. Those interfaces are realized by abstract objects that gather common properties of a footprint. Each instrument's footprint inherits those properties from the abstract object.

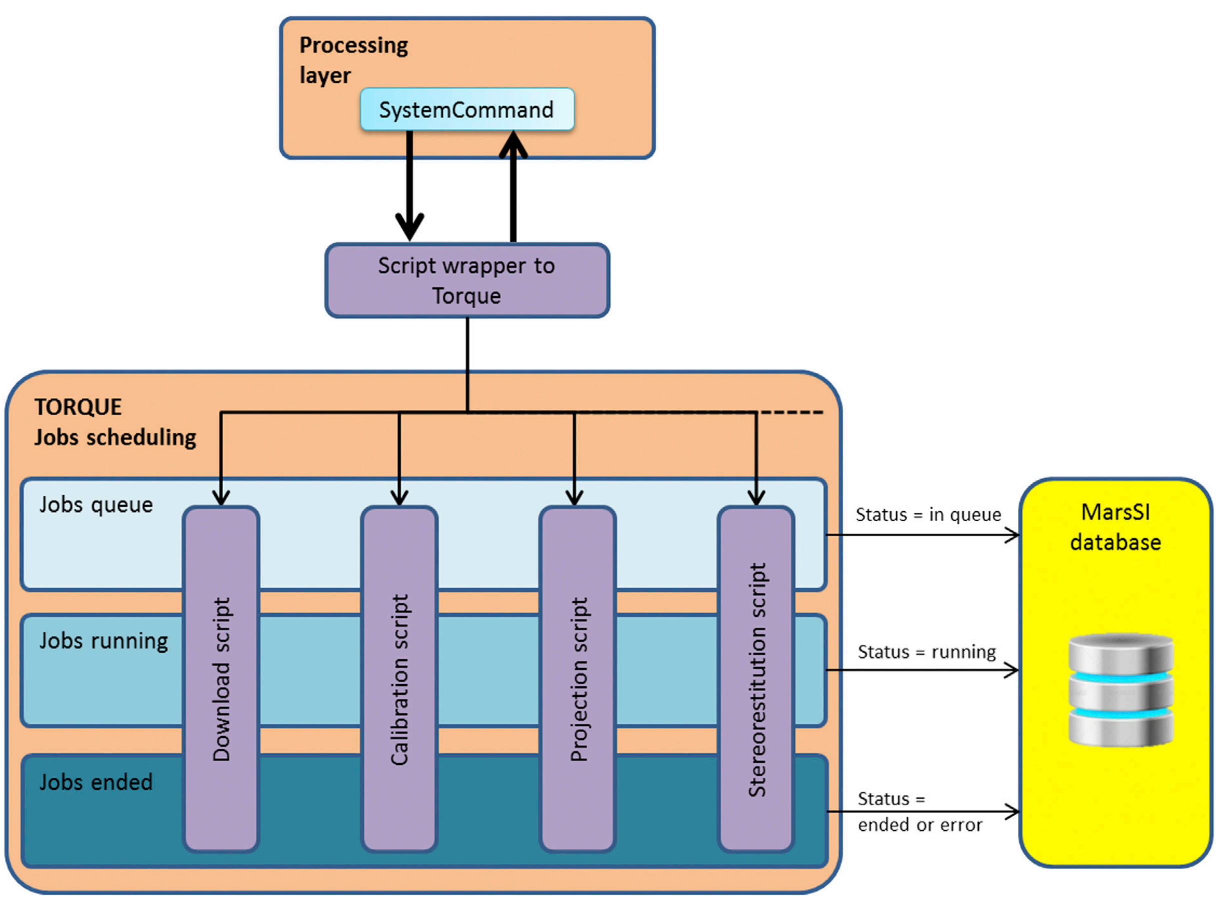

Fig. 10. Processing layer design. The processing layer launch a command which starts a script wrapper on the operating system. This script launches processing jobs into TORQUE. Each processing job updates its status in the MarsSI's database.

