Final Report

Final Publishable Summary Report

Report Meta Data	
Grant Agreement Number	607177
Project Acronym	CROSS DRIVE
Project Title	Collaborative Rover Operations and Planetary Science Analysis System based on Distributed Remote and Interactive Virtual Environments
Funding Scheme	Collaborative Project
Project Starting Date	2014-01-01
Project End Date	2016-12-31
Name, Title, and Organisation of the scientific representative of the project's coordinator	Dr. Andreas Gerndt Head of Department, Deputy Director of Institute Simulation and Software Technology German Aerospace Center (DLR)
Telephone	+49.531/295-2782
Telefax	+49.531/295-2767
E-mail	andreas.gerndt@dlr.de
Project Website Address	http://www.cross-drive.eu

Table of Contents

Table of Figures

Table of Tables

1. Executive Summary

CROSS DRIVE stands for “Collaborative Rover Operations and Planetary Science Analysis System based on Distributed Remote and Interactive Virtual Environments” and aims at creating the foundations for collaborative distributed virtual workspaces for European space science. Space exploration missions have produced huge data sets of potentially immense value for research as well as planning and operating future missions. However, current expert teams, data, and tools are fragmented leaving little scope for unlocking this value through collaborative activities.

The question of how to improve data analysis and exploitation of space-based observations can be answered by providing and standardising new methods and systems for collaborative scientific visualization and data analysis, space mission planning, and mission operation. This will not only allow scientists to work together, with each other's data and tools, but importantly to do so between missions. The proposed collaborative workspace encompasses various advanced technological solutions to coordinate central storage, processing and 3D visualization strategies in collaborative immersive virtual environments to support space data analysis.

Three case studies have been carried out and demonstrated the utility of the workspaces for European space science: Mars atmospheric data analysis, rovers landing site characterization, and rover target selection during its real-time operations. The use cases exploited state-of-the-art science data sets. They were collected in view of the ESA ExoMars 2016 TGO and 2018/2020 rover missions’ scenarios.

Impact on beneficiaries had been maximised both through providing an expandable backbone infrastructure and three levels of workspace for: scientists directly engaged, other external scientists, and the public.

2. Final Publishable Summary Report

Section 2.1 provides a short summary of the project including context and objectives. Section 2.2 provides a description of the work performed during the period. Section 2.3 describes the expected results and their anticipated impact. And Section 2.4 provides details of the project web site.

2.1. Project Context and Objectives

CROSS DRIVE targets at creating the foundations for collaborative distributed virtual workspaces for European space science. Space exploration missions have produced huge data sets of potentially immense value for research as well as planning and operating future missions. However, current expert teams, data, and tools are fragmented leaving little scope for unlocking this value through collaborative activities.

The question of how to improve data analysis and exploitation of space-based observations can be answered by providing and standardizing new methods and systems for collaborative scientific visualisation and data analysis, space mission planning, and mission operation. This will not only allow scientists to work together, with each other's data and tools, but importantly to do so between missions. The consortium brought together unprecedented expertise from space science, scientific visualisation, Virtual Reality (VR), and collaborative systems. The developed collaborative workspace encompasses various advanced technological solutions to coordinate central storage, processing and 3D visualization strategies in collaborative immersive virtual environments to support space data analysis.

2.1.1. The Workspaces

The collaborative workspace platform is focused on the data analysis and operations of planetary missions. Its purpose is to allow scientific and engineering teams, distributed across the world, to work together in a shared 3D space using data from past and ongoing missions, visualise scientific data and the spacecraft and rover as well as their trajectories and status information, and allow the users to freely navigate and collaboratively interact with the displayed data.

In order to allow different forms of collaboration in different contexts, three workspaces have been investigated in the CROSS DRIVE project: Core Collaboration Workspace for the core mission team, External Public Workspace for engaging selected scientists, and Web Portal for broader dissemination and engagement of scientific community and the public. Impact on beneficiaries has been maximised through an expandable backbone, and reusable standardisation and tools.

2.1.2. The Use Cases

A specific focus has been given to the preparation of the ExoMars 2016 Trace Gas Orbiter (TGO) and ExoMars 2018/2020 Rover missions. Three case studies demonstrated the utility of the workspaces for European space science: Rovers landing site characterization, Mars atmospheric data analysis, and rover target selection during its real-time operation. The use cases exploited state-of-the-art science data sets and have been constructed in view of the ESA ExoMars missions' scenarios.

The main target mission is the scenario when a Mars satellite and rover will be jointly operated. Intensive real-time science analysis processes are expected during the rover operations. And in order to reduce costs, part of the science team would have to be remotely connected to the Mission Control Centre at ALTEC. The three test use cases were defined to evaluate the efficiency of CROSS DRIVE's architecture as well as the foreseen data processing and analysis methods:

1. **Landing sites characterisation**: This use case visualises, analyses and presents relevant aspects of research in landing site selection for Mars robotic missions. Science users are able to analyse geologic features of selected areas of Mars, apply basic GIS functionality and a

selection of real-time analysis tools, and analyse the surface and subsurface structure of the terrain. Relevant sample datasets can be visualised as 3D terrain model using the Mars Cartography Virtual Reality System.

2. **Mars atmospheric data analysis and benchmarking**: Global views of Mars in order to analyse concepts related to the global circulation like geo-potential maps and time/spatial variations of selected variables have been considered. Tests include comparisons among measured data and output of off-line complex models, among data from different payloads, and among data collected from different locations or time. Correlation and benchmarking between satellite and ground based measurements have been considered as well.
3. **Rover target selection**: This test addressed operation planning of planetary rovers and satellites by using the Collaborative Workspace. In particular, the system allows analysis of geologic features of terrains as viewed by the on-board cameras of the rover, comparison among rover images/DTM and satellites' images/DTM, analysis of the morphology of the terrain in correlation with the expected landing trajectories, provision of commands to the satellite and rover, and review of the data coming from the rover after commands execution.

2.1.3. The Consortium

The CROSS DRIVE consortium has been composed in a way that all the necessary competencies were available and provided by the partners with excellent reputation for their dedicated tasks. The consortium has been formed by considering the main European players of planetary science, space mission planning, robotics, and Virtual Reality today.

CROSS DRIVE consortium allowed government, academic, and commercial organisations to effectively and efficiently contribute to collaborative solutions for space missions and space data analysis. Partners were selected from 5 different nations (Germany, UK, Italy, Belgium, Japan) providing a heterogeneous consortium for research on collaborative visualization techniques supporting space science data analysis. The collaboration of various types of partners was within CROSS DRIVE's scientific scope therefore it was balanced with 2 industry (ALTEC and TAS-I), 2 academic institutions (USAL and TOHO) and 3 national research institutes (DLR, INAF, and BIRA).

2.2. Main Scientific and Technical Results and Foregrounds

CROSS DRIVE has been subdivided in seven Work Packages. **WP1** addressed the overall management of the project, covering administrative and financial issues as well as providing project control procedures. **WP2** has focused on the specification of data sources, algorithms, simulators, distributed computing infrastructure, and associated workspaces for the addressed use cases. The science specification defined the datasets for the Mars atmosphere, geology and geodesy used for the evaluation. It also defined the use cases (WP7) early during the project in order to address the development made by WP4 and WP3.

WP3 objectives were to ensure good and fluid dissemination of the investigations and results between the partners of the CROSS DRIVE project, but also toward the general scientific community, the space agencies, and the general public. This was primarily done through the definition, creation, and maintenance of a web-portal and website. And many highly visible presentations on fairs / events, on conferences / workshops, at Universities, at companies, and for other project consortia were held.

The project aimed at the collection and integration of different experiences and software solutions for VR systems: planetary cartography and GIS by DLR, space system engineering by Thales Alenia Space, and remote collaborative platforms by the Salford University. These three elements, together with archiving and computing systems by ALTEC, have been analysed and developed within **WP4** which led to a versatile collaborative framework for Science and Exploratory Space Missions.

WP5 and WP6 aimed at the definition and analysis of the core science processes for the selected use cases. These two work packages dedicated to planetary science were focusing on Mars geology and geodesy (WP5) and Mars atmospheric science (WP6). While they played a similar role within the rationale of the project's overall work flow, their specific objectives and task definitions were tailored to the specific requirements and tools of the respective disciplines. First of all, specific science analysis and computations had to be defined by the science partners and drove, with specific requirements, the design of the collaborative workspaces in view of the final tests and demonstrations. Moreover, WP6 provided specific algorithms which had been integrated into the collaborative workspace environment for "off-line" and "real-time" computations to be used during the tests and demonstrations of the selected use cases.

