The Mars Planetary Mapping Pilot Project

This report forms the final deliverable for ESA’s contracts with the British Geological Survey, and the TNO/Deltares Geological Survey of the Netherlands, and also their subcontractors: the Mullard Space Science Laboratory and the University College London, and the Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, Netherlands. The project was undertaken from February 2009 until July 2010. The project teams consisted of the following people:

**British Geological Survey:**

**TNO/Deltares Geological Survey of the Netherlands:**
J.L. Gunnink, J.H.P. Oosthoek.

**Mullard Space Science Laboratory and University College London:**
J.-P. Muller, P.J. Grindrod.

**Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, Netherlands:**
F.J.A. van Ruitenbeek, W. Bakker, H. van der Werff.

**European Space Agency:**
P. Martin, T. Zegers.
# Table of contents:

Abstract .................................................................................................................................... 4  
List of Acronyms ...................................................................................................................... 5  
Table of Figures ....................................................................................................................... 8  
1 Introduction ............................................................................................. 9  
2 Planetary Mapping Workflow ................................................................... 9  
3 Key Deliverables ....................................................................................... 9  
4 Summary of WP0: Site Selection & contributions by Prof. J.-P. Muller: ... 10  
5 Summary of WP1: Data Management (BGS) ............................................. 13  
5.1 Website capabilities ........................................................................................................ 13  
5.2 Access URLs .................................................................................................................... 13  
5.3 Technology ...................................................................................................................... 13  
5.4 Page navigation & web services ...................................................................................... 14  
6 Summary of WP2: Information Extraction: Delivering the Information Layers (Deltares, UCL, and ITC) ................................................................... 15  
6.1 Processing OMEGA data by ITC: .................................................................................... 15  
6.2 The processing chain contains the following steps: ....................................................... 15  
6.2.1 Extraction and calibration from raw data sets downloaded from the Planetary Science Archive of ESA: ................................................................. 16  
6.2.2 Spectral sub-setting of the hyperspectral image-cube; ............................................... 16  
6.2.3 Atmospheric and albedo correction using Kwik Log Residuals method; ................... 17  
6.2.4 Noise filtering; .............................................................................................................. 17  
6.2.5 Production of interpretable image features; ................................................................. 17  
6.2.5.1 Hyperspectral edge detection ..................................................................................... 17  
6.2.5.2 Wavelength position of dominant absorption features ..................................................... 17  
6.2.5.3 Summary products ..................................................................................................... 18  
6.2.5.4 Colour composites ...................................................................................................... 19  
6.2.6 Geocorrection ............................................................................................................... 21  
6.2.7 Stretching and thresholding of information products ................................................. 21  
7 Summary of WP3: Visualisation; delivering Mapping and Modelling tools: (BGS): ......................................................................................................................... 23  
8 Summary of WP4: Geological Mapping and Modelling (TNO): ................ 24  
9 Results: independent test by Dr Peter Grindrod (UCL): ........................... 26  
10 Conclusions ............................................................................................. 27  
11 References .............................................................................................. 28  
APPENDIX ............................................................................................................................ 29  
CONFERENCE ABSTRACTS & PRESENTATIONS: ........................................................... 29
Abstract

This report describes a pilot study designed to transfer the modern, digital methods and workflows used in terrestrial geological mapping to planetary mapping. The study was undertaken by an integrated project team that included experienced geological mappers from the British and Dutch geological surveys and planetary geology experts from University College London and the Faculty of Geo-Information Science and Earth Observation (ITC) in the Netherlands. It gave a thorough demonstration of a potential future planetary mapping workflow, which was demonstrated to interested staff from ESA at the final project meeting. At the same time, it provided a realistic test of the approach, because the test site selected is of significant interest to the planetary mapping community; with interesting geological features and sufficient potential for safe landing areas, the Nili Fossae area of Mars has been a candidate landing site for some time and may be considered for one of the next mission opportunities at Mars in the coming decade.

Data were available from a number of US and European missions; the focus in this study was placed on the ESA datasets from the High Resolution Stereo Camera and the OMEGA hyperspectral instrument. Having chosen the landing site, the first step of the workflow was to process the raw data to highlight features of interest in derived information products. These included digital elevation models extracted from the stereo data and mineral maps made using the hyperspectral data. These data were integrated in a project GIS and then visualised using both a digital stereo workstation and the BGS’s GeoVisionary system, a 3D, immersive virtual environment for geologists to work in.

These tools were used to interpret the data, in order to produce a geological map for the Nili Fossae area. A leading planetary geologist was brought in on a sub-contract, to advise the project team on this aspect of the study. The raw data, extracted information products and final geological map were all stored in a web map server, with sufficient metadata to facilitate their discovery and use by other planetary scientists. Links were also built and demonstrated to other platforms for the data, such as Google Mars. Dissemination is ongoing and included papers at relevant conferences and contributions to workshops during the lifetime of the project. It is hoped that, through such dissemination and stakeholder engagement, the study will pave the way for these techniques to be adopted in planetary mapping on a routine basis in the future.
List of Acronyms

**ArcGIS**  A suite of Geographic Information System products produced by ESRI

**BAE**  British Aerospace, a defence, security and aerospace company

**BGS**  British Geological Survey

**B&W**  Black and White

**Co-I**  Co-Investigator

**CTX**  The Context Camera provides wide-area context views for higher resolution instruments (e.g., HiRISE) on the NASA Mars Reconnaissance Orbiter

**DELTARES**  Is a leading, independent Dutch-based research institute and specialist consultancy relating to water, soil and the subsurface. In 2008 TNO’s Subsurface and Groundwater unit became part of Deltares.

