MINERVA: A 3D GIS and Visual Analysis Framework

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Abstract— Data products from planetary orbiter and rover missions are typically open access, however, it is often cumbersome to retrieve the data and data sources and modalities are different for each instrument. Derived products are even harder to come by, while analyses and annotations mostly are restricted to instrument teams or even individual scientists. MINERVA is a framework currently in development for the access and collaborative interpretation of planetary science data, including instrument products, analyses, and annotations. It shall allow members of different instrument teams to cooperate in virtual workspaces by sharing observations, and analyzing and annotating data in a collaborative fashion. Our framework comprises three components: an interactive 3D Viewer with 3D-GIS functionality, a database that maintains the knowledge about data products and their spatiotemporal context, and a visual analytics platform that shall help finding correlations between the data coming from different instruments to discover new modes of scientific exploitation.

Index Terms—Planetary Science Data Framework, Geographic/Geospatial Visualization, Remote Structural Geology, Integration Spatial and Non-Spatial Data Visualization

1 Introduction

Due to public funding, most planetary missions, terrestrial or extraterrestrial, are obliged to provide access to data products that are created by their various instruments. Retrieving data from long-running missions can be cumbersome, while recent missions show an effort towards presenting and hosting data in the most accessible way, for instance, the Copernicus Sentinel-2 mission [1]. We can expect similar dissemination efforts for the upcoming ExoMars missions, however, it is unlikely to have such a streamlined access promptly after the downlink. Further, instrument products, such as images, are only the first step in scientific workflows. They are typically followed by derived products, such as panoramas or 3D reconstructions, and then follows analysis and annotation through members of various instrument teams and planetary science disciplines. We identified three gaps in current tool chains: (1) There is no tool that shows products from all instruments of a rover mission and potential derived products in their common spatiotemporal context. Planetary scientists are lacking this unified view on products of different instruments, for instance, showing a 3D reconstruction derived from MSL Mastcam images and Chem-Libs measurements to determine the chemical composition of a rock layer. Planetary science is an extremely broad discipline, where collaboration is imperative, especially in use cases with short time frames, such as science target planning. (2) There is also no tool available for effective collaboration, where members of different instrument teams can share their analyses and their annotations in their common spatiotemporal context. (3) Further, there is a lack of tools for analysing metadata beyond instrument products themselves, such as temperature, exposure duration, or solar elevation. This data is typically available in metadata files associated with a product, but there are no efficient means that put them readily into a common context.

MINERVA (**M**ars **IN**teractive **E**xploration based on **R**econstruction and **V**isual **A**nalysis) offers a collaborative, holistic planetary science data infrastructure to allow members of different instrument teams to cooperate synergistically in virtual workspaces by sharing observation information, analysing and annotating the data, and also by discovering new modes of scientific exploitation through visual analytics. MINERVA represents a novel framework of interoperable and collaborative components based on an interactive 3D Viewer with 3D-GIS functionality, a database that maintains the knowledge about spatiotemporal data products, and a visual analytics platform that will help find new interconnections between the data coming from different instruments. MINERVA will be evaluated in the course of the ExoMars Rover Mission (launched in 2020), which provides a heterogeneous set of scientific data captured by different instruments from the surface of the Red Planet. The MINERVA concept will bring about a significant game-changing advance in investigating and exploiting planetary science data for the ExoMars Rover mission and beyond.

1.1 Design Goals

The MER and MSL missions have shown that cooperation between different science teams of a planetary robotic surface mission requires a holistic support for full understanding of the heterogeneous data from the investigated area in a collaborative way. Even for MSL such a support for an effective collaboration between different instrument teams is still missing. In the course of several workshops over the past two years we derived the following design goals for MINERVA to address problems and requirements, but also to tackle newly identified research challenges:

- establish spatiotemporal relationships between individual products of different instruments
- establish spatiotemporal context to the environment from orbital down to microscopic detail, and above and below the surface
- handle different coordinate systems implicitly and provide scientists with an intuitive access to instrument metadata
- collaborative visual analysis through means to study contributions of other scientists and potential merging of analysis results
- comprehensive visualization of heterogeneous data sources in a 3D scene
- support large collections of complex scientific products, such as spectra or image sets
- foster cooperation between scientists through means for communication, access rights, priorities, versioning, and sharing analysis results and key findings
- the framework should be applicable to planetary science in general beyond the ExoMars mission in terms of concepts and component implementations

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1.2 Contributions

The overall goal of MINERVA is to enable a holistic workflow for the analysis of huge amounts of heterogeneous data originating from planetary science. From an application point of view, the idea of MINERVA is to develop a unique set of interoperating analysis tools which will be evaluated in the course of the ExoMars mission. Another important goal is to have MINERVA validated by ExoMars science teams as unique framework where they can maintain and share their science data. Besides rover data it will utilize data from remote sensing products as available by then (HiRISE, HRSC, CASSIS). Mainly, the following innovative features and techniques are planned:

- import facility for various overlays for rover operations purposes (e.g. displaying planned and executed paths, analyzing terrain for traversability, showing locations of engineering cameras' data with icons)
- generic import facility for science teams data via PDS4 [4]
- a database for scientific data products, to be annotated both on top of the GIS elements (ortho-image and DEM) and ExoMars PanCam 3D vision data products (3D renderings of the region around the rover)
- 3D data analysis tools based on GIS elements (ortho-image and DEM), i.e. to measure distances and other features that help the interpretation of correlation between observations from different instruments
- exploitation of visual analytics methods to interrelate observations of different science instruments in an interactive and more comprehensible way
- maintaining cooperation aspects between scientists based on their annotations (e.g. spatial maintenance of scientific sites and objects and their sharing across teams) and respecting intellectual property situations

2 Mission Scope

The ExoMars 2020 mission will provide a heterogeneous set of data from different instruments captured on the surface of Mars. Imagery for science target selection, navigation, or close-up detailed visual analysis for geology, complemented by multi-spectral imagery from orbiters will be supplemented with georeferenced sensor data such as from the WISDOM ground-penetrating radar instrument. The Analytic Laboratory Drawer inside the Rover body punctually observes samples acquired by a drill. A comprehensive and efficient analysis of this wealth of science data demands a sophisticated workflow that can cope with its heterogeneity and allows an overview of interconnections between different data entities. Based on the instrument data available as PDS4 archives, concepts are required for the support of a holistic analysis of all the versatile scientific data from the entire rover mission. The MINERVA goal is to provide for the first time an integrative, holistic and analytic support for planetary scientists. This will not merely make the analysis more efficient but the tight integration of different interactive tools will allow insights, which would be hard or impossible to obtain using isolated methods. We investigate innovative visual analysis methods based on semantic annotations, meta-information and data modalities. MINERVA will also consider specific ExoMars requirements and the exploitation of the solution for future missions and terrestrial applications.

3 The Framework

MINERVA is still in development and will be until the end of 2019. In this section we will discuss the concept and architecture of the MINERVA framework and the respective purposes and goals of its three components, the database, the 3D visualization engine, and the visual analytics platform. However, the current state of our implementation already presents an end-to-end workflow from data ingestion to visual analysis in 2D and 3D which will be discussed in Section 4 and show in Figure 2.

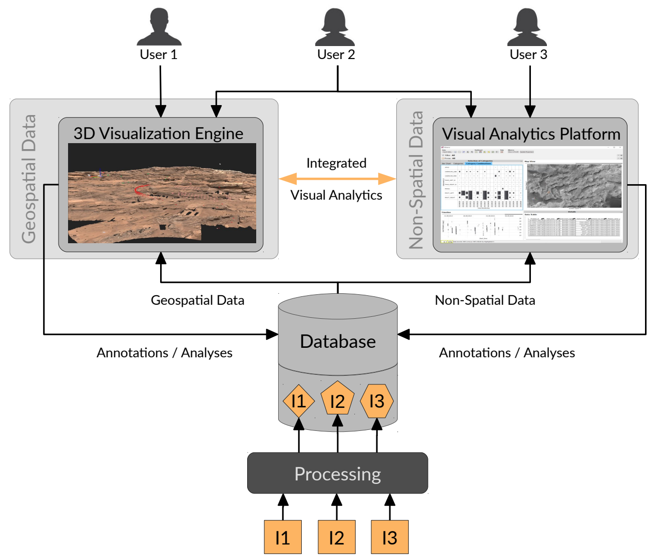

Figure 1: MINERVA architecture, the instrument teams use the generic importer tools (or in the case of vision the existing vision processing) to ingest mission data into the database (I1,I2,I3). From there it is available to the 3D Visualization Engine with integrated GIS functionality and the Visual Analytics Platform. Different users can share the same locations, observations, and launch visual analysis of different instruments at a time. A communication protocol allows the usage of visual analysis methods on spatial and non-spatial representations across applications.

3.1 3D Visualization Engine

PRo3D [13], the planetary robotics 3D viewer, is an interactive 3D visualization tool to allow planetary scientists to work with high-resolution 3D reconstructions of the Martian surface. We are extending PRo3D by GIS functionality in 3D space with the advantages of the full 3D geospatial context, effectively turning it into a 3D GIS. To meet the special requirements of planetary scientists this research task will generate a high degree of innovation for geospatial data analysis in the following aspects:

- The investigation of visualization methods considering multiple data sources, which increases the overall comprehension. This especially concerns display techniques for non-spatial data (sensors, metadata) in their 3D geospatial context.
- Novel analysis capabilities for geologists by researching new concepts of smart spatial measurement tools. The idea is to parameterize interaction techniques based on features which are extracted from the geometry of the terrain. Examples are line snapping based on edge detection or plane snapping by considering the inclination of surfaces. This is not possible with a conventional 2D GIS.
- Find intuitive ways to hierarchically structure large measurement and annotation data sets according to their semantics so that they can be compared and statistically evaluated. This significantly improves the comprehensibility and yields deeper insights into correlations and interdependencies.
- Provide interoperability with other tools of the framework, especially concerning the linkage to non-spatial data. The database can be directly accessed by the 3D Visualization Engine.