Finally, **WP7** was devoted to the preparation and execution of the main use cases. These were focused on data analysis and the operative planning processes of a Mars satellite and rover together with the dissemination of their joined science data in view of the ESA ExoMars 2016 and 2018/2020 missions.

The subsequent sections will present the work performed and the results achieved in more detail.

2.2.1. CROSS DRIVE's Global System Design

The system of CROSS DRIVE combines different elements that contribute to the primary objective of the project. The architecture includes Virtual Reality facilities and all the infrastructure and software resources needed to support the collaborative sessions proposed in the project statement. The collaborative workspace platform we propose is focused on the data analysis and operations of planetary missions. Its purpose is to allow scientific and engineering teams, distributed across the world, to work together in a shared 3D space using data from past and ongoing missions, visualise scientific data, the spacecraft, and rovers as well as their trajectories and status information, and allow the users to freely navigate and collaboratively interact with the displayed data. From the system point of view, it represents a distributed platform that integrates various data sources, simulations, and various display systems such as CAVEs, Powerwall, and workstations.

The central connection node of the infrastructure is provided through the CROSS DRIVE Server located on a Demilitarized Zone (DMZ) area of ALTEC's network. Such solution allows the company to expose an external-facing service to a larger and untrusted network. The CROSS DRIVE Server manages the access of the client applications and ensures the synchronization of the available resources. The access from the main VR facility is however regulated through the proper set-up of the firewall rules.

An overview of the architecture is provided in Figure 1 where the set-up of the third Use Case is reported. The CROSS DRIVE Server located at ALTEC manages the messages exchange across all the client applications connected to the central node. The visualization tools, Terrain Renderer and VERITAS, are synchronized. And updates of the 3D scene are distributed to all the clients.

The system has been conceived to connect Science Home Bases, where scientist are located during interactive sessions, and the Engineering Center, which hosts the Engineering team involved in the operations of the rover mission (subsystem experts and operations engineers). The Mission Control Center (MCC) is the element that orchestrates the execution of the sessions, providing also the connection with the Mars and Moon Terrain Demonstrator (MMTD) facility. This environment is used to keep real hardware in the loop (the rover structural mock-up) and achieve a higher level of fidelity of the system response during operational scenarios. The architecture of the CROSS DRIVE software is also defined to ease the process of integration of additional clients when the connection of different applications is needed. The core libraries have been in fact implemented to make the development of the interface with the main workspace as straightforward as possible.

The CROSS DRIVE system has been also conceived to provide archive and computing capabilities. A prototype tool, represented by a web application, has been developed to assess the feasibility of a user friendly interface with archiving purposes.

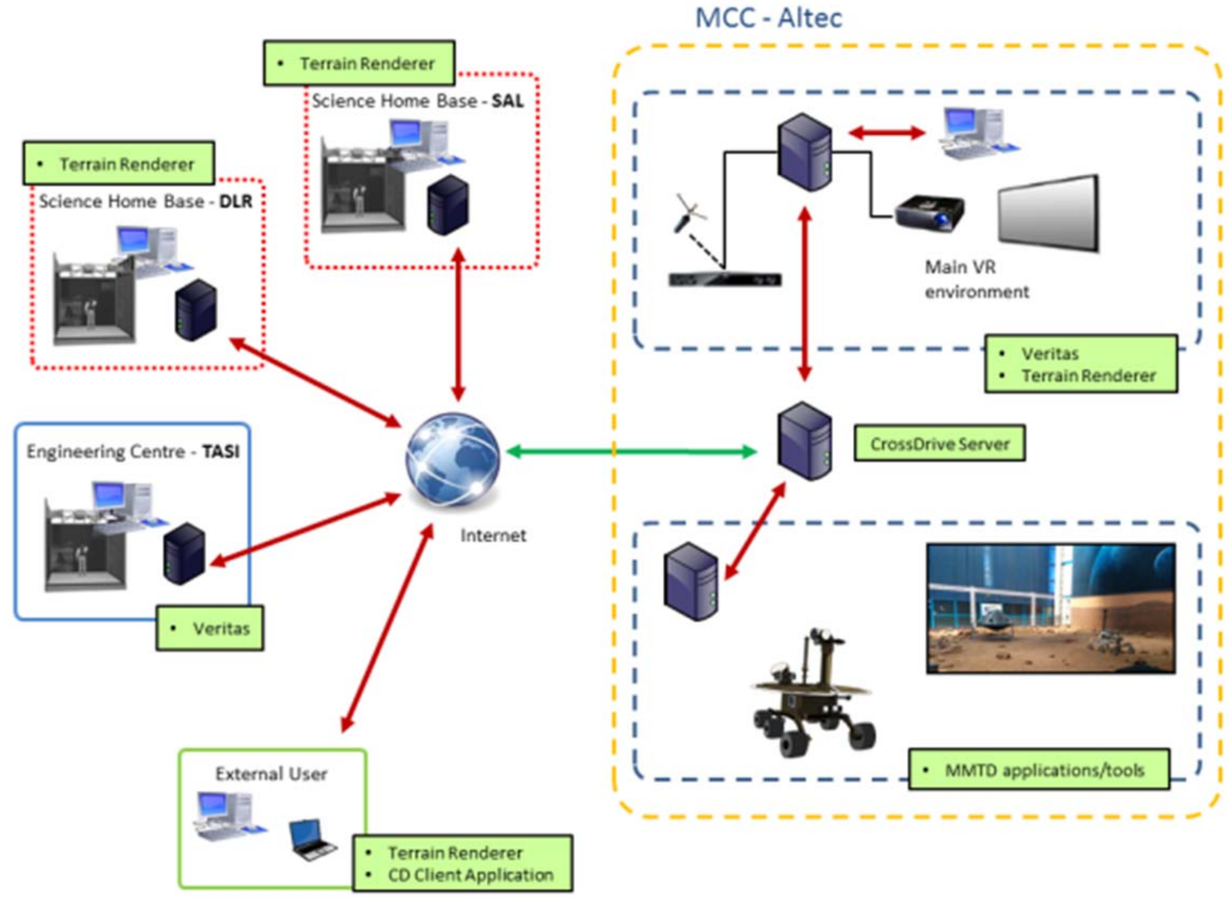


Figure 1: CROSS DRIVE functional overview – Use Case 3

The Virtual Reality facilities connected through the CROSS DRIVE collaborative workspace are listed below:

- Virtual Reality laboratory – DLR, Braunschweig
- ThinkLab Virtual Reality laboratory – University of Salford
- Cose Centre Virtual Reality laboratory (COSE VrLab) – TASI, Turin
- Virtual Reality laboratory – ALTEC, Turin

The main Virtual Reality facilities provide immersive environments that enable users to interact with the 3D scene. They are equipped with 3D projectors, wide screens, tracking systems and interaction devices that improve the exploitation and navigation of Mars datasets. The core users access the collaborative workspace through the main facilities but the connection of external users is allowed with desktop versions of the main visualization tools, Terrain Renderer, and VERITAS. In this case, the external users, basically defined as the users that cannot access the workspace through the Virtual Reality laboratories, can however interact with the same 3D scene but with reduced interaction capabilities. The libraries developed for the connection to the framework have been also used to implement an additional client application for external users. In this case, the 3D scene is analysed on a 2D map but all the main graphical features created during the collaborative session are visible (landmarks, annotations, landing ellipses, path lines, landmarks, etc.).