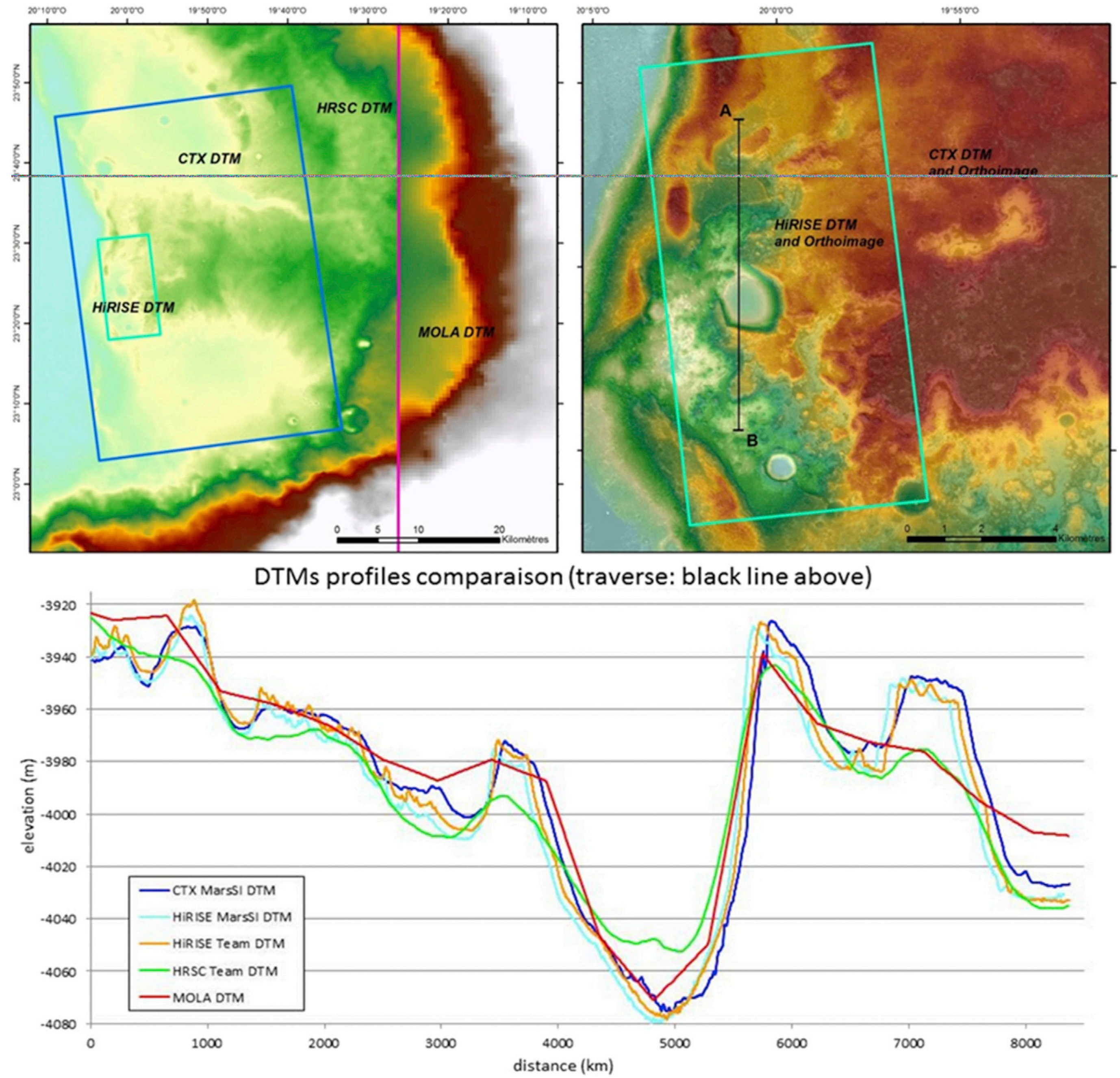

Fig. 11. Examples of DEMs generated by MarsSI and compared with lower resolution DEMs. The top images show the same area (inside Oyama crater) with, on the left, DEMs from HiRISE, superposed on CTX, superposed on HRSC, superposed on MOLA, and on the right the same HiRISE and CTX DEMs with transparency on their associated ortho-images. The north-south line indicates the location of the elevation profiles. HRSC DEM from H5235_0000_DA4 product, CTX DEM from orbits 007388 and 024912, HiRISE DEM from orbits 022288 and 022354).

DatasetTools) with the script's name and parameters. System Command calls, outside the java environment, a script wrapper that redirects parameters, according to the script's name, into TORQUE. Inside TORQUE, the image processing script is run as well as a PostgreSQL command that updates status of the image. This status will be visible for user when he clicks on the refresh command. The script also handle errors when the final image is missing.

4. Proposed data processing

4.1. CTX

The Context Camera (CTX) is a camera on board the NASA Mars Reconnaissance Orbiter acquiring grayscale (black & white) images at ~6 m per pixel scale over a swath 30 km wide, that can be as long as 160 km, or more. CTX images can be used as context images for the MRO HiRISE and CRISM observations to monitor changes occurring on the planet for instance. The camera also acquires stereo-pairs of selected, critical science targets (Malin et al., 2007).

CTX files from the PDS website are not calibrated or map projected, only EDR-level files are available. The uncalibrated data have a strong variation in pixel brightness between the center and the edge across track. These EDR data can be calibrated and map-projected to Radiometric Data Record (RDR) data and the Merged Radiometric Data Record (MRDR) data respectively. CTX calibration uses the Integrated Software for Imagers and Spectrometers level 3 (ISIS3) processing tool available to the community through the USGS (e.g. Anderson et al., 2004; Edmundson et al., 2012), and generates jp2 format file. In addition, when at least

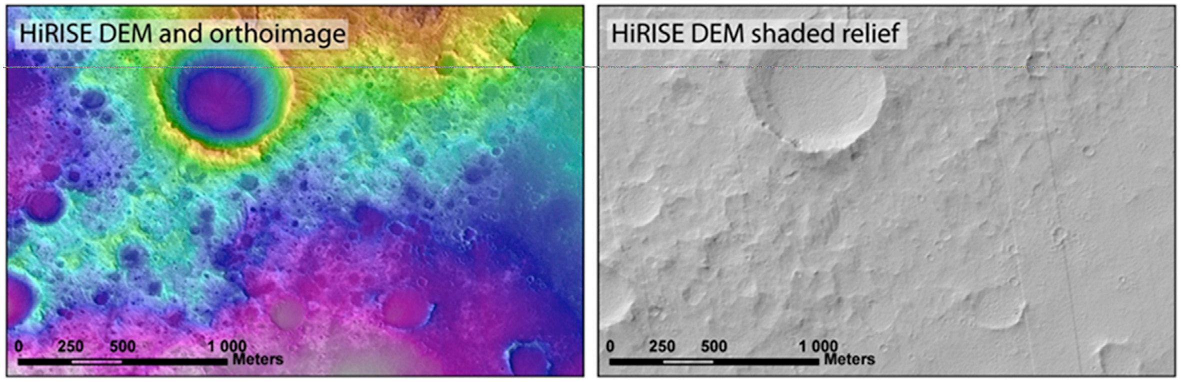

Fig. 12. The Figure shows close-ups on the HiRISE DEM and its associated ortho-image, and a shaded relief from the same DEM.(HRSC DEM from the HRSC MC-11 (East) DEM mosaic, CTX DEM from orbits 007388 and 024912, HiRISE DEM and ortho-image from orbits 037505 and 037993).

2 CTX images from the same surface have been acquired with different geometry, stereo-restitution can generate a DTM of the surface (see section V).