**DEM**  Digital Elevation Model (an elevation model which can also include the tops of vegetation and buildings when present)

**DLR**  The German Aerospace Centre

**DTM**  Digital Terrain Model (usually restricted to a ground surface)

**ESA**  European Space Agency

**ESTEC**  European Space Research and Technology Centre

**EU-FP7**  European Union Seventh Framework Programme

**GIS**  Geographical Information System

**GPS**  Global Positioning System

**HiRISE**  The High Resolution Imaging Science Experiment is a 0.5m reflecting telescopic camera on the Mars Reconnaissance Orbiter, which can take B&W pictures with pixel resolutions up to 25cm from an orbit height of 250 km, resolving objects about 75cm across.

**HRSC**  High Resolution Stereo Camera on the ESA Mars Express satellite
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I3DVF</td>
<td>Immersive 3D Virtual Facility at the BGS</td>
</tr>
<tr>
<td>IDL</td>
<td>Interactive Data Language, a scientific and data visualisation computer language developed by the company ITT Visual Information Solutions</td>
</tr>
<tr>
<td>IR</td>
<td>Infrared wavelengths of electromagnetic energy (0.72-1000 microns)</td>
</tr>
<tr>
<td>ITC</td>
<td>Faculty of Geo-Information Science and Earth Observation (ITC) in the Netherlands</td>
</tr>
<tr>
<td>KML</td>
<td>Keyhole Markup Language, is an XML-based schema for expressing geographic information in 2D and 3D internet browsers</td>
</tr>
<tr>
<td>MOLA</td>
<td>Mars Orbiter Laser Altimeter, was an instrument on the NASA Mars Global Surveyor satellite</td>
</tr>
<tr>
<td>MSL</td>
<td>Mars Science Laboratory, will contain a suite of instruments on a NASA rover (recently named Curiosity) due for launch in November 2011, and due for precision landing in August 2012.</td>
</tr>
<tr>
<td>MSSL</td>
<td>The Mullard Space Science Laboratory, is the United Kingdom’s largest university space research group belonging to the Department of Space and Climate Physics of the University College London</td>
</tr>
<tr>
<td>NASA</td>
<td>The National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>OMEGA</td>
<td>A 352-band hyperspectral visible and infrared (0.35-5.1 microns) mineralogical mapping spectrometer (Observatoire pour la Minéralogie, l’Eau, les Glaces et l’Activité) on the ESA Mars Express satellite</td>
</tr>
<tr>
<td>PANGU</td>
<td>Planet and Asteroid Natural scene Generation Utility: a University of Dundee, Space Technology Centre project supported by ESA</td>
</tr>
<tr>
<td>PDS</td>
<td>Planetary Data System</td>
</tr>
<tr>
<td>PMPP</td>
<td>ESA’s Planetary Mapping Pilot Project</td>
</tr>
<tr>
<td>PSA</td>
<td>ESA’s Planetary Science Archive</td>
</tr>
<tr>
<td>PSS</td>
<td>The Elsevier journal: Planetary and Space Science</td>
</tr>
</tbody>
</table>
SOCET SET  A suite of digital photogrammetry software programs to generate digital elevation models and orthophotos, developed by BAE Systems

SoW  Schedule of Work

SWIR  Short Wave Infrared (1.4-3.0 microns)

THEMIS  A 10-band middle to long infrared spectrometer (6.78-14.9 microns) on the Mars Odyssey satellite

TNO  TNO Geological Survey of the Netherlands, which is part of the Netherlands Organisation for Applied Scientific Research

UCL  University College London

UK NASA RPIF  United Kingdom NASA Regional Planetary Image Facility at the University College London

USGS  United States Geological Survey

WCS  Web Coverage Service Interface Standard, allows interoperable web access to grid coverages such as satellite images, digital aerial photos, and digital elevation data

WFS  Web Feature Service Interface Standard, provides a web interface to request geographic features using platform-independent calls

WMS  Web Map Service, is a standard protocol for serving georeferenced map images generated by a map server using data from a GIS database.
Table of Figures

Figure 1 Location of the Nili Fossae study region, located to the north-west of the Isidis Basin on Mars and indicated by a white square on top of the MOLA digital elevation model (dark = low elevations, white = high elevations). ................................................................. 11

Figure 2. Colour shaded 50m HRSC derived DEM of the Nili Fossae project area....................... 11

Figure 3 Nadir HRSC image mosaic of scenes H0988, H1347 and H3047 at 12.5m pixel resolution of the Nili Fossae project area.............................................................................................................................. 12

Figure 4. Colour HRSC image mosaic of scenes H0988, H1347 and H3047 at 50m pixel resolution of the Nili Fossae project area.............................................................................................................................. 12

Figure 5. WMS Flowchart.............................................................................................................. 14

Figure 6. Example of SWIR-1 Albedo image for OMEGA scene ORB 0422 with 2459m pixels. .. 18

Figure 7. Example of SWIR-1 log residual image with a median 7 filter for OMEGA scene ORB 0422 with 2459m pixels. Red= Wavemin, Green= Band 2081, Blue=Band 2592............... 18

Figure 8. Example of SWIR-1 log residual image with a median 7 filter for OMEGA scene ORB 0422 with 2459m pixels. Red= band depth 1900 (H2O), Green= drop 2300 (phyllosilicates), Blue=drop 2400 (sulphates).................................................................. 21

Figure 9. Example of SWIR-1 stretched log residual image with a median 7 filter for OMEGA scene ORB 0422 with 2459m pixels. Red= band depth 1900 (H2O), Green= drop 2300 (phyllosilicates), Blue=drop 2400 (sulphates).................................................................. 21