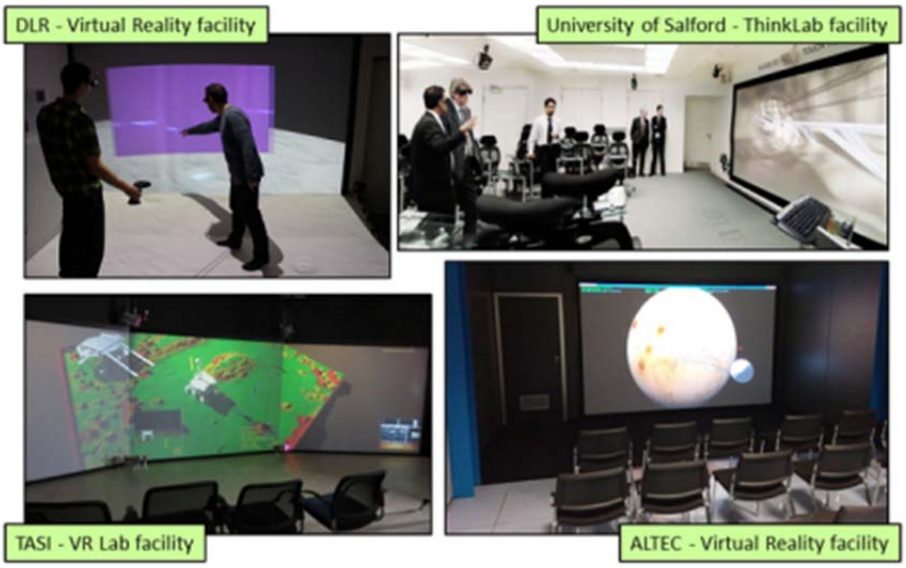


Figure 2: CROSS DRIVE Virtual Reality facilities

A common communication layer allowes the exchange of all the information needed to update the 3D scene on the basis of the interaction of users with the virtual environment. Such an approach allows keeping the visualization tool separated while exchanging data about the graphical features in real-time. This ensures a straightforward communication among clients, reduces time delays, and keeps applications synchronized. The integration of the MMTD facility with the CROSS DRIVE framework has been achieved through the development of a client application using the same communication layer integrated by visualization environments.

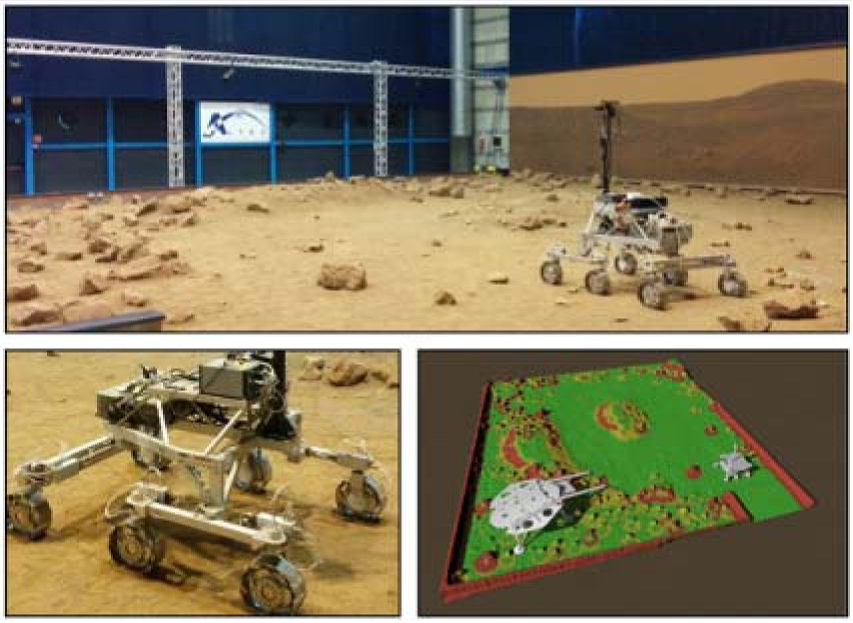


Figure 3: MMTD facility, rover locomotion system mock-up, and 3D scene

2.2.2. Mars Geology and Geodesy Data and Tools

The CROSS DRIVE project has been targeted on creating the foundations for collaborative distributed virtual workspaces for European space science. For that, various scientific data has been shared, and the relevant scientific tools have been provided. The scientific specifications that the different developed tools had to follow in order to be appropriate in virtual environments have been described in detail in [1] and [2]. In [3], the main features related to the definition of requirements for scientific tools has been described. They are mainly needed for the integration within the Collaborative Workspace with the final aim to reduce the issues that can occur during data exchange.

Detailed mapping of topography is central to the understanding of the processes shaping the surfaces of the planets. Mars geodesy and geology/geomorphology are therefore working hand in hand to study morphometric properties, e.g., of volcanic, tectonic, fluvial/lacustrine and glacial/periglacial landforms on Mars. The availability of topographic data with high global accuracy (MOLA) and high spatial resolution (e.g. HRSC, HiRISE) has enabled quantitative analyses of surface processes, which were almost impossible before.

The identification and characterization of planetary environments rely on the synthesis of information from diverse data sets over a large range of spatial scales. New applications to investigate topographic datasets on Mars and joint analysis of these and other datasets, as attempted by CROSS DRIVE, are therefore of high general interest to the planetary geoscience community.

A major focus of the Mars Geology and Geodesy Work Package of CROSS DRIVE was therefore dedicated to the generation of a data base comprising geocoded planetary data products for the surface and subsurface of Mars at different spatial scales and including surface spectroscopy images. The CROSS DRIVE data base includes map-projected raster digital elevation models (DEMs) and processed images from HRSC, CTX, CRISM, HiRISE, as well as additional data sources (MOC, OMEGA).

The database is an outcome of the work performed in WP5 “Mars Geology and Geodesy” Task T5.1 “DEM and map-projected images”, with the main goal of preparing datasets needed for analysis in tasks T5.2 “Surface and Subsurface Mapping” and T5.3 “Landing Site Characterisation” and for the related Use Case demonstrations performed in WP7 “Use Cases and Validations”. The data base was designed to facilitate 1) map-view display for visualisation of data coverage and surface features at multiple scales (i.e., of regional and local interest), 2) localization in terms of geographic coordinates and mapping / annotation of geolocated surface features, 3) display of surface elevations and morphometric relief properties derived from elevation models, 4) 3D rendering of planetary images or other mapping textures, 5) display of vertical profile data (e.g. SHARAD radargrams) and other 2D plots (e.g. reflectance spectra from hyper-spectral data) for specific locations, 6) geometric measurements based on the above data displays.

These modes of data imply a set of basic common requirements for all datasets that can be summarized as follows: The datasets should provide both regional coverage by medium to low resolution images and more localized coverage by high-resolution data. All surface images should be orthorectified and map-projected. Digital elevation data should be available for the entire study area. Data records for vertical profiles (e.g. SHARAD) or other 2D plots (e.g., pixel spectra) should be available. As the latter are not represented as maps, they are associated with georeferencing information for each sample, and new technical concepts for joint visualisation together with 3D data of the surface had to be applied and tested. To facilitate import and combination of data sets, all data sets should follow the same format standard (PDS3) and be represented in the same geodetic reference system and map projection. Figure 4 illustrates the diversity in terms of spatial resolution and coverage among the surface datasets included, using small samples from the different datasets.

Beyond their use for the three CROSS DRIVE Use Case tests, the data products have been analysed in a case study on the regional geology and subsurface structure of the Elysium region of Mars (T5.2 “Surface and Subsurface Mapping”). The analysis of SHARAD radargrams applied for this purpose was supported by numerical clutter simulations on the basis of the digital elevation model.

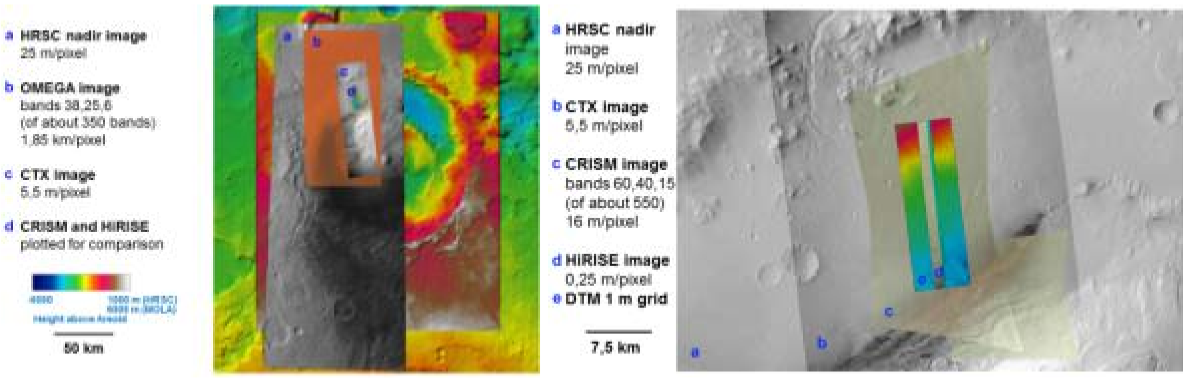


Figure 4: Left: Extent of the local CROSS-DRIVE target area at Gale Crater. Area measures approximately 210 km by 275 km and is defined by the surface coverage of the HRSC 50 m DTM. Note that a different color table is applied to the HRSC and MOLA (background) shaded relief maps to highlight local morphology. Also shown are example files for other datasets for illustration (only one example per dataset). The right image shows a small part of the area covered by the upper image; the color-coded display of the HIRISE DTM is from the same dataset and is marked with the letter "d" in the top part of the figure.