4.2. HIRISE

The High Resolution Imaging Science Experiment (HiRISE) instrument (McEwen et al., 2007; Delamere et al., 2010) onboard the NASA Mars Reconnaissance Orbiter spacecraft is a camera producing high resolution images with a spatial resolution up to 25 cm/pixel and a swath wide of 5.0–6.4 km. HiRISE produces color images in the visible and near infrared ranges using three band passes: the Blue-Green (BG) filter (<600 nm), the RED filter (550–850 nm centered at 700 nm) and infrared (IR) filter (>800 nm), creating 3 HiRISE color images with a central swath of color 1.0–1.3 km wide. The widest image is provided by the RED detectors and is usually used for geomorphology analyses and for stereo restitution to generate DTM products providing information about the surface elevation/topography (see section V).

In MarsSI, all the available acquired HiRISE RED and COLOR images and the DTM stereo-rectified products processed by the HiRISE team can be located with their footprints by displaying respectively the "MRO - HiRISE" layer and the "MRO - HiRISE Team DTM" layer in the Maps space. The HiRISE products that have been already processed by the HiRISE team and stored in the Planetary Data System (PDS) archive can be directly downloaded using MarsSI by processing the desired observation product in the "RDRV11" section for the COLOR and RED products or the "DTM" section for the DTM product in the "Data to process" window of the "Workspace" tab.

The HiRISE products can also be processed through MarsSI using the available processing pipeline. The HiRISE RED stereo images can be processed to generate DTM stereo-rectified products (see section V). The HiRISE RED and COLOR images can be processed from the EDR (raw) data to a final map projected products. Like CTX processing, MarsSI uses several programs available from ISIS3.

4.3. CRISM data

CRISM (Murchie et al., 2007, 2009) onboard the NASA Mars Reconnaissance Orbiter is a visible/near-infrared imaging spectrometer which was designed to operate in two modes relevant to surface studies: (1) a targeted mode yielding images 10 km by 10 km (Full Resolution Target or FRT at 18 m/pixel, and Half Resolution Short or HRS at 36 m/pixel) or 10 km by 20 km (Half Resolution Long or HRL at 36 m/pixel); (2) a survey mode yielding 10 km large and hundreds of km long strips, mostly at 200 m/pixel, and occasionally at 100 m/pixel. CRISM has two detectors: the L detector has 438 channels sampling the 1.0–4.0 μm wavelength range and the S detector has 107 channels sampling the 0.36–1.06 μm range, both at 6.55 nm spectral resolution. The survey mode was designed to record only a subset of 72 spectral channels from the L and S detectors. In targeted mode, the actual hyperspectral image of the surface is labeled "07", as it is the 7th image in a sequence of 15 including 4 darks at image resolution and 10 EPF (Emission Phase Function) images at 10-times lower spatial resolution.

All targeted image types can be displayed in MarsSI by activating the "MRO – CRISM Targeted" layer while survey (mapping) image types are available in the "MRO – CRISM Survey" layer.

A regular CRISM observation with calibrated radiance or reflectance ("I/F") is dubbed "TRR" (short for Target Reduced Data Record – TRDR), and the auxiliary information file is dubbed "DDR" (Derived Data Record). Both data files (TRDR and DDR), with their labels, are needed for a complete processing and analysis.

CRISM TRDR VNIR (S detector) data can be downloaded only with MarsSI, but no processing is available (yet). For TRDR infrared data (L detector), MarsSI offers processing in the form of a "CATRDR" data level in the user workspace. MarsSI "CATRDR" data level is based on an implementation of the CAT pipeline (CRISM Analysis Tools, an add-on to IDL/ENVI available from the CRISM team (Murchie et al., 2007; Pelkey et al., 2007). As a first step, the L cube is converted to the CAT format and corrected for the observation geometry (reflectance divided by the cosine of the incidence angle, available in the associated DDR cube) and for absorptions due to atmospheric CO_2, using the CAT algorithm developed for CRISM based on the 'volcano-scan' approach (McGuire et al., 2009). This step generates 2 new files, a data cube containing the reflectance data (I/F unit) in the IR range (from 1002 to 3920 nm) of the central image of a FRT observation and a data cube further corrected for the incidence angle and for atmospheric CO_2 absorptions using the volcano-scan algorithm.

In a second step, the TRDR cube, already corrected for incidence angle and atmospheric absorption, is processed through a custom procedure that we dub "ratioing", in which every spectrum is divided, on a column-by-column basis, by a column-wise median spectrum computed over the central half of the data cube (eg., lines 121 to 361 for a 480-lines cube). This "ratioing" procedure dramatically reduces detector noise (mostly column-dependant), corrects for most residual atmospheric absorptions (CO_2 gas and/or water vapor/ice), and enhances small spectral features in ratioed spectra. However, there are also caveats, such as the risk to introduce artifacts in ratioed spectra if the median spectra used for division itself was not blank but had spectral features: in such cases, the ratioed spectra will show inverted spectral features (an absorption in the median spectrum will yield a positive peak in the ratioed spectrum). Thus the end user should however be very cautious of artifacts, which can be checked by looking at the supplied "medianratioline" file.

The third step of the MarsSI CRISM pipeline computes, using the medianratio cube, a suite of so-called 'spectral parameters' or 'spectral criteria' such as band depths or combination of band depths (as initially implemented in the CAT for multispectral CRISM data (Pelkey et al., 2007). We take advantage of the higher number of spectral channels in hyperspectral targeted CRISM observations compared to original CAT multispectral parameters: signal-to-noise is improved by using medians of spectral channels and the specificity of many parameters is improved by combining several criteria. The definition of a subset of the custom criteria available in MarsSI is given in Thollot et al. (2012) and the remaining can be made available on request to the authors (pending publication in a future paper). The MarsSI end-user must be aware that, even if designed for detection of a specific mineral or mineral family (reflected in the parameter name), one parameter may or may not pick-up spectral features exclusive to this mineral: thus, actual spectra (ratioed or not) should be verified before concluding to any mineralogical identification by comparing it to laboratory spectra.

Finally, the pipeline projects the data cube for use in a GIS in combination with other datasets (DTMs, CTX or HiRISE, etc.). As with the CAT, this final step uses the Equirectangular projection, based on the Mars2000 sphere.