3.2 Visual Analytics Platform

Another novel aspect of the MINERVA solutation is to investigate how Visual Analytics can support the understanding of complex heterogeneous non-spatial data. Based on the platform Visplore [14], an

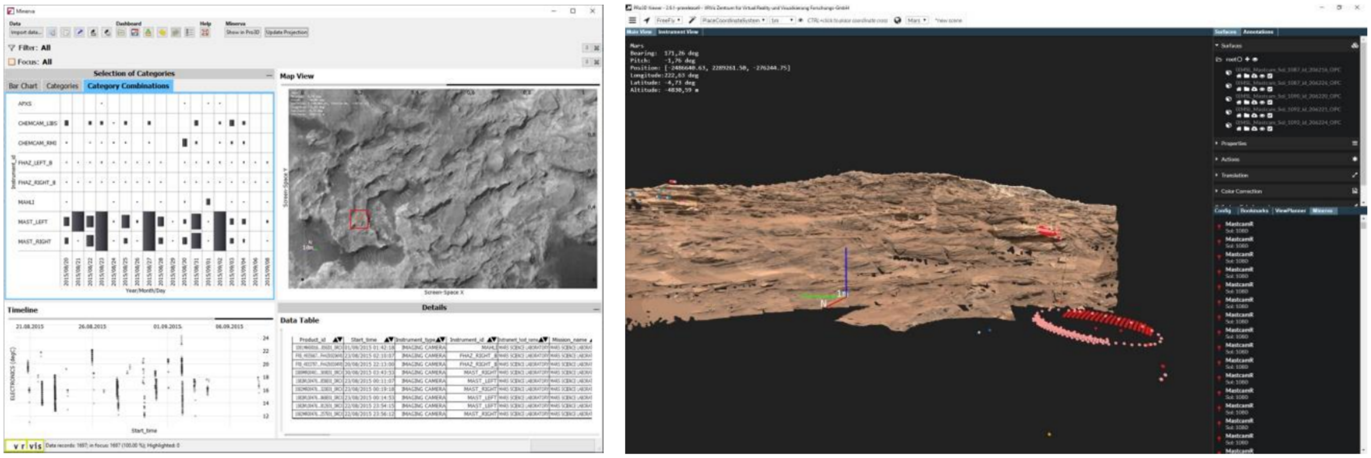

Figure 2: Selection of products in the visual analytics component Visplore (left) and their localization relative to a Martian surface reconstruction in the 3D viewer PRo3D (right). Data Credits: NASA/CalTech/MSSS/ASU

important project goal is to design and develop dashboards that enable a comprehensive analysis also of the non-spatial part of the data. Each dashboard comprises multiple views that visualize the data using a variety of interactive techniques, ranging from well-known statistical diagrams (e.g., scatter plots and histograms) to novel visual techniques for overviews of large amounts of data. All dashboards are linked with each other and with the 3D visualization tool. The linking is based on highlighting products in all views which are interactively selected in any of them. This enables the user to specify the focus of interest guided by the visualization and to efficiently relate spatial information, temporal information, meta-information, and results of measurements such as spectra. The key innovations for non-spatial data analysis are:

- A simultaneous inspection of large collections of spectral and imaging data in their spatiotemporal context. This enables users to compare data from different regions at different time periods, which in turn allows a faster identification of instrument data with distinct characteristics, e.g., spectra of a certain shape. Thus, facilitating the pinpointing of regions that are better suited for a more detailed inspection. To fulfill this task, concepts from information visualization like coordinated multiple views [15] and interactive methods for ensemble data [8, 10] are adapted for this project.
- Visually relating data from heterogeneous instruments using novel interactive visualization techniques and the common database. This may lead to detecting correlations between the features extracted from the instrument data, that otherwise would have been overlooked. The key scientific challenge here is to find unifying overviews of the highly heterogeneous data.
- Include meta-information from the instruments in the analysis, e.g., for detecting correlations between measurement results and instrument parameters. A visual inspection of meta-information such as instrument parameters may also facilitate the validation of the measurements as well as support a guided selection of products.
- Real-time feedback for user interactions. The key to interactive visualization is the dialog between the user and the data, which can only be achieved by fast feedback for interactions like selecting products or extracting features. For this, the platform builds on concepts like parallelism [9], tuned in-memory data management, and progressive approaches [3].
- Annotation of product collections to enhance the possibility of collaboration between scientists. Those annotations shall be persistent to allow further usage in future cooperative analysis.