As our knowledge on the properties and processes of the celestial bodies and their surfaces is derived to a large extent from planetary image data, the methodology to manipulate and visualize planetary images in a way that efficiently supports scientific analysis is also highly relevant to planetary science. This was taken into account by specifications for CROSS DRIVE Renderer tools for joint visualization of surface and subsurface developed from an application perspective, as well as testing and feed-back to the development group of the Renderer (WP4) on the basis of experience gained during the Elysium case study. After verification using clutter simulation, radar features were interpreted and correlated with surface datasets directly in a 3D context, as illustrated in the example show in Figure 5.

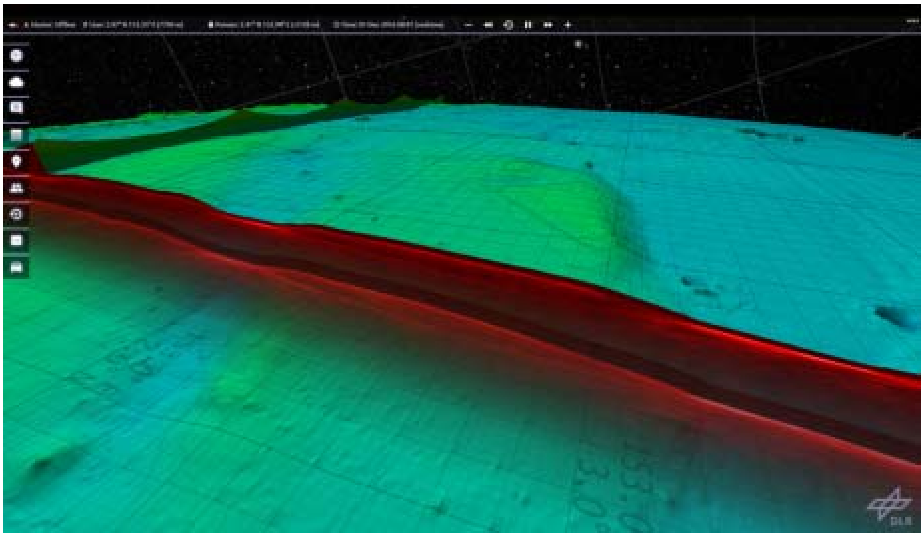


Figure 5: Joint 3D display (CROSS DRIVE Renderer) of SHARAD radargrams and color-coded elevation models, for regional correlation of surface and subsurface features. A radar reflector verified by numerical clutter simulations can be traced below a positive topographic feature and follows approximately the surface level of the surrounding plains. Context images obtained by HRSC and CTX suggested a contact surface that separates two depositional units of Medusae Fossae Formation.

A further topic in planetary exploration that requires in-depth analysis of a multitude of co-located data sets is the scientific characterisation of past, present and future landing sites (such as the Curiosity landing site in Gale crater, Figure 6). This topic is central to CROSS DRIVE Use Cases 1 and 3 and has been addressed specifically in CROSS DRIVE Task 5.3 Landing Site Characterisation. Using lander missions such as ESA ExoMars and NASA InSight as background, typical requirements concerning both datasets and tools needed for studying properties of the landing site areas have been considered for the development of relevant CROSS DRIVE Use Case scenarios, databases, and analysis tools. Besides the scientific objectives to be addressed, it is central for landing missions to assess in detail the feasibility aspects and risks associated with a number of surface-related characteristics such as surface slope and roughness, regolith and rock characteristics as well as environmental conditions. Within the landing site study of WP5 we focussed on measurements and analysis of layering structure from regional scale to outcrop scale, using terrain models and orthoimages produced from orbit-derived images and from surface-based rover images. Figure 6 illustrates the diversity of layering structures on Mars, together with examples for related 3D data products from rover stereo images produced in the project. Rover data products were added to the CROSS DRIVE data base according to the specific requirements of Use Case 3 (rover operations). We also applied these in our WP5 case study, together with HiRISE data, for investigating and validating the new CROSS DRIVE layer measurement tool against conventional GIS-based strike and dip measurements in map-projected images.

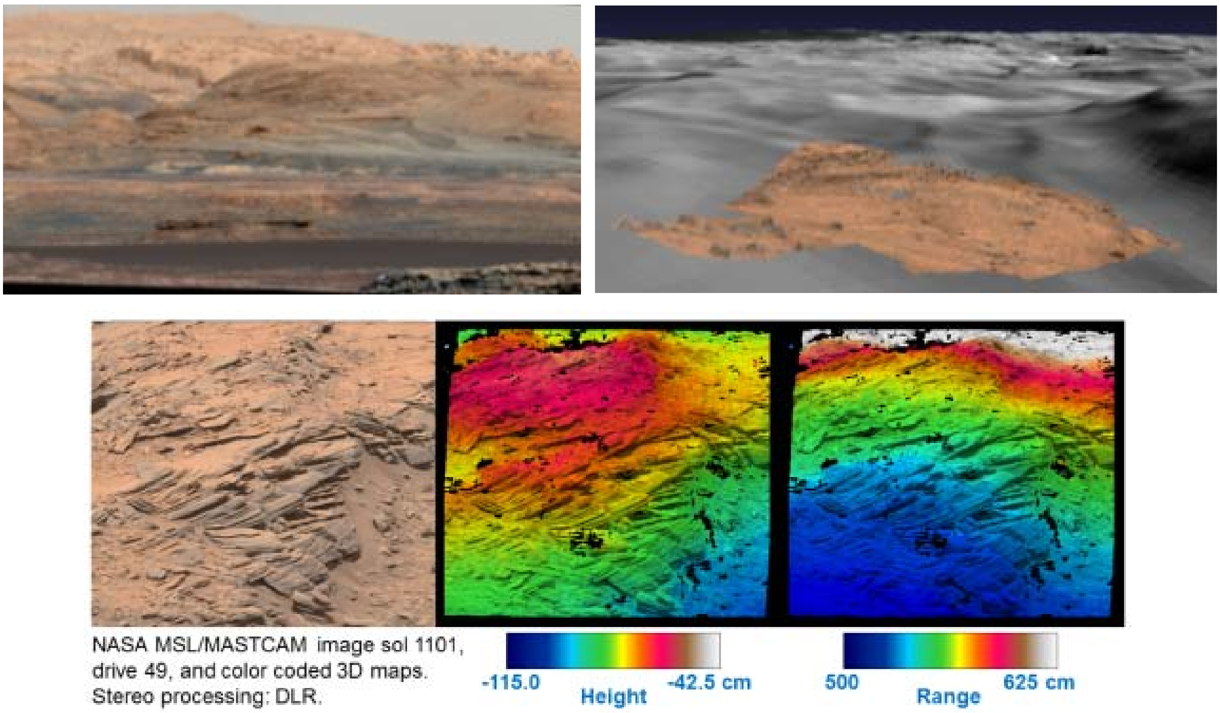


Figure 6: Layering structures on Mars, from regional scale (Aeolis Mons, Gale Crater, upper left) to outcrop scale (upper right and bottom). The 3D display (upper right) shows a mosaic of MASTCAM rover images co-registered with a HiRISE image. Bottom, from left to right: MASTCAM color image, MASTCAM image overlain by color-coded height and range data, respectively. Note: layers extending from kilometres to few centimetres are seen in these images. (Images: NASA MSL/MASTCA; photogrammetric processing: DLR)

2.2.3. Mars Atmospheric Data and Tools

Various data and tools needed for atmospheric science have been prepared for implementing, testing, and validating the three use cases relevant to the Mars mission (see Section 2.2.7). One of the specific objectives was to exploit Mars satellite data to provide the complete description of atmospheric state. For that, data taken by PFS-MEx at level 1/2, SPICAM-MEx at level 1/2, ground-based observations, NOMAD-TGO at level 1 and by Global Circulation Models (GCM) have been collected and used as basis for the different visualization algorithms implemented in DLR's Terrain Renderer described in the next Section. These specific algorithms allowed the scientists to explore the Mars atmosphere within the virtual environment.