4.4. HRSC data

The High Resolution Stereo Camera (HRSC) onboard the ESA Mars Express spacecraft is a multi-channels stereo color camera, with the purpose of completing global imagery of Mars in panchromatic and color images, and to provide systematic stereo-imagery for DTM production. The HRSC camera produces multiple data products for each observation: 5 panchromatic images taken at 5 different emergence angles, upon which the nadir channel, and 4 images taken with 4 color filters taken at 4 different emergence angles. The nadir image has in general a higher resolution than the other images (Neukum et al., 2004a,b; Jaumann et al., 2007). This multiple data enables one to produce color images and DTMs through stereo-restitution using the different viewing angles. The resolution of the HRSC images is highly variable, and can vary from around 10 m/pix to 100's m/pix. The HRSC dataset covers the whole planet at different resolutions, most surfaces have been imaged several time: many HRSC footprints on MarsSI are overlapping. There is no proposed processing of HRSC images in MarsSI to date except their downloading.

4.5. THEMIS data

THEMIS (THermal Emission Imaging System) onboard the NASA Mars Odyssey spacecraft is a multispectral imager allowing the analysis of the morphology, the composition and the physical property of the martian surface. It has 9 channels in the thermal infrared between 6.78 μm and 14.88 μm and 5 channels in the visible near-infrared between 0.42 μm and 0.86 μm (Christensen et al., 2004). There are 3 types of THEMIS data: the infrared data, at 100 m/pixel, acquired by day and by night, and the visible images, from 18 to 35 m/pixel. The infrared images cover approximately areas 30 km by 100 km on the surface and have a global coverage of the planet except at high latitude for the images acquired by night.

Only the infrared data are available for download on MarsSI. The calibration pipeline is not yet available in MarsSI but will eventually be implemented when confidence in the product quality is deemed sufficient. For viewing convenience, the footprints coverage has been split in 4 layers:

1 THEMIS IR Day L – Long ground track during day time for infrared sensor
2 THEMIS IR Day S – Short ground track during day time for infrared sensor
3 THEMIS IR Night L – Long ground track during night time for infrared sensor
4 THEMIS IR Night S – Short ground track during night time for infrared sensor

4.6. OMEGA

OMEGA, the “Observatoire pour la Minéralogie, l’Eau, les Glaces et l’Activité” (Bibring et al., 2004), is a visible and near-infrared imaging spectrometer onboard ESA's Mars Express spacecraft. OMEGA covers the wavelengths 0.38–5.1 μm with 352 spectral channels, 7–20 nm wide. Spatial resolution varies from ~300 m to 5 km per pixel. OMEGA's Signal-to-Noise ratio (or ‘S/N’) is better than 100 over the whole spectral range (and can reach 1000 for some spectels), allowing detection of absorption bands as shallow as ~1% (Bibring et al., 2004).

The OMEGA instrument is made of two co-aligned grating spectrometers, one operating in the visible and near infrared (VNIR) in the range 0.38–1.05 μm, the other in the short wavelength infrared (SWIR) in the range 0.93–5.1 μm. Footprints of OMEGA data can be visualized in MarsSI by activating the “MEX –OMEGA” layer and data can be downloaded as EDR (raw) Level-1B. The calibrated OMEGA data (Level-2) can be accessed via the PSUP portal (Poulet et al., 2018).

5. Stereo-restitution

Digital Elevation Models (DEM) (or digital terrain models (DTM)) are numerical representations of topography in raster format. They are obtained by the interpolation of 3D point clouds on a regular grid. They are defined by their resolution (size of the pixels), their extension (number of lines and rows of the raster), their localization and their precision. They can be georeferenced in latitude – longitude mode or projected in a given reference frame. DEM are essential data sets to study the internal and external processes that shape the surface of planetary bodies (for the Moon - e.g. Barker et al., 2016 – for comets – e.g. Auger et al., 2015 –for Mars – e.g. Smith et al., 2001; Baratoux et al., 2001; Kirk et al., 2008; Gwinner et al., 2016). They are also needed to construct ortho-images which are images on which the distortion of the topography has been removed.

5.1. Possible DEM footprints

The stereo-restitution pipeline is only functional for HiRISE and CTX images. Footprints, which can be used for the generation for DEMs from image stereo-pairs, have been computed from the whole collection of CTX and HiRISE images and are regularly updated. For a CTX DEM, a DEM footprint is defined as the overlapping surface of two CTX images that overlap at least of 60% along track. The emission angle of the images has to be less than 5°. In order to avoid small DEM, the length along track has to be at least equal to the width of the overlap. More than 61,900 CTX DEM footprints are available for processing in MarsSI at time of this manuscript writing. The HiRISE footprints represent the overlap of two HiRISE images without other limitation. More than 30,600 HiRISE footprints are offered for calculation at the time of this manuscript writing. The program creating the DEM footprints is parallelized, which allows a prompt re-calculation after each new MRO data release.

5.2. DEM generation of CTX and HIRISE

The core of the DEM generation is realized by the NASA Ames pipeline (Shean et al., 2016; Moratto et al., 2010; Broxton and Edwards, 2008) which is part of the NASA NeoGeography toolkit. The user first selects the footprint of the future DEM and ortho-image on MarsSI. When a footprint is selected the user can inspect the images through the PDS in order to avoid the construction of DEM from bad quality images (too noisy or with low texture due to fog or sand storms). If the quality of the images is estimated to be good, the user places the footprint in the cart and the process of DEM calculation automatically starts. The images are downloaded from PDS if not already available on the MarsSI server. The images are then calibrated by ISIS3 routines (Edmundson et al.,2012). Then the images are sent to the pipeline using the “cam2map4stereo” and the “stereo” program. The default parameters defined by MarsSI are suitable for most of the situations and are a good compromise between processing time and quality of the DEM. The 3D point cloud obtained at the end of the "stereo" procedure is adjusted on the MOLA DEM (Smith et al., 2001) in order to remove low frequency errors. Finally, a DEM and ortho-image are computed and projected in a sinusoidal projection centered on the image. The position of the correlated uncorrelated pixels is available as an auxiliary image. This image can help to estimate qualitatively the quality of the DEM.