Figure 10. Dr Peter Grindrod discussing the 3D shapefiles of the Nili Fossae geological interpretation displayed on top of some OMEGA mineral maps, in the GeoVisionary floor-to-ceiling, i3DVF facility at the British Geological Survey. ................................................................. 23

Figure 11. Dr Doug Tragheim discussing the 3D Nili Fossae geological interpretation, displayed on top of higher resolution (100m) THEMIS decorrelation stretch 875 and 975 mosaicked images in the GeoVisionary floor-to-ceiling, i3DVF facility at the British Geological Survey. ................................. 24

Figure 12. Extract of final geological map interpretation of the Nili Fossae region using a combination of ArcGIS, SOCET SET and GeoVisionary software tools. ................................................................. 25

Figure 13. Legend to accompany the Nili Fossae geological map interpretation............................ 26
1 INTRODUCTION

Through SoW 001, ESA invited BGS and Deltares to respond to their requirement for a pilot project demonstrating the application of terrestrial geological mapping tools and approaches developed by geological surveys to the planetary surveying context. The goal of the pilot project is to design and build a demonstration system that will enhance data management, information extraction, visualisation and mapping of planetary data products, using a selected sample of Mars Express data, some publicly available in ESA’s Planetary Science Archive (PSA) and the rest provided by a HRSC Co-I in this team, derived from publically available data. The system will enhance archiving, distribution and usage of high-level data products for planetary science in the future. One test site on Mars will be selected in consultation with ESA and leading planetary scientists, based on both its scientific interest and its potential for demonstrating the capabilities of the new system. That system will make use of operational tools developed for terrestrial applications, with the objective of establishing the benefits of using sophisticated, but now standard, geological surveying tools to enhance planetary science applications.

2 PLANETARY MAPPING WORKFLOW

The planetary mapping workflow emerging from the pilot study has the following main elements:

- Site selection based on a range of scientific and societal requirements
- Data gathering and progressive compilation in a GIS
- The enhancement of raw data into information products
- Visualisation of multiple datasets over the area of interest
- Interpretation of the geology in the light of all available data
- Deposition and management of all project data in a web map server

The only element missing in comparison to the terrestrial workflow is field work. This makes the use of immersive visualisation methods all the more important, as they allow the geologist to undertake virtual field work where previously none was possible.

3 KEY DELIVERABLES

The project will produce four main deliverables to meet ESA’s stated requirements:

1. Prototype data management system (Web Map Server) that stores relevant data and allows planetary scientists to discover, explore and access them.
2. Information products on a range of themes, such as mineral maps, elevation models and hazard zonations (contained within the delivered Project GIS).
3. State-of-the-art tools to analyse and visualise such data, as part of a documented planetary mapping workflow (demonstrated at the final workshop and also via a customised fly-through of the project datasets on the WMS).
4. Derived geological map for the demonstration test site (on the WMS/GIS).
Each deliverable represents a key element of the modern geological surveying workflow and has a work package dedicated to its production. These are described in the next section.

4 SUMMARY OF WPO: SITE SELECTION & CONTRIBUTIONS BY PROF. J.-P. MULLER

Several Martian sites were initially considered by Deltares and UCL for this project, and discussed by all the project team at the kick-off meeting on 24 February 2009. These were: Becquerel Crater (containing rhythmically-banded interior layered deposits), Iani Chaos (chaotic terrain with hematite and sulphates), Mawrth Vallis (layered phyllosilicates), Eberswalde Crater (a delta), Gale Crater (>2km sequence of interior layered deposits of sulphates and phyllosilicates), and Nili Fossae (valley networks, phyllosilicates and clay-rich basement, overlain by olivine-rich basalts and upper lava flows). Three of these sites had already made it into the final seven of the Mars Science Laboratory (MSL) site-selections: (Eberswalde, Mawrth Vallis and Nili Fossae). Our project site-selection criteria was based on the availability of existing 50m HRSC DTMs and 12.5m ortho-images, as well as sufficient coverage of raw, unprocessed OMEGA hyperspectral data from the ESA Mars Express orbiter satellite. Other factors included safe landing constraints (40°N to 5°S, with topographic elevations < 0 Mars datum, and slopes <2 degrees) of a future Mars Mission. In addition, it was felt that the choice of study area should be relevant to a possible future European ExoMars mission, containing mineralogic and morphologic diversity, and potential habitability and biosignature preservation. The Nili Fossae site was eventually chosen after much discussion.

After selection of the Nili Fossae test site, Prof. J.-P. Muller provided a 50m Digital Terrain Model mosaic derived from HRSC along with a 12.5m orthorectified mosaic of the HRSC nadir image and individual orthorectified HRSC orbits of the 3 main colour bands. These were derived in the course of another ESA contract on PANGU datasets. Prof. Muller provided expert advice both within all of the meetings held during the PMPP and in between the meetings via email as well as demonstration of visualisation work developed in his group. These visualisations included fusion of multi-resolution DTMs over Nili Fossae, advice on how to process CTX data including orthorectification and the web-GIS, MarsWeb, which has been developed for rapid crater detection and isochron measurement.
Figure 1 Location of the Nili Fossae study region, located to the north-west of the Isidis Basin on Mars and indicated by a white square on top of the MOLA digital elevation model (dark = low elevations, white = high elevations).

Figure 2. Colour shaded 50m HRSC derived DEM of the Nili Fossae project area.
Figure 3. Nadir HRSC image mosaic of scenes H0988, H1347 and H3047 at 12.5m pixel resolution of the Nili Fossae project area.