These innovations are expected to provide a significantly improved analysis of the data for the scientific community.

3.3 Database

We realize the database management system (DBMS) using EOxServer [2]. EOxServer is a software component for managing geospatial datasets that provides mechanisms to search registered items and to deliver them using open standard protocols. It is necessary to extend EOxServer by the following innovations:

- Server side support for coordinated exploitation and value addition. With current tools, there is a considerable lack of real-time, interactive data exploration, in a sense, that users of the system can dynamically add annotations and data to a scene which is promptly propagated to other currently logged in users of the system.
- Delivery of heterogeneous planetary science observations via Open Standards. In the current landscape of planetary GIS systems, some Open Standards are well used while others that are also applicable are neglected. The usage of WCS provides a better suited interface for transmission raster data. The transactional extension of WFS (WFS-T) enables the user to dynamically submit annotations to certain regions. The further leverage of Open Standards helps to create interoperable systems and future extensions of MINVERVA by enabling to plug in additional components or replace existing components with a minimal effort.
- Improved interfaces to planetary data repositories. The database aims to improve the support of the various data repositories and their respective contents. This includes repositories such as the PDS and PSA and data from the sensors of the upcoming ExoMars mission. The detailed innovations provide a considerable improvement to the range of existing planetary GIS systems in terms of interoperability, improvements to data and metadata support and improved user experience and for data exploitation.

4 Current Development State

Section 3 was about the concept and the general goals of MINERVA. In this section we elaborate on what parts of MINERVA have been realized and how they have been implemented for each of the three components.

4.1 EOxServer (DBMS)

4.1.1 Data Ingestion

Data ingestion in the ExoMars scenario is suggested weekly, using a command line interface (CLI) harvesting the ROCC DAR (Rover Operations Control Center Data Archive). The input interfaces will use generic, instrument-independent external interfaces from PDS4, resulting in a set of generic xml- or json-based schemes. Figure 3 shows an example of a json file stemming from PDS3 input of a MAHLI

```
},
"Image": {
   "Image_height": "1200",
   "Image_width": "1632",
   "Bits_per_value": "8",
   "Number_of_bands": "3"
   "Start_time": "2015-09-02T06:54:29.277",
   "Stop_time": "2015-09-02T06:54:30.623"
},
"Instrument": {
   "Name": "MARS HAND LENS IMAGER CAMERA",
   "Type": "IMAGING CAMERA",
   "Focal_length_in_pixel": "4645.2010830481 4644.8426406147",
   "Pose": {
      "Frame": "Mars",
      "Position": "-2486639.762959 2289259.7627105 -276249.60945501",
      "Position_unit": "meter"
      "Orientation": "86.499884 7.048773 -50,392477"
      "Orientation_unit": "degree"
   },
},
"Mission": {
   "Name": "MARS SCIENCE LABORATORY"
},
"Product": {
   "Version": "V1.0",
   "Creation_time": "2015-12-08T20:19:34.823",
   "Product_ID": "1092MH0003060010400939C00_DRCX",
   "Producer": "MALIN SPACE SCIENCE SYSTEMS"
},
"PDS": {
   "Original": {
      "PDS_VERSION_ID": "PDS3",
      "RECORD_TYPE": "FIXED_LENGTH",
      "RECORD_BYTES": "1632",
      "FILE_RECORDS": "3600",
      "IMAGE": "(\"1092MH0003060010400939C00_DRCX.IMG\")",
```


Figure 3: Example of a json file stemming from PDS3 input of a MAHLI image product.

observation of the MSL mission. All entries under 'PDS' are currently being ignored by the DBMS representation. For a first end-to-end testing the entries under `Image`, `Instrument`, `Mission` and `Product` are relevant. Additional elements are taken from the `PDS` section into the DBMS as agile development proceeds.

The ingestion of new products will be done using a synchronisation mechanism and a set of CLI commands, to register the synchronised products. The EOxServer has an upstream FTP, prepared by dedicated data ingestors as a target and will periodically check for new, updated, and deleted files, and will download and (re-)register the records and delete stale files. The files will be indexed and inserted into the database using CLIs called by the synchronization tool.