PFS-MEx Level 2 data: The Planetary Fourier Spectrometer (PFS) on-board the European mission Mars Express (MEx) is a double-pendulum interferometer optimised for atmospheric studies. Thanks to the wide spectral range covered (1-50 µm) and its relatively high spectral resolution (1.3 cm^{-1}), PFS performs absolute simultaneous observations of multiple CH_4, H_2O, H_2O_2, CO and CO_2 absorption lines or bands. In about seven Martian years, PFS collected nearly 3.000.000 spectra. With full spatial coverage every year, PFS is sounding the Martian atmosphere at different local times and seasons, allowing diurnal, seasonal, and inter-annual analyses of several atmospheric species and parameters. PFS retrievals of 3D fields of temperature profile, 2D maps of dust opacity, and 2D maps of water ice opacity have been provided. All maps are provided for specific georeferenced points on regular grid (i.e., equally-spaced values for latitudes and longitudes). Longitudinal and latitudinal intervals of the grid are 5° and 1°, respectively. The 3D database of PFS atmospheric temperature fields is provided for the southern hemisphere from 30°S to 90°S during the Ls interval from 45° - 135°. Temperatures extend from the surface to an altitude of approximately 90 km (Figure 7).

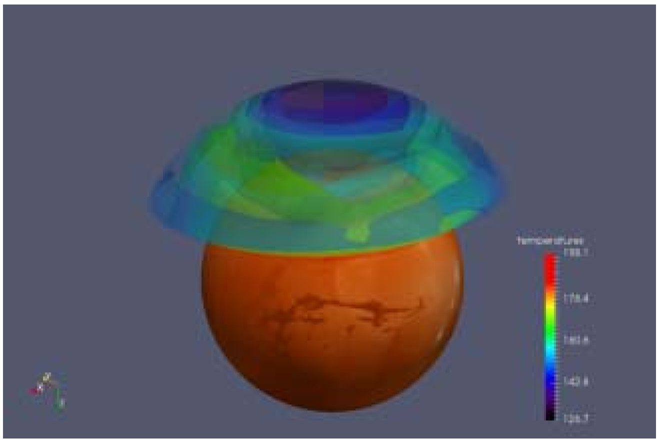


Figure 7: PFS-MEx Level 2 data

A global dataset of integrated dust and water ice opacities is also provided with the same spatial resolution as the 3D database of atmospheric temperatures. The dust opacity is delivered for two different seasons, outside and during the so-called "dust storm season" (Figure 8). The global dataset of water ice opacity is also provided for two different seasons, in order to show the difference in the spatial and time distribution of water ice opacity during the "aphelion cloud belt" season and the northern autumn and winter (Figure 9). The "aphelion cloud belt" is the season starting from Ls = 60° until around Ls = 120° with high abundance of water ice in the atmosphere over the tropics (30°S to 30°N) and the Tharsis region. This activity is due to the ascending branch of Hadley circulation which transports water vapour to the mid-latitude regions condensed to water ice.

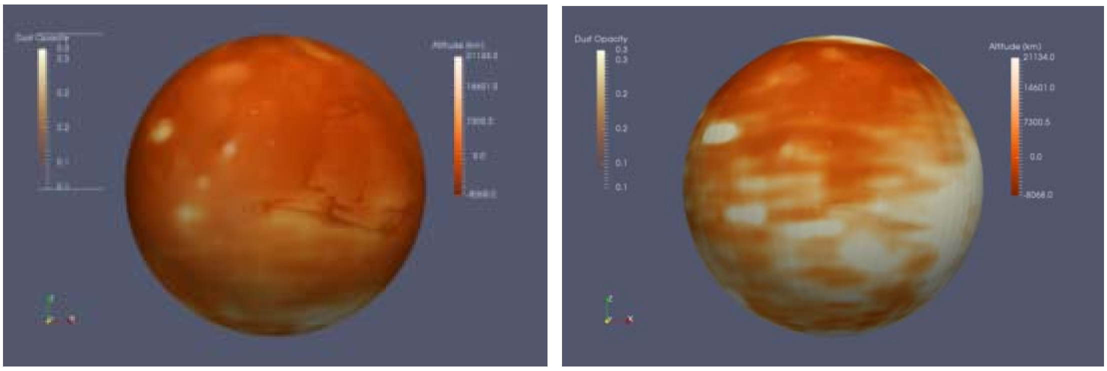


Figure 8: Dust opacity for non-dust season (left) and during "dust storm season" (right)

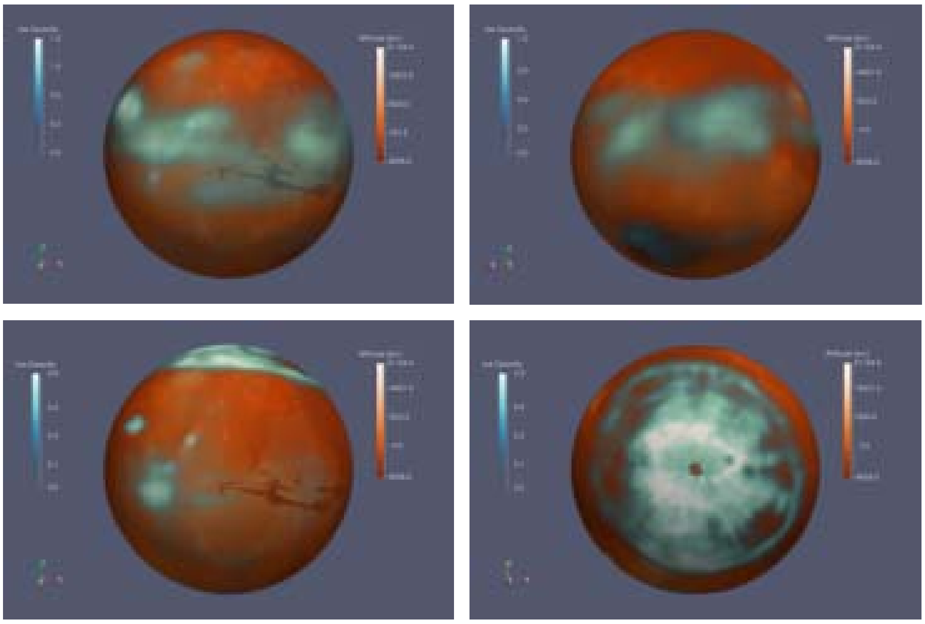


Figure 9: Global view of ice opacity during "aphelion cloud belt season" (top panels) and during northern autumn and winter (bottom panels)

Ground-based observations: Ground-based observation data taken by high-dispersion echelle spectroscopy ($\lambda/\Delta\lambda \sim 20{,}000$) of the Infrared Camera and Spectrograph (IRCS) of the Subaru telescope have been collected and provided. Subaru is 8.2 m telescope of the National Astronomical Observatory of Japan, located at the Mauna Kea observatory (4.2 km) at Hawaii island. The ground-based observations by SUBARU/IRCS were performed on January 4–5, 2012 and April 13, 2012. Table 1 summarizes the observation conditions. The observed seasons on Mars correspond to spring (*Ls* = 52.4° and *Ls* = 52.9°) and summer (*Ls* = 96.2°) in the northern hemisphere of Mars for January 2012 and April 2012, respectively.

Date and time (UT)	*Ls*[1] (°)	MY[2]	Doppler shift (km/s)	Diameter (″)	Airmass[3]	Slit direction	Observing areas (°)	Local Time
4/January/2012 13:12–16:26	52.4	31	-15	9.3	1.14–1.09	E–W	0N–40N 220-360W	10–17
5/January/2012 12:34–16:28	52.9	31	-15	9.4	1.25–1.10	N–S	0-80N 256–302W	13–15
13/April/2012 8:24–10:49	96.2	31	+11	11.5	1.05–1.56	N–S	40-80N 34W–60W	9–10

Table 1: Parameters of Mars observations data taken by SUBARU/IRCS

The SUBARU/IRCS data includes 2D map of H_2O vapour, HDO vapour, and HDO/H_2O ratio observed at the MY31 Ls=52°, and 2D map of HDO vapour at MY31 Ls=96° (see Figure 10).

---

[1] Solar longitude. This value is given in degrees and ranges from 0 to 360 ("Ls=0 degree" corresponds to the northern spring).

[2] Martian Year. Martian Year 1 begins on April 11th 1955.

[3] Cosine of elevation angle of Mars.