Figure 4. Colour HRSC image mosaic of scenes H0988, H1347 and H3047 at 50m pixel resolution of the Nili Fossae project area.
Prof. Muller demonstrated the MarsWeb system including rapid crater measurement at the Mid-Term Review at BGS. He also described the 3D Imaging facilities at the UK NASA RPIF of which he is director in the Centre for Planetary Sciences on the main campus of UCL. Nine geoscientists had been trained in how to use this system and subsequently six of these had booked and used the system to create HiRISE DTMs. He also participated in the EU-FP7 project bid led by TNO which was later abandoned.

5 SUMMARY OF WP1: DATA MANAGEMENT (BGS)

As a result of the activities carried out as part of this work package, a website was created for finding, assessing and downloading Mars data from this project or from any of the distributed planetary science repositories managed by ESA, NASA, USGS, DLR and others.

The data currently catalogued on this site are just those produced by or used by the pilot project but the system could be used to build a catalogue of data for any project site, the whole of Mars, or for other planets.

5.1 Website capabilities

- Geological data can be displayed on an interactive map.
- Data can be discovered by a text search, by data type or geographically.
- Metadata can be displayed for each data set.
- Metadata includes links to the source of the data for further details, preview and download services.
- Data sources may be any web-accessible repository, such as the ESA Planetary Science Archive or PDS Geosciences Node.
- Data coverage can be displayed on Google Mars via KML.
- Spatial data can be served to GIS clients (ESRI ArcMap and others) in Open Geospatial Consortium WMS, WFS and WCS formats.

5.2 Access URLs

Website URL
http://kwdmzesad.bgs.ac.uk/

WMS URL for GIS clients
http://kwdmzesad.bgs.ac.uk/geoserver/ows?service=WMS

5.3 Technology

Apache webserver  http://www.apache.org/
Tomcat servlet container  http://tomcat.apache.org/
Java server side programs  http://java.sun.com/
OpenLayers JavaScript web browser map client  http://openlayers.org/
5.4 Page navigation & web services

Figure 5. WMS Flowchart
SUMMARY OF WP2: INFORMATION EXTRACTION; DELIVERING THE INFORMATION LAYERS (DELTARES, UCL, AND ITC)

Much of the data in the PSA are not immediately accessible or useable by planetary scientists and need to be processed. WP2 resulted in co-registered DTMs from HRSC stereo images, slope and aspect data, surface roughness, colour orthoimages, other HRSC-derived products and OMEGA-derived surface mineralogy maps.

6.1 Processing OMEGA data by ITC:

This section describes the processing chain for OMEGA imagery that ITC has developed for a Planetary Mapping Pilot Project using the Nili Fossae area of Mars as study case. The result of the processing was a series of information products that could be used for further interpretation of the geology of the Nili Fossae area. In this procedure, publicly available calibration software was used, together with IDL-scripts and Python tools developed by ITC and other image-processing packages. The Python tools that have been developed will be publically available.

The following OMEGA scenes were processed:
orb0232_2, orb0422_4, orb0966_5, orb2272_4, orb3025_5 and orb3047_5.

Omega data was downloaded from the Planetary Science Archive (PSA):
http://www.rssd.esa.int/index.php?project=PSA&page=mexIndex
Calibration software (numbered soft01.zip to soft05.zip) was downloaded from:
ftp://psa.esac.esa.int/%2f%2f/pub/mirror/MARS-EXPRESS/OMEGA/MEX-M-OMEGA-2-EDR-FLIGHT-EXT1-V1.0/SOFTWARE/

6.2 The processing chain contains the following steps:

1) Extraction and calibration from raw data sets downloaded from the Planetary Science Archive of ESA;
2) Spectral sub-setting of the hyperspectral image-cube;
3) Atmospheric and albedo correction using Kwik Log Residuals method;
4) Noise filtering;
5) Production of interpretable image features;
   5.1) Hyperspectral edge detection;
   5.2) Wavelength position of dominant absorption features;
   5.3) Summary products;
   5.4) Colour composites;
6) Geocorrection;
7) Stretching and thresholding of information products.

The above steps are detailed below:
6.2.1 Extraction and calibration from raw data sets downloaded from the Planetary Science Archive of ESA;

The IDL procedure alpha.pro, which is essentially a shell around the softxx tools provided by ESA, has to be run on the raw OMEGA data. It basically runs the softxx tools in the background and it facilitates the management of the calibrated data cubes that result from the calibration. The calibrated OMEGA cubes will be written to disc together with several other data sets.

Input:
ORB*.NAV (containing geometric information and other housekeeping information) and ORB*.QUB (containing the hyperspectral cube)

Output:
ORB*_jdat: calibrated radiance@sensor data
ORB*_geocube: copy of the geometric information in the NAV-file
ORB*_mola: MOLA elevation model
ORB*_lonlat: geolocation of each pixel in Martian latitude and longitude (this file must be used for the creation of a geometric lookup table (*.GLT) for geocorrection of the imagery)
ORB*_solar_spectrum.txt: This ascii file contains a solar spectrum. This file can be used during further processing of the OMEGA imagery.

6.2.2 Spectral sub-setting of the hyperspectral image-cube;

The calibrated radiance files that resulted from the first processing step (ORB*_jdat) contain radiance data measured using three sensors:
VNIR sensor: bands 257 (364nm) – 352 (1070nm)
SWIR1 sensor: bands 1 (926nm) - 128 (2694nm)
SWIR2 sensor: bands 129 (2527nm) – 256 (5089nm)

Spectral subsets were made because of the wavelength overlap between the sensors, the slight spatial shift between the three sensors and some problems with the calibration of the VNIR data.