After one year, 304 CTX DTM and 98 HiRISE DTM have already been calculated by MarsSI and are available for download. These MarsSI DEMs can also be displayed on PSUP Marsvisu interface (Poulet et al., 2018).

5.3. DEM example and comparison

Figs. 11 and 12 shows examples of CTX and HiRISE DEMs generated by MarsSI, and superimposed on MOLA, HRSC and HiRISE DEMs for comparison. The limits between the different DEMs are still slightly visible due to differences in resolution that lead to high resolution elevation differences pixel to pixel, to edge effects, and to slight horizontal shifts between datasets. However, the high-resolution DEMs fit in very well inside the low resolution one. The elevation profiles comparison shows also the consistency between the DEMs, and the horizontal shift that is to be taken into account when using a DEM of a given dataset on top of an image of another dataset. But, when using the DEM on top of the associated ortho-image, the match is made at the pixel level, enabling very high resolution topographic studies, as illustrated by the close-up on the HiRISE DEM.

6. Discussion and perspectives

In the broad array of web-GIS applications distributing planetary data, a generic data processing tool is desired by the scientific community. Indeed, more than 100 registered users have ordered on-demand data processing via MarsSI. Designed by a team of planetary scientists, the application fully matches the needs for orbital data processing for geological investigations of the martian surface thanks to imagery, compositional data and 3D context. Future developments are still required for martian geological studies. Indeed, several sets of data still need to be available for processing (e.g. THEMIS and TES data). As the design of MarsSI allows the integration of new data processing chains, and offers standardized and shared storage/compute resources, such developments can be easily implemented.

In addition to imagery, 3D context and composition data, imaging the subsurface is also crucial to reconstruct local geologic contexts. Ground penetrating radar such as MARSIS (Mars Advanced Radar for Subsurface and Ionosphere Sounding; Picardi et al., 2005) onboard MEX and SHARAD (Shallow Radar; Seu et al., 2004) onboard MRO are the next step for MarsSI upgrade. These data also need processing before any scientific interpretation. Indeed, the return signal of ground penetrating radar is a mix of both surface clutter and the subsurface contribution. But only subsurface contribution is the signal of interests (Herique et al., 2009). To date, row radargrams distributed by NASA and ESA are not ready to use information because they contain both surface clutter and subsurface information. To focus on subsurface signal, a simulation of the surface clutter is required for each acquired radargram. Such simulations need DEMs of the observed scene as well as the acquisition conditions. Subsurfaces interfaces of interests can only be highlighted by comparing the computed surface clutter and the raw radargram. The computation of surface clutter is long and requires long computation time. We observe in the radar community the same shortcomings as in the surface community with identical computations being done several times inside a single team or inside the community but never shared or distributed. We plan to propose on-demand radar surface clutter simulation for MARSIS and SHARAD data based on algorithms developed by Herique et al. (2009).

MarsSI currently has about 100 registered users, but there is no enforce limit. The current computational capacities linked to MarsSI allow reduced waiting time for long processing such as HiRISE DTM calculation (no more than 24 h in average). As the processing are scheduled by processing queue, increasing the number of users without increasing the dedicated computation resources could substantially delay the delivery of the ordered product. There is a potential to link JMARS users (about 2000 users) to MarsSI. This would allow JMARS users to visualize the data proposed for processing and be redirected to MarsSI. However, if that were allowed, the computational capacity of MarsSI would require upgrades.

In addition to orbital data, the way MarsSI has been designed will allow the same kind of services for martian in-situ data. Instead of Mars global maps as navigation context, a local map of the rover playground can be implemented. The application has also been designed to deal with other planetary targets. Concerning ongoing mission, Cassini mission produced a very large volume of data since 2004 that are largely undistributed or distributed only in EDR format. Remote sensing data on Saturn's satellites acquired by ISS, VIMS and CIRS could be very easily implemented. This is also true for data obtained on Saturn's rings, except that they have to be projected on the ring plane in a specific reference frame for further analysis (e.g. Altobelli et al., 2008; Leyrat et al., 2008). Like Mars, MarsSI could also benefit lunar processing since the Moon has also been intensely targeted. Finally, in the context of future European missions, MarsSI could be adapted to Mercury in the preparation of the BepiColombo mission and Jupiter's worlds for the JUICE mission.

Finally, interoperability between MarsSI and other web-services in planetary science will be required. For instance, processed data products will need to be integrated to Planetary Virtual Observatory (EuroPlanet VESPA; Erard et al., 2018). Already, MarsSI is part of PSUP application (Poulet et al., 2018). All the processed data of MarsSI are integrated into SItools 2 generic tool developed by the French Space Agency with the standard of Planetary Virtual Observatory.

7. Conclusion

Inside the portal of Planetary data called PSUP (Planetary SUrface Portal) (see companion paper Poulet et al., 2018), we have designed a distributed information system called MarsSI (Mars System of Information) to manage martian orbital data. The users of MarsSI are able to easily and rapidly select observations, to process raw data via proposed automatic pipelines and to get back final products which can be visualized under geographic information systems. MarsSI also proposes DTM computation on demand from HiRISE or CTX pair-images. This application funded by the European Union's Seventh Framework Programme (FP7/2007–2013) (ERC project eMars, No. 280168) has been developed for the Mars surface, but the design is generic enough to be applicable to any other planetary objects of the solar system.

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References

Altobelli, N., Spilker, L.J., Leyrat, C., Pilorz, S., 2008. Thermal observations of Saturn's main rings by Cassini CIRS: phase, emission and solar elevation dependence. Planet. Space Sci. 56, 134–146.

Anderson, J.A., Sides, S.C., Soltesz, D.L., Sucharski, T.L., Becker, K.J., 2004. Modernization of Integrated software for imagers and spectrometers. In: Thirty-fifth Lunar and Planetary Science Conference. Houston, TX, 2004.