The data ingestion functionality has already been tested with a working PDS3 interpretation scheme that uses a keywords library assembled from MSL instruments' metadata to be relevant for MINERVA, containing data types and calculation rules. The PDS3 data elements are translated into MINERVA-readable data types (e.g. images, histograms, spectra) etc. accompanied by .json metadata blobs. Presently some pre-calculations using the SPICE library are made to simplify geometric operations within PRo3D and Visplore, and to make GIS search more efficient and allow for working in the Cartesian IAU-Mars coordinate system [1]. In addition, global coordinates of each data item are given in a planetodetic system. The test ingested the full MSL missions' data set within about 2000 Sols for 5 instruments (Mastcam, Front Hazcam, MAHLI, APSX, Chemcam), summing up to 137.000 product entries and a data amount of about 200 Gigabytes. Usability within PRo3D and Visplore was proven by testing of search queries, as well as display of data dependencies within Visplore. The following listing shows the CLI command used for the conversion:

```
PythonInterpreter.exe D:\Dev\ImproApps\Source\
  ImproApplications\Applications\Tools\MINERVA\
  ImportMsl.py
    --pds-root-directory
      "D:\Projects\MINERVA\data products"
    --python-run-exe

D:\Dev\ImproApps\Build\Applications\Release\
  PythonRun.exe --import-camera-image-digpy
D:\Dev\ImproApps\Source\ImproApplications\
  Applications\Geometry\ImportCameraImage\
  ImportCameraImage.digpy
    --spice-kernels-file
      Y:\Common\SpiceKernels\MSL\20190116\
      kernels_MSL_20190116.txt
      -l D:\Temp\MINERVA\Log.log
```

[1] Such static geometric conversion could be later replaced by reference to the latest available SPICE kernels, respectively

4.1.2 Query Interfaces

As with many modern database interfaces, EOxServer provides clients with a REST service that can be accessed via http requests. So as a client we put together an URL forming a web request, send this to EOxServer, and get a result. A REST service is stateless and the database is unaware of what particular client sends the request, so we can also enter query URLs like this into the web browser:

```
https://minerva.eox.at/
  opensearch/collections/all/json/
  ?cql=(planetDayNumber>925 AND planetDayNumber<929)
```

The registered and indexed product files are accessible via two query interfaces OpenSearch [6] and Web Feature Service (WFS) [5]. **OpenSearch** allows searching for available collections and also products within collections. Via the Contextual Query Language (CQL) [12] parameter in the URL, complex queries can be sent or simple ones using the provided simple parameters. OpenSearch provides two distinct operations: The first one is the retrieval of the description document, detailing information about the service capabilities and search patterns. This includes one or more URL templates to be used to generate HTTP requests that perform the actual search. The second type of search interface uses a provided URL template, fills out any necessary parameters and sends the request in the described fashion. The request supports the following result formats: Atom, RSS, and GeoJSON.

For complex scenarios, the OpenSearch implementation supports a two-step approach: first, the client searches for the relevant collections. The resulting list of collections contains links to collection-specific description documents with its own set of URL templates and custom parameters. The second search is now based on a specific collection and searches all products within, applying the provided search parameters. Further, EOxServer pages the query results into subsets of maximum 150 products so the clients (e.g. PRo3D or Visplore) do have a fast response. With indices and counts the client can page through potentially the whole database by constructing respective queries. The **WFS** interface allows users to query collections and products and also enables authorised users to add annotations to existing products. The registered products will have several metadata fields indexed in the database, including spatial and temporal information exposed via the services for both lookup and extraction.

4.2 PRo3D (3D Visualization Engine)

For PRo3D, as a first step we developed a simple query GUI, that allows users to specify a range of `PlanetDayNumber`s, i.e. Sols., and `InstrumentTypes` they want to retrieve from the database. Internally, we construct a URL, as discussed in Section 4.1, with the respective CQL parameter based on the values provided through the GUI. We then receive the first page of the result, which indicates how many products our query would return. Users can then confirm the query to retrieve the full result or adapt their query, typically to create a smaller result set. We show the resulting products grouped by their `InstrumentType` in accordion controls, which can be expanded on demand. Each product entry has a colored pin on the left, while clicking on this pin triggers a 'fly-to' command, which animates the 3D camera to automatically navigate to the respective position. This guided camera animation allows users to localize query results in 3D space and inspect their spatial context. As visual representations for each product we draw a colored screen-space scaled dot in 3D space at its location, which puts the instrument locations and the outcrop reconstructions into context, as it can be seen in Figure 2 and Figure 4.