ORB*_vnir: subset of bands 257 (364nm) – 352 (1070nm); not further used in this procedure
ORB*_swir1: subset of bands 1 (926nm) - 128 (2694nm)
ORB*_swir2: bands 129 (2527nm) – 256 (5089nm)
6.2.3 **Atmospheric and albedo correction using Kwik Log Residuals method;**

Removal of systematic atmospheric effects and albedo was done using a normalization method that uses in-scene statistics only. It removes systematic effects of atmosphere (mostly CO₂), systematic instrument noise, and it removes the effect of albedo (or intensity). Advantage of this method is that no artifacts are introduced because of the application of an atmospheric model that doesn’t fit the local atmospheric conditions during acquisition time of the hyperspectral scene. Disadvantage is that local variations that deviate from the mean are not removed (as a function of elevation) and the results are to some extent scene-dependent. Results of the atmospheric corrections have been compared to those that use scaling of atmospheric models to the depth of the CO₂ feature.

The Python program tkLogResiduals.py to run the atmospheric correction produced the following output:

- **ORB*_lr:** log residuals corrected image cube
- **ORB*_alb:** albedo (or intensity) image (Fig. 6)

6.2.4 **Noise filtering;**

The pseudo-reflectance spectra produced by the kwik log residuals method contained abundant noise, such as uncorrelated spikes that are visible as pepper-and-salt patterns in the images. In order to reduce the uncorrelated noise, a hyperspectral median filter was applied, which works both in the spatial and spectral domain in a 3x3x3 images. This reduced uncorrelated noise and spatial patterns related to surface composition became clearer. Disadvantage is that one-pixel anomalies disappear.

The Python tool to run the filter tkMedian.py (1+3*2 neighborhood, 7 neighbors) produced the following output:

- **ORB*_med7:** Smoothed image cube

6.2.5 **Production of interpretable image features;**

6.2.5.1 **Hyperspectral edge detection**

Hyperspectral edge detection was used for identifying areas with hyperspectral gradient indicating areas of changing surface composition. Results helped to differentiate minerallogically homogenous areas from those with mineral changes. The hyperspectral edge-detection tool tkEdgy produced the following output:

- **ORB*SAM:** Image containing edges.

6.2.5.2 **Wavelength position of dominant absorption features**

The wavelength position of reflectance minimum in a selected wavelength region was useful to determine the dominant absorption feature on a pixel-by-pixel basis in an image. It gives a direct link with the potential mineral that dominates in a pixel. The wavelength position was determined in two wavelength regions:
**ORB\_wavelmin\_2081\_2592** (Fig. 7): Between 2081 and 2592 nm: This wavelength interval contains absorption features of for instance sulphates, phyllosilicates, carbonates;

**ORB\_wavelmin\_1371\_1500**: Between 1371 and 1500 nm: This wavelength region contains absorption features of hydrated minerals (and also water vapour, water ice and CO\_2 ice)

Figure 6. Example of SWIR-1 Albedo image for OMEGA scene ORB 0422 with 2459m pixels.

Figure 7. Example of SWIR-1 log residual image with a median 7 filter for OMEGA scene ORB 0422 with 2459m pixels. Red= Wavemin, Green= Band 2081, Blue=Band 2592

### 6.2.5.3 Summary products

An inventory of surface and atmospheric components in the hyperspectral cube was made by calculating summary products. These summary products are a set of spectral parameters calculated from the radiance or reflectance spectra and respond to the presence of the mineral or atmospheric component in an image. The summary products produced here were obtained from the paper of Pelkey et al. (2007). The resulting summary products had to be further analysed to confirm the presence and/or absence of various minerals and gases and to map these with greater accuracy.
The program tkSummaryProducts produced a new file containing images of a stack of 39 summary products:

**ORB* _sp:** A total of 39 summary products are calculated. Some of the products require vnir or swir2 data sets. We applied the tool to the SWIR1 sensor. For details on the products and their calculation I refer to the manual (Bakker, 2009) and the paper of Pelkey et al. (2007). The summary products that have been studied in the framework of the Planetary Mapping Pilot Project are listed here:

*Surface parameters:*
- BD1435 (band depth of 1435 nm feature): CO₂ ice
- BD1500 (band depth of 1500 nm feature): H₂O ice
- BD1750 (band depth of 1750 nm feature): Gypsum
- BD2210 (band depth of 2210 nm feature): Al-OH containing minerals
- BD2290 (band depth of 2290 nm feature): Mg, Fe-OH containing minerals
- BD2600 (band depth of 2600 nm feature): H₂O vapor
- OLINDEX: Olivine index
- LCPINDEX: Low-Ca pyroxene index (orthopyroxene, for instance enstatite)
- HCPINDEX: High-Ca pyroxene index (clinopyroxene, for instance diopside)
- DROP2300 (drop of 2300 nm feature): hydrated minerals, particularly phyllosilicates
- DROP2400 (drop of 2300 nm feature) hydrated minerals, particularly sulphates
- BD1900 (band depth of 1900 nm water feature): H₂O
- BD2100 (band depth of 2100 nm feature): monohydrated minerals (sulphates)
- ICER2 CO₂: index for ice mixtures, CO₂ ice will be ~1, H₂O ice and soil will be 1
- BDCARB (band depth of bands 2330 nm and 2530 nm): carbonate overtones, 2.33 and 2.53 band depth
- VAR: spectral variance, olivine and pyroxene will have high values.