Auger, A.-T., Groussin, O., Jorda, L., Bouley, S., Gaskell, R., Lamy, P.L., Capanna, C., Thomas, N., Pommerol, A., Sierks, H., Barbieri, C., Rodrigo, R., Koschny, D., Rickman, H., Keller, H.U., Agarwal, J., A'Hearn, M.F., Barucci, M.A., Bertaux, J.L., Bertini, I., Cremonese, G., Da Deppo, V., Davidsson, B., Debei, S., De Cecco, M., El-

Maarry, M.R., Fornasier, S., Fulle, M., Gutiérrez, P.J., Güttler, C., Hviid, S., Ip, W.-H., Knollenberg, J., Kramm, J.-R., Kührt, E., Küppers, M., La Forgia, F., Lara, L.M., Lazzarin, M., Lopez Moreno, J.J., Marchi, S., Marzari, F., Massironi, M., Michalik, H., Naletto, G., Oklay, N., Pajola, M., Sabau, L., Tubiana, C., Vincent, J.B., Wenzel, K.P., 2015. Geomorphology of the Imhotep region on comet 67P/Churyumov-Gerasimenko from OSIRIS observations. Astron. Astrophys. 583, A35. https://doi.org/10.1051/0004-6361/201525947.

Bailen, M.S., Sucharski, R.M., Hare, T.M., Akins, S.W., Gaddis, L.R., 2017. Using the PDS planetary image locator tool (pilot) to investigate small bodies. In: 3rd Planetary Data Workshop. Abstract #1986.

Baratoux, D., Delacourt, C., Allemand, P., 2001. High-resolution digital elevation models derived from viking Orbiter images: method and comparison with mars Orbiter laser altimeter data. J. Geophys. Res. 106 (E12), 32927–32941. https://doi.org/10.1029/2000JE001454.

Barker, M.K., Mazarico, E., Neumann, G.A., Zuber, M.T., Haruyama, J., Smith, D.E., 2016. A new lunar digital elevation model from the lunar Orbiter laser altimeter and SELENE terrain camera. Icarus 273, 346–355. https://doi.org/10.1016/j.icarus.2015.07.039.

Bibring, J.-P., Soufflot, A., Berthe, M., Langevin, Y., Gondet, B., Drossart, P., Bouyé, M., Combes, M., Puget, P., Semery, A., Bellucci, G., Formisano, V., Moroz, V., Kottsov, V., team, O., 2004. OMEGA : observatoire pour la minéralogie, l'eau, les glaces et l'activité. In: Wilson, A. (Ed.), Mars Express: the Scientific Payload. ESA Publications Division, pp. 37–49.

Broxton, M.J., Edwards, L.J., 2008. The ames stereo pipeline: automated 3D surface reconstruction from Orbital imagery. In: Lunar and Planetary Science Conference, p. 39 abstract #2419.

Christensen, P.R., Jakosky, B.M., Kieffer, H.H., Malin, M.C., McSween Jr., H.Y., Nealson, K., Mehall, G.L., Silverman, S.H., Ferry, S., Caplinger, M., Ravine, M., 2004. The thermal emission imaging system (THEMIS) for the mars 2001 Odyssey mission. Space Sci. Rev. 110, 85–130.

Christensen, P.R., Engle, E., Anwar, S., Dickenshied, S., Noss, D., N.Gorelick, Weiss-Malik, M., 2009. JMARS – a Planetary GIS. American Geophysical Union. Fall meeting 2009, abstract #IN22A-06.

Cunningham, G.E., 1996. Mars global surveyor mission. Acta Astronaut. 38 (4–8), 367–375. https://doi.org/10.1016/0094-5765(96)00035-5.

Delamere, A.W., Tornabene, L.L., McEwen, A.S., Becker, K., Bergstrom, J.W., Bridges, N.T., Eliason, E.M., Gallagher, D., Herkenhoff, K.E., Keszthelyi, L., Mattson, S., McArthur, G.K., Mellon, M.T., Milazzo, M., Russell, P.S., Thomas, N., 2010. Color imaging of mars by the high resolution imaging science experiment (HiRISE). Icarus 205 (1), 38–52. https://doi.org/10.1016/j.icarus.2009.03.012. January 2010.

Edmundson, K.L., Cook, D.A., Thomas, O.H., Archinal, B.A., Kirk, R.L., 2012. Jigsaw: the ISIS3 bundle adjustment for extraterrestrial photogrammetry. Int. Ann. Photogram., Remote Sens. Spatial Inf. Sci. I-4, 203–208.

Edwards, C.S., Nowicki, K.J., Christensen, P.R., Hill, J., Gorelick, N., Murray, K., 2011. Mosaicking of global planetary image datasets: 1. Techniques and data processing for Thermal Emission Imaging System (THEMIS) multi-spectral data. J. Geophys. Res. 116, E10008. https://doi.org/10.1029/2010JE003755.

Erard, S., Cecconi, B., Le Sidaner, P., Rossi, A.P., Capria, M.T., Schmitt, B., Génot, V., André, N., Vandaele, A.C., Scherf, M., Hueso, R., Määttänen, A., Thuillot, W., Carry, B., Achilleos, N., Marmo, C., Santolik, O., Benson, K., Fernique, P., Beigbeder, L., Millour, E., Rousseau, B., Andrieu, F., Chauvin, C., Minin, M., Ivanoski, S., Longobardo, A., Bollard, P., Albert, D., Gangloff, M., Jourdane, N., Bouchemit, M., Glorian, J.-M., Trompet, L., Al-Ubaidi, T., Juaristi, J., Desmars, J., Guio, P., Delaa, O., Lagain, A., Soucek, J., Pisa, D., 2018. VESPA: a community-driven virtual Observatory in planetary science. Planet. Space Sci. 150, 65–85.