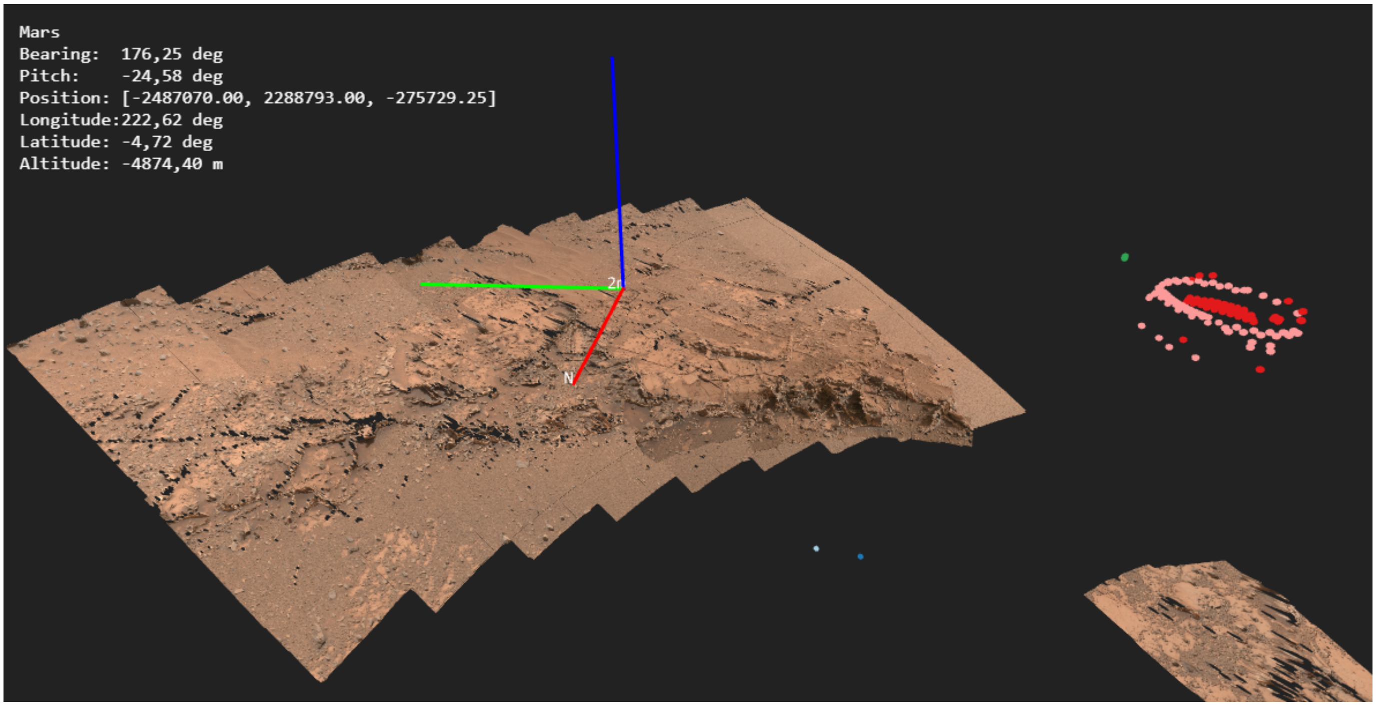

Figure 4: MSL product locations as dots of Mastcams (red), Navcams (blue), and ChemCam (green) in spatial context with the Garden City outcrop reconstruction. 3D data was derived from Mastcam images of the Sols 925, 926, and 929. Data Credits: NASA/CalTech/MSSS/ASU

4.3 Visplore (Visual Analytics Platform)

The dashboard designed for MINERVA contains multiple coordinated views which visualize spatial information, temporal information, meta-information, and spectral results. Selecting data in one view highlights that data in all views, which is efficient for relating heterogeneous aspects of the data. The dashboard is also linked to PRo3D, which allows users to coordinate selections in spatial and non-spatial views, as we will illustrate in Section 4.4. Currently, the dashboard contains the following views:

- The purpose of the **Aggregation View** is to show the distribution of products with respect to categorical meta-information such as the mission, the instrument, or temporal categories (e.g., the month). The user may flexibly adjust the drill-down level by specifying one or multiple categorical data attributes for subdividing each axis. We found it very intuitive to show the frequency of products grouped by `InstrumentType` with respect to the `PlanetDayNumber`, as it is illustrated in Figure 5.
- The **Map View** (see Figure 2) shows a snapshot from PRo3D's view, which is retrieved from PRo3D on-demand. The main advantage is to leverage Visplore's selection capabilities such as rectangular or lasso-like selections, which can be used to select products in specific regions. It is also helpful to quickly put selected products into a spatial context without switching to PRo3D.
- The **Time Line View** shows all products as dots along a time axis while the Y-axis is used for quantitative attributes such as numerical measurement parameters (e.g., the electronics temperature). It is easy to select data in a certain time frame, or to see trends, e.g., how instrument temperatures change over time.
- The **Spectrum View** shows the spectral data from all products of the same instrument type as overlaid curves. The user may select curves by drawing a line. All curves intersecting that line are considered selected. This may, for example, be used to focus the analysis on products that exhibit similar spectral characteristics, as shown in Figure 6. Currently, we support spectral products from the Chem-Libs and the APXS instrument and intend to extend that later. Before visualization, we retrieve the spectra from EOxServer during runtime.