*Atmospheric parameters:*
- BD2000 (band depth of 2000 nm feature): atmospheric CO₂
- IRR2 (infrared ratio): clouds / dust
- BD1270 (band depth of 2000 nm O₂ feature): O₂ emission, signature of ozone
- BD1400 (band depth of the 1400 nm H₂O feature): H₂O vapour
- R2700 (reflectance at 2700 nm): high aerosols

6.2.5.4 **Colour composites**

The following colour composites were created for exploratory analysis of spectral variation due to the presence of selected minerals and other surface materials:

(Note: Care has to be taken when interpreting the colour composites. The pixel-colours depend on the stretching interval that was chosen to display the color composite…and use a model of mixtures of colours to interpret mineralogy). Red: Green: Blue:
This colour composite shows variation in the content of the three mafic minerals.

BD1900: D2300: D2400: (Figs. 8 and 9)
Identification of hydrated minerals based on the 1900 nm water feature (red) and differentiation between Fe/Mg-phylllosilicates (drop 2300 nm, green) and sulphates (drop 2400 nm, blue).

BD2100: D2400: BD1900:
Indication for the presence of mono- and poly-hydrated minerals (including sulphates). After the appropriate stretching, monohydrated materials appear in red, hydrated sulphates in green, yellow and aqua, non-distinct polyhydrated material in blue (Pelkey et al., 2007).

ORB*_Rqcc: Ratio (~2100 nm/~2170nm): ratio (~2170nm/~2205nm): ratio (2357nm/2258nm):
This color composite of band ratios was empirically determined from terrestrial studies of epithermal alteration systems. It responds to the presence of sulphates and kaolinite in red, illite and montmorillonite in yellow and green, and unaltered rocks and carbonates in blue.
Stretching interval for the three ratio images (histogram equalized):
R: 0.970-1.022
G: 0.988-1.016
B: 0.959-1.020
6.2.6 Geocorrection

The images produced contained image-pixel coordinates. For overlay in GIS they were geocorrected using a geometric lookup table that has been created using the latlon information that was extracted from the geocube. The resulting image is in Martian latitude-longitude coordinates (with MOLA sphere).

ORB*_geoc: geocorrected images in lat lon coordinates.

6.2.7 Stretching and thresholding of information products.

Thresholds of the information products for classification of the various minerals are based on statistics (the highest 2% values) and not yet on the analysis of spatial patterns appearing in the
summary products, shape of reflectance spectra and mapping results reported in the scientific literature. The thresholds are subjective and further analysis has to be carried out to increase the accuracy of the mineral maps. Thresholds for a selected group of minerals based on ORB2272_4 (this scene was chosen because of its mineral diversity):

Gypsum (based on BD1750 parameter): > 0.010100  
Al-phyllosilicates (based on BD2210 parameter): > 0.009500  
Fe/Mg philosilicates (based on BD2290 parameter): > 0.018100  
Olivine (based on OLINDEX parameter): >0.104200  
Low-Ca pyroxene (based on LCPINDEX parameter): > 0.000970  
High-Ca pyroxene (based on HCPINDEX parameter): > 0.001560  
Phyllosilicates (based on D2300 parameter): > 0.023894  
Hydrated sulphates (based on D2400 parameter): > 0.00310  
Hydrated minerals based on the BD1900 parameter): > 0.01420  
Monohydrated minerals (based on BD2100 parameter): > 0.0190  
Carbonates (based on BDCARB parameter): > 0.01820

For each parameter average spectra were calculated for pixels containing the highest 2% values. The spectra were saved to:

**ORB*_speclib_2%**  
Classified image file:  
**ORB*_class**

**Acknowledgements**  
We thank J. -P. Bibring (Principal Investigator of the OMEGA instrument) and the European Space Agency for provision of OMEGA data and calibration software.
7 SUMMARY OF WP3: VISUALISATION; DELIVERING MAPPING AND MODELLING TOOLS (BGS)

Work Package 3 was designed to demonstrate the strengths of modern mapping tools based on remotely sensed data that are used in terrestrial mapping and their applicability to the planetary context. It supported the geological analysis in WP4, and also delivered visualisation of the Nili Fossae planetary data layers, maps and models in both stereo immersive visualisation environments, using the BGS/Virtalis GeoVisionary System, and the BAE SOCETSET System; and simplified versions for viewing via the web, such as Google Earth/Mars.

The GeoVisionary system allows large and complex geoscience datasets such as elevation and mineral maps to be integrated and explored in an immersive, stereo 3D environment. Advanced data access protocols mean that large datasets can be served rapidly and seamlessly, enhancing the geologist’s experience of the visualisation. Common 2D GIS functionality is built in via a live link with ARCGIS; other similar links are under construction. This enables a geologist to add vectors such as lines whilst in the immersive environment, or whilst running the 2D GIS in an adjacent window. Other advanced features include the ability to use a hand-held tablet, exactly the same as BGS field geologists use in the field; by falsely streaming GPS coordinates to the tablet, it appears that the user is in the right place in their world, and any lines captured have the correct x, y and z value.