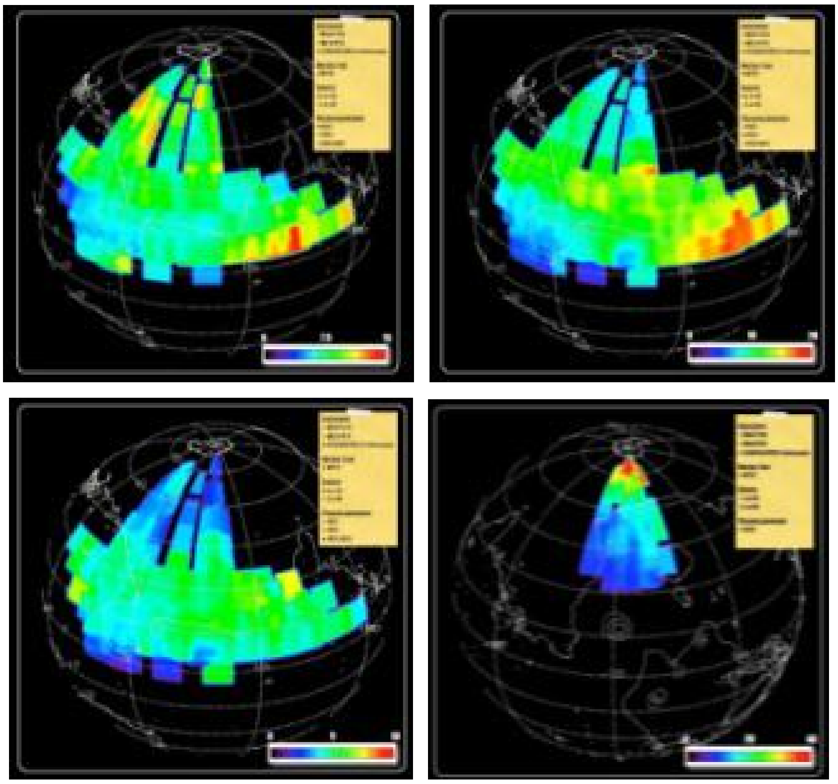


Figure 10: SUBARU/IRCS maps of H2O vapor (top left), HDO vapor (top right), HDO/H2O ratio (bottom left), and HDO vapor (bottom right)

GCM data: As GCM data is more "complete" in the sense of global and temporal coverage and properties of the atmosphere compared to observational data gathered from orbit and landers, it can provide insight into those observations. The simulated data have been incorporated into the Virtual Reality system and used as an analysis tool for interpreting observational data in Use Case 2. GEM-Mars is a global general circulation model for the Mars atmosphere based on the dynamical core of the Global Environmental Multiscale model which is part of the operational Canadian weather forecast system. It is a grid-point model using a semi-Lagrangian advection scheme with semi-implicit time integration. The model includes parameterisations to reproduce the Mars water and carbon dioxide cycle. It also includes a multi-layered soil model for heat conduction, including a subsurface ice table in the (sub-)polar regions, parameterizations for the surface layer (Monin-Obhukov similarity theory), planetary boundary layer (PBL) turbulent diffusion, gravity wave drag parameterization, eddy and molecular diffusion. A basic gas-phase atmospheric chemistry package is also incorporated. The provided dataset is a result of a simulation using the most recent version of the dynamical core v4.2.0, with a horizontal resolution of 4x4 degrees, 103 staggered vertical levels up to ~150 km and a 30 minute timestep. The model outputs a snapshot of computed variables every 12 timesteps, allowing the diurnal cycle to be roughly represented. The provided three-dimensional fields include temperature, pressure, wind, air density, dust extinction, chemical species volume mixing ratio, including water vapour and water ice mixing ratios. Two-dimensional fields include surface temperature and pressure, local time, solar zenith angle, total column water vapour and ozone, dust and water ice opacity, albedo and topography.

Real-time tools: Tools have been developed for the off-line and real-time analysis of the Level 1 and Level 2 data from selected instruments. The tool, ASIMUT_OnLine, can simulate spectra under diverse conditions found on different planets. The central code, ASIMUT-ALVL, has been developed at IASB-BIRA for Earth observations, and then adapted to missions and instruments to Venus and then Mars. ASIMUT-ALVL can also be used to retrieve atmospheric information (abundance, surface temperature, etc.) from observations (Level 1 radiances or transmittances). The On Line version of the code further developed under CROSS DRIVE builds heavily on this tool. Improvements have been implemented, driven by the specific needs of the CROSS DRIVE project. The web interface has been developed in order to let internal and external people to have access to the program. In the current implementation all files reside on the IASB server(s) and the execution program is executed on IASB machines. In the future both the data files and the running activities will be done under the VR system of CROSS DRIVE. Moreover, the interface has been created using standard web technologies (HTML, CSS and Javascript) to be compatible with most platforms. The client web interface allow the creation of a user configuration file which enables the connection, creation of a job, submission of a job, following-up of the job. The ASIMUT On Line tool can be accessed at the following URL: http://www.crossdrive.eu/sportal/asimutalvl.

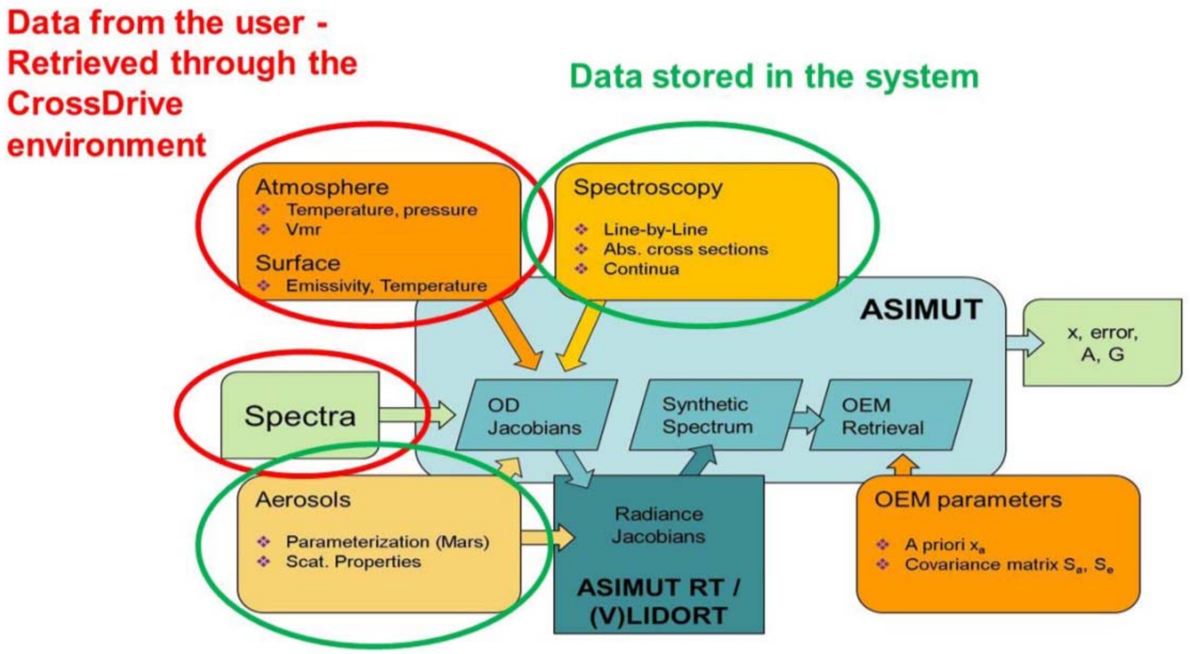


Figure 11: General description of the ASIMUT-ALVL tool and the ancillary data that are needed

2.2.4. Scientific Data Visualization with DLR's Terrain Renderer

The Terrain Renderer developed for CROSS DRIVE at DLR consists of a main component which relies on the ViSTA VR Toolkit [4] which is built on top of the OpenSG scenegraph [5] and additional libraries (Figure 12). The libraries of the main component are:

1. TRCommon, which gives basic functionality for Terrain Rendering
2. VistaPlanet, which uses the TRCommon to give the application the ability to render a planet
3. CROSS DRIVE Network / Collaboration Manager, this library adds the functionality for collaborative workspaces and defines the model
4. CROSS DRIVE Common, which acts as a controller to the CROSS DRIVE Network specified model
5. CROSS DRIVE Renderer, which acts as a view to the specified model

Note that TRCommon and VistaPlanet were not developed within the CROSS DRIVE project. Only bug fixes, general maintenance and feature improvements to these two libraries were done in all stages of the project. With the approach to separate functionality in different libraries, the requirement of structured, flexible and extensible software was achieved.