4.4 Workflow Example

The MINERVA architecture is flexible and extensible and is designed to support many possible workflows. Most of these workflows go far beyond what is possible for our target users with their current tools. In this section, we discuss a specific end-to-end workflow in order to illustrate the potential. We also show that the 3D visualization engine and the visual analytics platform, i.e. PRo3D and Visplore, are linked via a communication channel.

Visplore is capable of showing millions of data points on very limited screen-space estate. Therefore, adhering to the Shneiderman's information-seeking mantra [11], we provide an overview of the products first, then filter the data, and inspect details of the products and their spatiotemporal context on demand with PRo3D. After loading a dataset of products into Visplore, users can create a selection of products, which results in a subset. Spectra or other columns are retrieved asynchronously for this subset. At the same moment PRo3D is connected to Visplore and users can choose to view the current subset in PRo3D. Technically, we send a message via a socket protocol from Visplore to PRo3D containing a set of IDs. PRo3D receives these messages and retrieves the respective products from the database and shows them in their spatiotemporal context. In this context PRo3D and Visplore form coordinated multiple views [15] across applications.

4.5 Use Cases

MINERVA will offer its users the opportunity to visualize, analyse, and annotate the mission data in their spatiotemporal context and also in the context of other meta-information from scientific measurements. Here is a subset of use cases collected throughout discussions with instrument teams, either during workshops or direct communication:

- Support scientists in geo-referencing of scientific products (e.g. spectra) for the characterization of regions and the identification of their boundaries.
- Enable holistic overviews and correlations of product cues from multiple heterogeneous instruments. The scientists will be able to

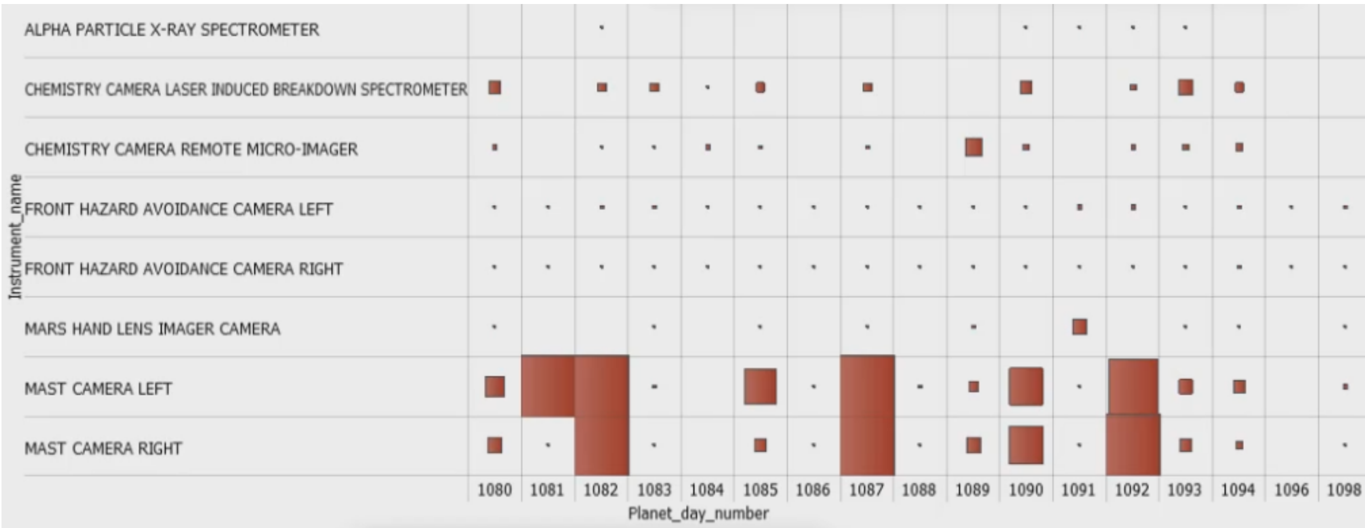

Figure 5: The aggregation view shows the frequency of products plotted against their instrument type and the planet day number. Here we can see that Mastcam Images dominated the time between Sol 1080 and Sol 1098 with clusters on Sol 1082, 1087, and 1092. On Sol 1081 only the left Mastcam was extensively used.

enrich the database by the output of interactive or semi-automatic tools for scientific assessment.

- Measure and annotate on 3D surfaces with PRo3D and share these augmentations with other users via the database.
- Offer multi-user handling to give different users different rights for loading and manipulating 'session profiles' to support teams of scientists to exchange data e.g. on the same outcrops.
- Search for spatial and temporal correlations in laboratory instruments' data (spectrometers etc.).
- Get a spatial overview of products locations having certain characteristics (e.g., a spectrum with a certain shape) and/or particular meta-information, e.g. rover orientations, focal length.
- Gain an overview of distribution of products by time / rover orientation / etc.
- Simultaneously inspect ensembles of spectra / images. This may include a characterization of the overall dispersion, a pairwise comparison of particular products, and the clustering of products by their characteristics.
- Provide bidirectional relation of product locations to corresponding product characteristics, e.g., identify spectral bands with high values / strong variation / etc. within a region.