Figure 10. Dr Peter Grindrod discussing the 3D shapefiles of the Nili Fossae geological interpretation displayed on top of some OMEGA mineral maps, in the GeoVisionary floor-to-ceiling, i3DVF facility at the British Geological Survey.
SUMMARY OF WP4: GEOLOGICAL MAPPING AND MODELLING (TNO):

For Work Package 4 TNO took the lead to create a geological map of the study area. Here the available image (HRSC, CTX, THEMIS), topography (HRSC, MOLA) and hyperspectral (OMEGA) data were combined in a Geographical Information System (GIS). During two weeks (October 2009 and February 2010) at the BGS in Nottingham, Jelmer Oosthoek (Deltares), supported by Douglas Tragheim (BGS), Frank van Ruitenbeek (ITC) and visiting planetary scientist Peter Grindrod (UCL), started mapping the Nili Fossae area using ESRI ArcGIS and Virtalis/BGS GeoVisionary software. The former is a 2D GIS product, the latter a 3D GIS tool which allows for a more realistic interpretation as the various data can be draped over the topography DTM. The resulting geological map will be available as a set of shapefiles incorporated in the WP3 webgis (BGS lead) and as a hard copy map.
Other end products for WP4 include a geological map legend (template provided by Peter Grindrod), a geological profile and a set of HRSC DTM derivatives (slope, slope times DTM, surface roughness).

Figure 12. Extract of final geological map interpretation of the Nili Fossae region using a combination of ArcGIS, SOCET SET and GeoVisionary software tools.
9 RESULTS: INDEPENDENT TEST BY DR PETER GRINDROD (UCL)

These comments are based on the time I spent at the British Geological Survey in February 2010. During that time I advised Doug Tragheim and Jelmer Oosthoek on both general planetary mapping conventions and the specific methodology adopted for this project.

Nili Fossae is an extremely interesting area of Mars, and therefore has a rich literature looking at the geological history of this area [e.g. Hoefen et al., 2003; Fassett and Head, 2005; Hamilton and Christensen, 2005, for recent examples]. Also, as it is a candidate landing site for the NASA Mars Science Laboratory, due to launch in 2011, there is also an ongoing interest in better understanding the processes that have occurred, using increasingly advanced instruments and datasets [e.g.
Ehlmann et al., 2008, 2009; Mustard et al., 2008; Rogers and Bandfield, 2009]. Thus, in my opinion, the challenge was to determine how much new information could be gleaned from an area that had already undergone a large amount of previous study, with most of the recent data of higher resolution than those used in this study.

My overall conclusion is that I was pleasantly surprised. The key to this success, I feel, is the integration of many different datasets into a working environment that crucially is based on the topography. This topographic information is vital in determining the superposition relationships (stratigraphy) in planetary geology, and so placing the available datasets over the topography resulted in findings what would have most likely otherwise been missed.

For example, the ability to view visible wavelength images draped over HRSC topography allowed us to define geomorphologic units and boundaries that would have been uncertain in a 2D environment. The ability to then also drape the OMEGA datasets, which were of lower spatial resolution, allowed us to take our inferences a step further and relate them to possible mineralogical processes. The exploration of these datasets was most productive when using the 3D GeoVisionary suite at BGS, as this method was able to bring out the topographic information at the same time as the geochemical information.

However, in my opinion, the most useful technique demonstrated during this study is the combination of a well-established 2D GIS package (ArcMap) with a new 3D software package (GeoVisionary) to allow ‘on-the-fly’ interpretations to be made. The ability to mark contacts, structures, and other geological features while fully immersed in a 3D environment is probably as close to real field mapping on Mars as is possible at the moment. I expect this technique could be applied to a much wider dataset, and would be almost perfectly suited to a combination of orbital and in situ information. I also expect that a wide range of planetary scientists that are already familiar with GIS environments would be interested in applying this technique that was new to me at least.

10 CONCLUSIONS

The modern geological survey workflow developed for terrestrial applications is well suited to transfer to the planetary geology environment. The same types of remote sensing data exist. Challenges of information extraction such as noise removal are common to both workflows. The field work step is not possible in the planetary context, today, making the immersive visualisation step all the more important. These elements provide a strong support to geological interpretation and map production. The tools in question were well-received by a leading planetary geologist; he rightly identifies the huge potential of these technologies for wider application in the planetary mapping community. The challenge now is to realise that potential by expanding the pilot study to the actual missions operating now and in the future.
REFERENCES


APPENDIX
CONFERENCE ABSTRACTS & PRESENTATIONS:


European Space Agency
International Conference on Comparative Planetology: Venus – Earth – Mars
ESTEC, Noordwijk, The Netherlands, 11-15 May, 2009

MARS PLANETARY MAPPING PILOT PROJECT. D.G. Tragheim1, S.H. Marsh1, R.C. Pedley1, J.L. Gunnink2, J.H.P. Oosthoek2, J.-P. Muller3, F.J.A. van-Ruitenbeek4  1British Geological Survey, Kingsley Dunham Centre, Keyworth, Nottingham, United Kingdom, NG12 5GG. dgt@bgs.ac.uk. 2TNO/Deltares, Geological Survey of the Netherlands, Princetonlaan 6, PO Box 80015, Utrecht 3508 TA, The Netherlands, 3Mullard Space Science Laboratory, Department of Space and Climate Physics, University College London, Holmbury St Mary, Dorking, Surrey, United Kingdom, RH5 6NT, 4ITC, International Institute for Geo-Information Science and Earth Observation, Hengelosestraat 99, Postbus 6, 7500 AA Enschede, The Netherlands.

Introduction: In February 2009 a new Mars Planetary Mapping Pilot Project for the European Space Agency (ESA/ESTEC) commenced, which will last for one year. It involves a collaboration between the British Geological Survey, TNO/Deltares Geological Survey of The Netherlands, Mullard Space Science Laboratory of the University College London, and ITC, the International Institute for Geo-Information Science and Earth Observation, The Netherlands. Its purpose is to demonstrate how specialist skills developed by Europe’s geological surveys and academic planetary scientists for terrestrial datasets, can be applied to ESA planetary datasets for Mars. The main deliverables from this contract will involve:

1. A prototype data-management system (Fig.1) which will store all relevant data and meta-data, and which will allow planetary scientists to discover, explore and access them through a variety of web interfaces in map and query forms. Links will be provided to other planetary datasets and web-map servers.