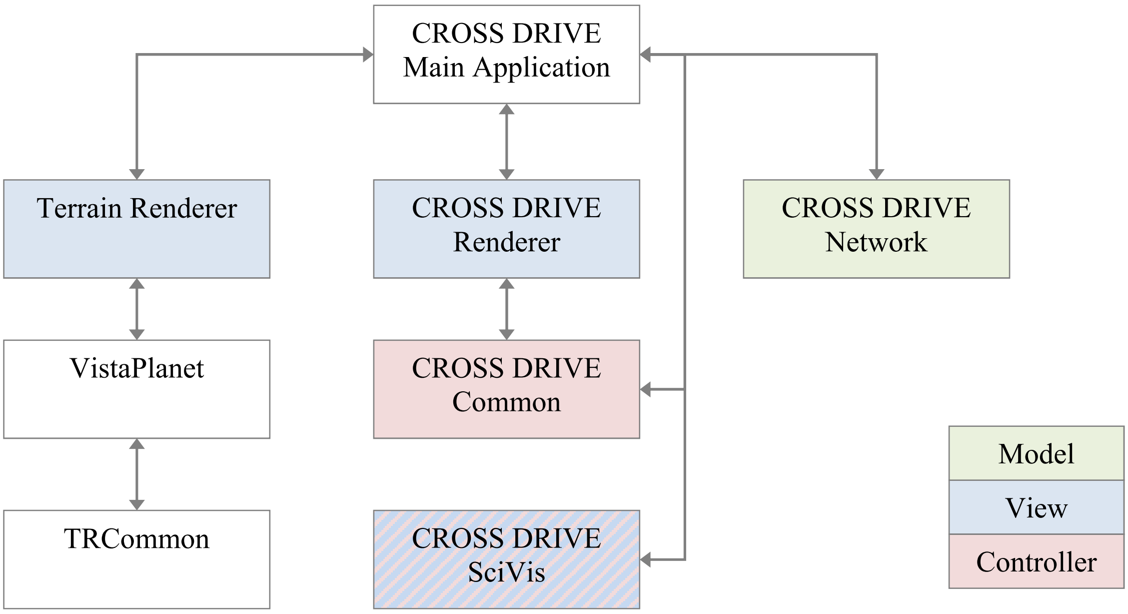


Figure 12: System architecture of DLR's Terrain Renderer

The main concept follows the Model-View-Controller (MVC) approach: The user's inputs in a VR environment are recorded by the hardware and the drivers and then interpreted by the ViSTA system. Afterwards, the main application forwards this information to the controller (e.g., CROSS DRIVE Common), which interprets these inputs again and manipulates the underlying model, which is defined within the CROSS DRIVE Network library. At all times the CROSS DRIVE Renderer provides the view to the model (Figure 13).

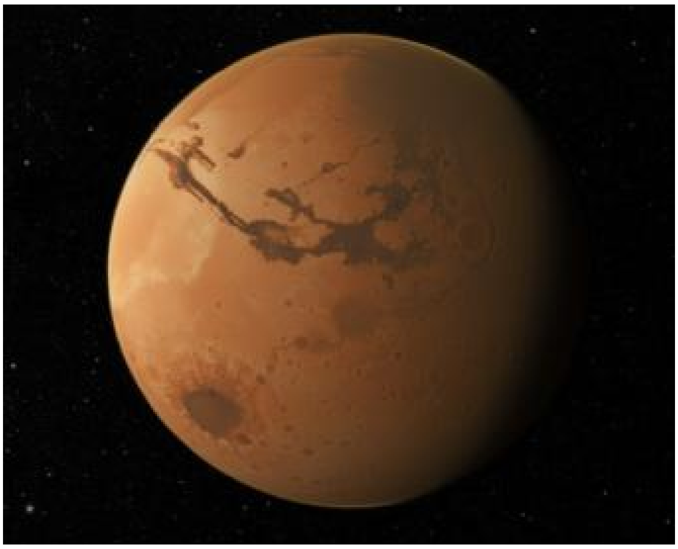


Figure 13: Realtime visualization of Mars, based on various mission datasets

The Terrain Renderer has been designed to be employed on all VR environments of the core users in the Collaborative Workspace, as described in D2.4 [6]. In addition, the system can be installed and used on desktop PC systems and laptops. The minimum system requirements are as follows:

- Windows 7 64 bit or Linux 64 bit
- 4 GB RAM

- 2 GB NVIDIA GPU with OpenGL 4.2
- Ethernet Interface

During development, the system has been tested on the following environments:

- Mobile / desktop workstation with conventional displays attached
- Workstation equipped with the HTC-Vive
- Desktop cluster with 2 – 12 displays and up to 6 workstations
- Side-by-side stereo for HD 3D TVs
- VR Environment (DLR-SST Powerwall, a 4-pipe projection system)

The prototype has been configured and tested to support the following interaction devices:

- Standard mouse / keyboard
- 3Dconnexion SpaceNavigator
- A.R.T. Flystick 2
- A.R.T. Flystick 3
- Thrust Master Gamepad

The Terrain Renderer includes the following capabilities:

Rendering of terrain DEM / image data: Using a pre-processing tool based on gdal [7], raw DTM and image data is reprojected to the HEALPix space [8] and stored in a level-of-detail (LoD) data structure. In this step it is possible to combine multiple input datasets, for example most parts of a DTM could be based on the full coverage MOLA dataset while smaller areas are modelled using datasets of higher spatial resolution, such as HRSC or HiRISE data. The HEALPix LoD data structure is made of twelve quad-trees storing the data in many patches at multiple resolution levels. Each frame a set of adequate patches is chosen for rendering, so that only as much information is drawn to the screen as can be visualized by the amount of available pixels (Figure 14, left). Based on these DEM patches, geometry is generated on the GPU and finally the terrain is rasterized. The image data patches are used as texture for the generated geometry (Figure 14, right). This technique allows for interactive frame rates while preserving visual fidelity.

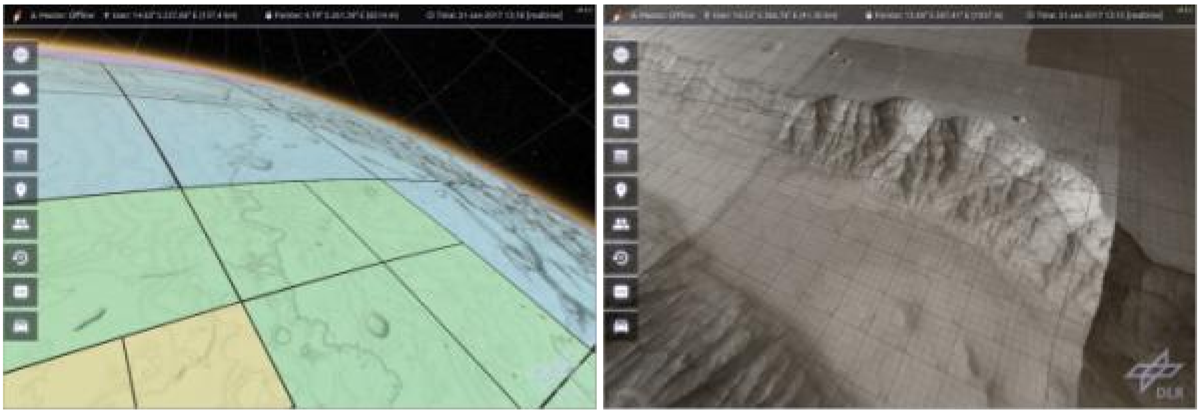


Figure 14: Visualization of the HEALPix based Level-of-Detail structure (left); detailed inspection using HRSC BW images (right)

State of the art rendering via OpenGL and GLSL: The surface of the planet is generated at runtime based on digital elevation and image data which allows for different shading options resulting in various map styles. Depending on the requirements of the use case, multiple options can be enabled or disabled. These include but are not limited to surface coloring based on the height or slope, display of contour lines, display of a latitude-longitude-grid with optional labels and the adjustment of ambient lighting. Some of these options can be seen in Figure 15.