Graf, J.E., Zurek, R.W., Eisen, H.J., Jai, B., Johnston, M.D., DePaula, R., 2005. The mars reconnaissance Orbiter mission. Acta Astronaut. 57, 566–578. https://doi.org/10.1016/j.actaastro.2005.03.043.

Gwinner, K., Jaumann, R., Hauber, E., Hoffmann, H., Heipke, C., Oberst, J., Neukum, G., Ansan, V., Bostelmann, J., Dumke, A., Elgner, S., Erkeling, G., Fueten, F., Hiesinger, H., Hoekzema, N.M., Kersten, E., Loizeau, D., Matz, K.-D., McGuire, P.C., Mertens, V., Michael, G., Pasewaldt, A., Pinet, P., Preusker, F., Reiss, D., Roatsch, T., Schmidt, R., Scholten, F., Spiegel, M., Stesky, R., Tirsch, D., van Gasselt, S., Walter, S., Wählisch, M., Willner, K., 2016. The high resolution stereo camera (HRSC) of mars express and its approach to science analysis and mapping for mars and its satellites. Planet; Space Sci. 126 https://doi.org/10.1016/j.pss.2016.02.014.

Herique, A., Kofman, W., Mouginot, J., Grima, C., Eyraud, C., Nouvel, J.F., Safaeinili, A., 2009. Surface echo reduction by clutter simulation, application to the Marsis data. In: IEEE Radar Conference, Pasadena, United States, pp. 1–4. https://doi.org/10.1109/RADAR. 2009.

Jaumann, R., Neukum, G., Behnke, T., Duxbury, T.C., Eichentopf, K., Flohrer, J., Gasselt, S.v., Giese, B., Gwinner, K., Hauber, E., Hoffmann, H., Hoffmeister, A., Köhler, U., Matz, K.-D., McCord, T.B., Mertens, V., Oberst, J., Pischel, R., Reiss, D., Ress, E., Roatsch, T., Saiger, P., Scholten, F., Schwarz, G., Stephan, K., Wählisch, M., 2007. The high resolution stereo camera (HRSC) experiment on mars express: instrument aspects and experiment conduct from interplanetary cruise through nominal mission. Planet. Space Sci. 55, 928–952. https://doi.org/10.1016/j.pss.2006.12.003.

Kirk, R.L., Howington-Kraus, E., Rosiek, M.R., Anderson, J.A., Archinal, B.A., Becker, K.J., Cook, D.A., Galuszka, D.M., Geissler, P.E., Hare, T.M., Holmberg, I.M., Keszthelyi, L.P., Redding, B.L., Delamere, W.A., Gallagher, D., Chapel, J.D., Eliason, E.M., King, R., McEwen, A.S., 2008. Ultrahigh resolution topographic mapping of Mars with MRO HiRISE stereo images: meter-scale slopes of candidate Phoenix landing sites. J. Geophys. Res. 113, E00A24 https://doi.org/10.1029/2007JE003000.

Kolbe, D., 1999. Mars express: evolution towards an affordable european mars mission. Acta Astronaut. 45, 285–292. https://doi.org/10.1016/S0094-5765(99)00145-9.

Leyrat, C., Spilker, L.J., Altobelli, N., Pilorz, S., Ferrari, C., 2008. Infrared observations of Saturn's rings by Cassini CIRS : phase angle and local time dependence. Planet. Space Sci. 56 (2008), 117–133.

Malin, M.C., Bell, J.F., Cantor, B.A., Caplinger, M.A., Calvin, W.M., Clancy, R.T., Edgett, K.S., Edwards, L., Haberle, R.M., James, P.B., Lee, S.W., Ravine, M.A., Thomas, P.C., Wolff, M.J., 2007. Context camera investigation on board the Mars reconnaissance orbiter. J. Geophys. Res. 112 (E5) https://doi.org/10.1029/2006JE002808.

Marco, F.R., Pham Huu, B., Rossi, A.P., Minin, M., Flahaut, J., Halder, A., 2018. A. Online Characterization of Planetary Surfaces: PlanetServer. an Open-source Analysis and Visualization Tool. 150, 141–156.

McEwen, A.S., Eliason, E.M., Bergstrom, J.W., Bridges, N.T., Hansen, C.J., Delamere, W.A., Grant, J.A., Gulick, V.C., Herkenhoff, K.E., Keszthelyi, L., Kirk, R.L., Mellon, M.T., Squyres, S.W., Thomas, N., et al., 2007. Mars reconnaissance orbiter's high resolution imaging science experiment (HiRISE). J. Geophys. Res. 112 (E5), E05S02 https://doi.org/10.1029/2005JE002605.

McGuire, P.C., Bishop, J.L., Brown, A.J., Fraeman, A.A., Marzo, G.A., Morgan, M.F., et al., 2009. An improvement to the volcano-scan algorithm for atmospheric correction of CRISM and OMEGA spectral data. Planet. Space Sci. 57 (7), 809–815.

Moratto, Z.M., Broxton, M.J., Beyer, R.A., Lundy, M., Husmann, K., 2010. Ames stereo pipeline, NASA's Open source automated stereogrammetry software. In: Lunar and Planetary Science Conference 41 abstract #2364. [ADS Abstract].

Murchie, S., Arvidson, R., Bedini, P., Beisser, K., Bibring, J.-P., Bishop, J., Boldt, J., Cavender, P., Choo, T., Clancy, R.T., Darlington, E.H., Des Marais, D., Espiritu, R., Fort, D., Green, R., Guinness, E., Hayes, J., Hash, C., Heffernan, K., Hemmler, J., Heyler, G., Humm, D., Hutcheson, J., Izenberg, N., Lee, R., Lees, J., Lohr, D., Malaret, E., Martin, T., McGovern, J.A., McGuire, P., Morris, R., Mustard, J., Pelkey, S., Rhodes, E., Robinson, M., Roush, T., Schaefer, E., Seagrave, G., Seelos, F., Silverglate, P., Slavney, S., Smith, M., Shyong, W.-J., Strohbehn, K., Taylor, H., Thompson, P., Tossman, B., Wirzburger, M., Wolff, M., 2007. Compact reconnaissance imaging spectrometer for mars (CRISM) on mars reconnaissance Orbiter (MRO). J. Geophys. Res. 112, E05S03 https://doi.org/10.1029/2006JE002682.