5 Future Work

The next research and development tasks will focus on collaborative aspects. It shall be possible to share analysis results via a common data repository. For that users and roles have to be considered. Users shall be able to upload products derived from analysis sessions as well as product augmentations back into the repository. In the future, Visplore shall allow users to efficiently compare different interpretations from planetary scientists and help to identify agreements and discrepancies. We are currently working on a labelling extension to annotate visual analytics results, so users can comment on how they reached a particular finding by using Visplore.

We will further extend the 3D GIS functionality of PRo3D. This includes to generate frustums of camera instruments and show them as footprints directly on the reconstructed 3D surface. PRo3D shows the exact location of other products by colour-coded 3D dots, but when clicking on such an icon the data can be explored in-depth with Visplore. Multiple selection on the surface will also be possible to consider several products within an area and compare their data. Adding SOL labels to the product locations and camera footprints will also provide scientists with temporal context.

The third development direction will be a tighter integration between PRo3D and Visplore, supporting interactive brushing and linking and also addressing certain challenges that arise when combining 3D spatial and non-spatial visualizations [7].

6 Conclusion

MINERVA will for the first time provide a consistent and holistic framework for planetary scientists supporting collaborative analysis of heterogeneous mission data. Data and analysis results are shared via a common spatiotemporal data repository. PRo3D offers 3D GIS functionality making a separate map viewer obsolete. GIS layers and items such as shape files become part of 3D space in form of extra surface textures, line graphics or 3D dots. Visplore enables an in-depth visual analysis of heterogeneous non-spatial data from various sensors. Linked views between PRo3D and Visplore allow scientists to relate geospatial and non-spatial data in an unprecedented way establishing the full context.

We presented our current progress to planetary scientist at two workshops, one held at VRVis in Vienna in July 2018 and another at Imperial College London in March 2019. The discussions showed that such a framework has a high potential to be widely accepted by planetary scientists and to have a significant impact on the way planetary science data is analyzed and managed in future missions. Valuable feedback and requirements obtained from these workshops and the ongoing collaboration with planetary scientists guide our further developments towards a mission-ready framework.

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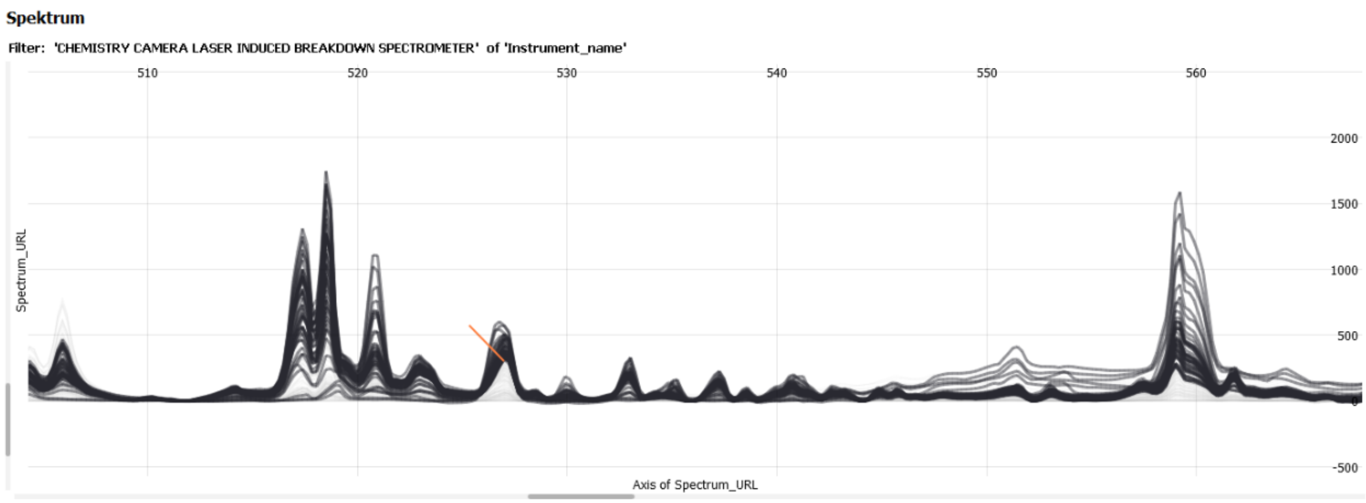

Figure 6: Spectral view shows spectra originating from the same instrument as alpha-blended curves plotted over each other. Here, we use a line brush to select Chem-Libs spectra with a peak at about 527nm. The selected curves are indicated by the darker color.

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