2. Example Information products (Fig.2) on a range of themes, such as digital elevation models from HRSC stereo images, and their derivatives such as slope, aspect, roughness; mineral maps showing surface mineralogy derived from hyperspectral OMEGA data.

3. Modern visualisation and analysis tools developed for terrestrial geological mapping applications, will be applied to the Mars data, as part of a documented workflow. This will involve both stereo immersive visualization environments and simplified versions for viewing via the web.

4. Detailed geological mapping and 3D modelling will be applied to a demonstration area. Following an initial appraisal and discussion amongst project partners with ESA, this will be in the Nili Fossae region (Fig.3).

This paper will present the background to the project and its initial results, in order to seek engagement with the wider planetary science community on this important topic. The results of this project will be demonstrated to ESA and representative members of the planetary community at a final meeting next year.
Fig.1 Data Management & Demonstration Web Map Server.

Fig.2: Example Information product: HRSC derived slope map.

Fig.3: Test site within Nili Fossae area (within the light boundary) chosen for detailed geological study (Map background is NASA MOLA data, light is high, dark is low elevation).
Figure 4. Reduced version of the original A0 sized poster presented at the 43rd ESLAB Symposium, International Conference on Comparative Planetology, Venus-Earth-Mars, Noordwijk, The Netherlands, 11-15 May 2009.

The ESA Mars Planetary Mapping Pilot Project: advanced terrestrial mapping methodologies applied to the Nili Fossae Region.

D.G. Tragheim\(^1\), B.R. Napier\(^1\), L. Bateson\(^1\), R.C. Pedley\(^1\), A.G. Smith\(^1\), A.P. Marchant\(^1\), S.H. Marsh\(^1\), J.L. Gunnink\(^2\), J.H.P. Oosthoek\(^2\), J.-P. Muller\(^3\), F.J.A. van Ruitenbeek\(^4\), W. Bakker\(^4\), H. van der Werff\(^4\), P. Martin\(^5\). 1British Geological Survey, Kingsley Dunham Centre, Keyworth, Nottingham, United Kingdom, NG12 5GG. dgt@bgs.ac.uk. 2TNO/Deltares, Geological Survey of the Netherlands, Princetonlaan 6, PO Box 80015, Utrecht 3508 TA, The Netherlands, 3Mullard Space Science Laboratory, Department of Space and Climate Physics, University College London, Holmbury St Mary, Dorking, Surrey, United Kingdom, RH5 6NT, 4ITC, International Institute for Geo-Information Science and Earth Observation, Hengeloestraat 99, Postbus 6, 7500 AA Enschede, The Netherlands. 5ESAC, PO Box 78, E-28691 Villanueva de la Canada, Madrid, Spain.

The British Geological Survey (BGS), in partnership with TNO Geological Survey of the Netherlands, the Mullard Space Science Laboratory (MSSL) of the University College London, and the International Institute for Geo-Information Science and Earth Observation (ITC) Netherlands, is now half-way through a one year “Mars Planetary Mapping Pilot Project” for the European Space Agency (ESA/ESAC). One of our main project goals is to demonstrate as part of a documented workflow, how we can apply geological 3D visualisation and analysis tools developed for Earth Observation, for Mars datasets held by ESA. The project focuses on a part of the Nili Fossae region, which was one of the seven final candidate Mars Science Laboratory (MSL) sites discussed at the 3rd MSL Workshop in September 2008.

Since 1993, BGS geologists have been using digital stereoscopic computer workstations with airborne and satellite imagery to assist with their geological interpretations on Earth. In 2005 a floor-to-ceiling 3D stereo viewing system called GeoVisionary was developed in association with Virtalis Ltd. This allows large raster datasets such as aerial photos, geological and topographic maps, or remotely sensed images to be rapidly draped over a terrain model, and cross-sections, seismic sections and borehole information to be hung underneath and viewed from any angle in 3D. Our goal is to demonstrate the utility of this technology to planetary scientists.

A Digital Terrain Model mosaic with 50m resolution of the Nili Fossae area was produced by MSSL (ESA PANGU contract; Kim & Muller, 2009, PSS in press) from three HRSC orbits: H0988, H1347 & H3047, and used to orthorectify B&W nadir (12.5m) and colour (50m) images. The HRSC orthorectified images were then mosaiced by TNO. Six hyperspectral OMEGA scenes were processed using a variety of image processing software by ITC. 39 summary product images were produced for each scene. These were reprojected and converted into geotiff format by TNO, and then brought into the 3D environments of SOCET SET and GeoVisionary by BGS.

In SOCET SET, new synthetic stereoscopic images were created from the terrain model and the orthoimages, before 3D viewing from a fixed vertical perspective. 3D shapefiles of geological features were then digitised using a terrain following cursor, by linking to ArcGIS. Several stereo-windows may be open at once containing different images of the same region. For example: a day IR image in one and a night IR image in the other; or different 3-band spectral combinations.

Once imported into GeoVisionary, any of the layers can be viewed stereoscopically from any direction in space, and the layer translucency interactively adjusted, to assess the relationship between two of them. Oblique perspective digitising with a terrain following cursor is possible. A particularly useful new tool is that topographic profiles in any direction can be constructed, and displayed at the bottom of the screen.

We demonstrate these advanced visualisation and interpretation techniques for data from the Nili Fossae region.