Murchie, S.L., Seelos, F.P., Hash, C.D., Humm, D.C., Malaret, E., McGovern, J.A., Choo, T.H., Seelos, K.D., Buczkowski, D.L., Morgan, M.F., Barnouin-Jha, O.S., Nair, H., Taylor, H.W., Patterson, G.W., Harvel, C.A., Mustard, J.F., Arvidson, R.E., McGuire, P., Smith, M.D., Wolff, M.J., Titus, T.N., Bibring, J.-P., Poulet, F., 2009. Compact reconnaissance imaging spectrometer for mars investigation and data set from the mars reconnaissance Orbiters primary science phase. J. Geophys. Res. 114, E00D07.

Neukum, G., Jaumann, R., HRSC Co-Investigator and Experiment Team, 2004a. HRSC: the high resolution stereo camera of Mars Express. ESA Spec. Publ. 1240, 1–19.

Neukum, G., Jaumann, R., HRSC Co-Investigator and Experiment Team, 2004b. HRSC: the high resolution stereo camera of mars express. In: Wilson, A. (Ed.), Mars Express: the Scientific Payload. ESA, Noordwijk, The Netherlands, pp. 17–35.

Pelkey, S.M., Mustard, J.F., Murchie, S., Clancy, R.T., Wolff, M., Smith, M., Milliken, R., Bibring, J.-P., Gendrin, A., Poulet, F., Langevin, Y., Gondet, B., 2007. CRISM multispectral summary products: parameterizing mineral diversity on Mars from reflectance. J. Geophys. Res. 112, E08S14.

Picardi, J.J., Plaut, D., Biccari, O., Bombaci, D., Calabrese, M., Cartacci, A., Cicchetti, S.M., Clifford, P., Edenhofer, W.M., Farrell, C., Frigeri, D.A., Gurnett, T., Hagfors, E., Heggy, A., Herique, R.L., Huff, A.B., Ivanov, W.T.K., Johnson, R.L., Jordan, D.L., Kirchner, W., Kofman, C.J., Leuschen, E., Nielsen, R., Orosei, E., Pettinelli, R.J., Phillips, D., Plettemeier, A., Safaeinili, R., Seu, E.R., Stofan, G., Vannaroni, T.R., Watters, E., Zampolini, 2005. Radar soundings of the subsurface of Mars. Science 310. https://doi.org/10.1126/science.1122165, pp. 1925-1928.

Poulet, F., Quantin-Nataf, C., Ballans, H., Dassas, K., Audouard, J., Carter, J., Gondet, B., Lozac'h, L., Malapert, J.-C., Marmo, C., Riu, L., Séjourné,, A., 2018. PSUP: a Planetary SUrface Portal, 150, 2–8.

Saunders, R.S., Arvidson, R.E., Badhwar, G.D., Boynton, W.V., Christensen, P.R., Cucinotta, F.A., Feldman, W.C., Gibbs, R.G., Kloss, C., L;ano, M.R., Mase, R.A., McSmith, G.W., Meyer, M.A., Mitrofanov, I.G., Pace, G.D., Plaut, J.J., Sidney, W.P., Spencer, D.A., Thompson, T.W., Zeitlin, C.J., 2004. 2001 Mars Odyssey mission summary. Space Sci. Rev. 110, 1–36. https://doi.org/10.1023/B:SPAC.0000021006.84299.18.

Seidelmann, P.K., Abalakin, V.K., Bursa, Milan, Davies, M.E., De Bergh, Catherine, Lieske, J.H., Oberst, Juergen, Simon, J.L., Standish, E.M., Stooke, P.J., Thomas, P.C., 2002. Report of the IAU/IAG Working Group on Cartographic Coordinates and Rotational Elements of the Planets and Satellites, 2000: Celestial Mechanics and Dynamical Astronomy, vol. 82, pp. 83–110.

Seu, R., Biccari, D., Orosei, R., Lorenzoni, L.V., Phillips, R.J., Marinangeli, L., Picardi, G., Masdea, A., Zampolini, E., 2004. SHARAD: the MRO 2005 shallow radar. Planet. Sp. Sci. 52, 157–166.

Shean, D.E., Alexandrov, O., Moratto, Z., Smith, B.E., Joughin, I.R., Porter, C.C., Morin, P.J., 2016. An automated, open-source pipeline for mass production of digital elevation models (DEMs) from very high-resolution commercial stereo satellite imagery. ISPRS J. Photogram. Remote Sens. 116.

Smith, D.E., Zuber, D.E., Frey, M.T., Gravin, V.H., Head, J.W., Muhleman, D.O., Pettengill, G.H., Phillips, R.J., Solomon, S.C., Zwally, H.J., Banerdt, W.B., Duxbury, T.C., Golombek, M.P., Lemoine, F.G., Neumann, G.A., Rowlands, D.D., Aharonson, O., Ford, P.G., Ivanov, B.A., McGovern, P.J., Abshire, J.B., Afzal, R.S., Sun, X., 2001. Mars Orbiter laser altimeter : experiment summary after the first year of global mapping of mars. J. Geophys. Res. 106 (E10), 23689–23722.

Thollot, P., Mangold, N., Ansan, V., Le Mouelic, S., Milliken, R.E., Bishop, J.L., Weitz, C.M., Roach, L.H., Mustard, J.F., Murchie, S.L., 2012. Most Mars minerals in a nutshell: various alteration phases formed in a single environment in Noctis Labyrinthus. J. Geophys. Res. Planets (1991–2012) 117 (E11).

Zinzi, A., Capria, M.T., Palomba, E., Giommi, P., Antonelli, L.A., 2016. MATISSE: a novel tool to access, visualize and analyse data from planetary exploration missions. Astron. Comput. 15, 16–28.