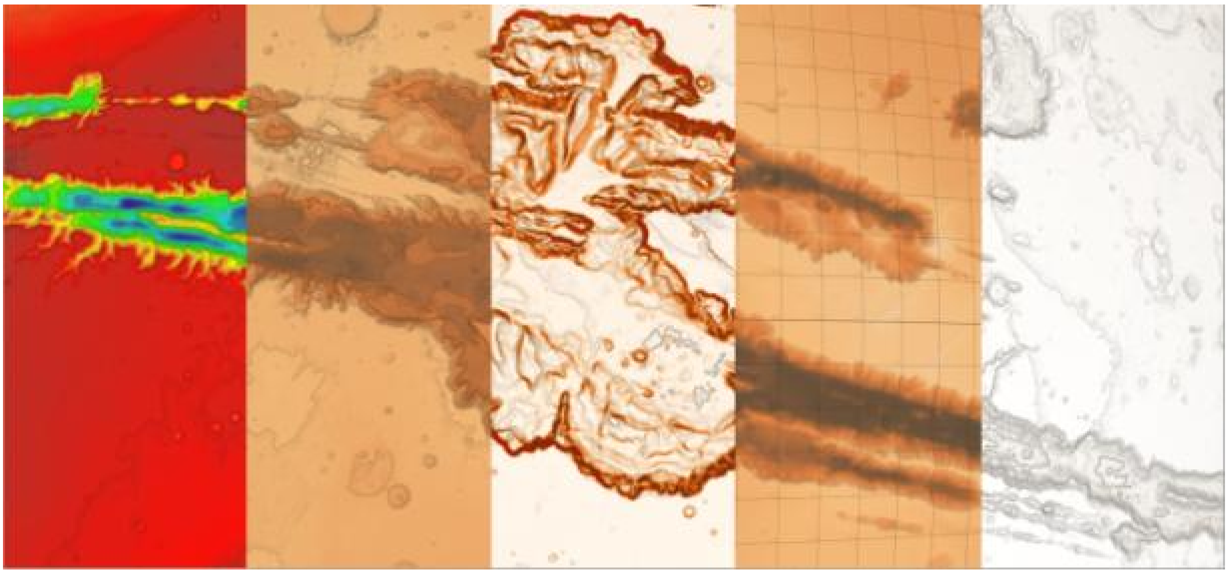


Figure 15: Multiple example configurations of the surface visualization of the Valles Marineris region: from left to right: MOLA color scale mapped on height; a more Mars-like color scale in combination with iso-lines; slope mapping with iso-lines; height-mapping with a longitude-latitude-grid; iso-lines with a subtle hill shading

Annotation and measurement tools: Since the Terrain Renderer has been designed to foster discussion and collaborative exploration among scientists; several tools have been included for this purpose. Some of these tools can be seen in Figure 16.

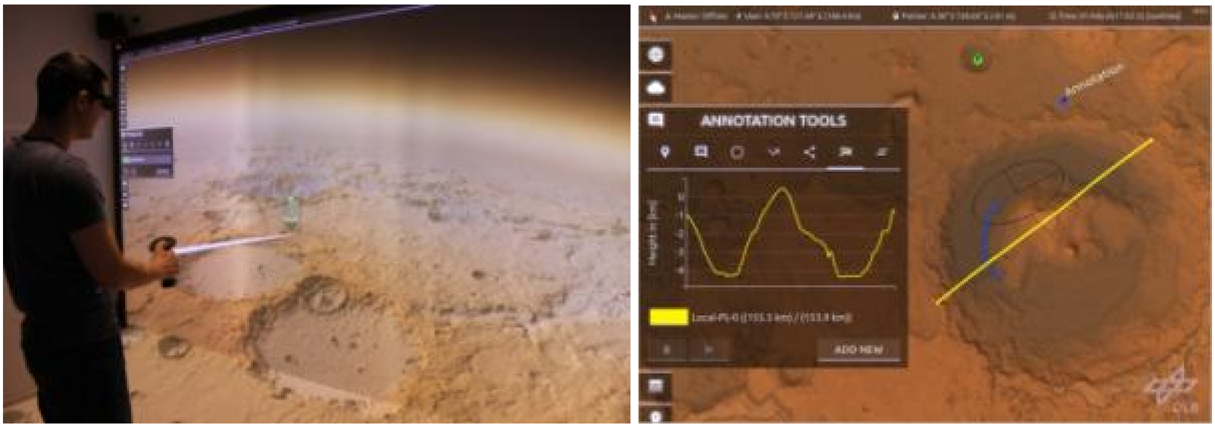


Figure 16: Placing a landmark in Virtual Reality on the surface of Mars (left); Examples of annotation and measurement tools of the Terrain Renderer (right)

The landmark is one of the simplest annotation tools (Figure 16, left). It represents a marking on the surface. The landmark can be selected and moved; furthermore its color can be changed. The annotation is a landmark with additional text. Like the landmark, the annotation can be placed anywhere on the planet's surface. It has the same properties as the landmark but an additional text property.

The landing ellipse is one of the more complex annotation tools. It has three virtual handles which can be used to manipulate the ellipse. Handle 1 is positioned at the ellipses center. Handle 2 / 3 are positioned at the perimeter. Moving handle 2 / 3 manipulates the ellipses radii as well as its orientation, whereas handle 1 influences the ellipses position. The color property of handle 1 is forwarded to the corresponding ellipse.

The profile line has, similar to the ellipse, handles which can be used for manipulation. Handle 1 can be interpreted as starting point and handle 2 as destination point. During movement of either start or end point, the surface is sampled and the profile line then follows the surface. The profile of the terrain is shown in the user interface (Figure 16, right).

The polygon and rover path are two similar tools. Both have initially one point. By selecting the created tool and clicking on the corresponding button in the user interface, new points can be added to the selected tool. Both objects can be selected and their color can be changed. This results in a color change of all its points including their handles. Additionally, each individual handle can be selected, moved and its color can be changed. This allows "marking" different points of a polygon or rover path. This is especially useful when marking specific points along a path with context information like "easy to reach", "dangerous", or similar.

In the later stages of the project, one additional tool has been added: The Dip & Strike Measurement Tool. With this tool, the scientist may place several points on the planet's surface, following some geologic particularity such as a clearly visible layer of rock on the surface. The software then fits a plane through these points and display its orientation (called Dip and Strike) in the user interface (Figure 17, left).

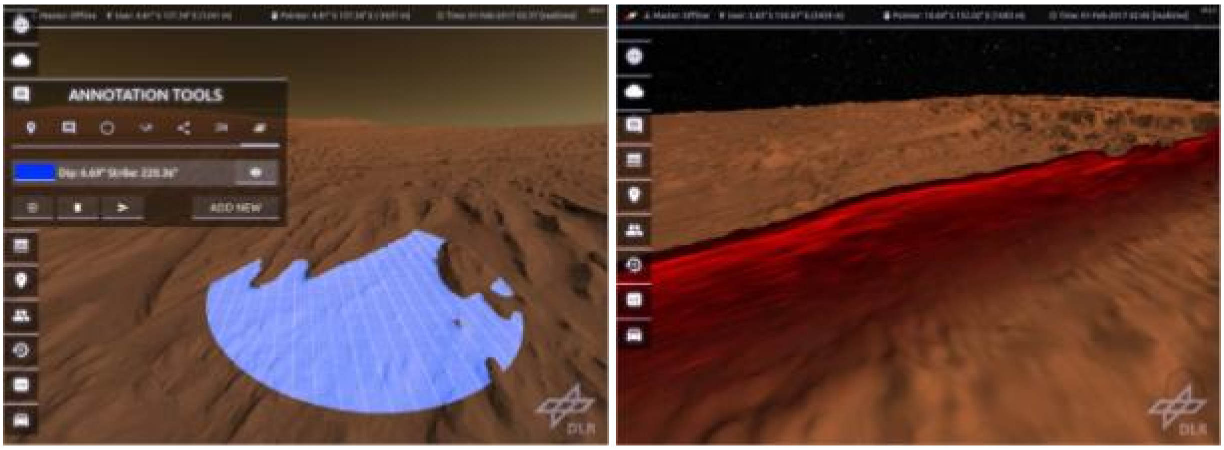


Figure 17: The Dip & Strike measurement tool for identification of geological layers (left); Visualization of subsurface radar data (SHARAD) (right)

Rendering of subsurface datasets (SHARAD): With the Terrain Render, it is not only possible to show surface data but also to visualize subsurface data (Figure 17, right). This has been achieved with an interesting technique which shows the radar dataset below the surface by making the surface in front of it semi-transparent. This approach is especially useful in stereoscopic 3D: due to the parallax, the user can clearly see the data below the semi-transparent surface.

Rendering of atmospheric data sets: The Volume Rendering approach is based on a GPU implementation. After generation of the proxy geometry all steps for each frame are performed within a GLSL Shader. With this we reach interactive framerates without compromising visual quality. The snapshots in Figure 18 (top row) show exemplarily results for this volume rendering approach. Similar to the volume rendering, the volume slicing approach is carried out on the GPU after the proxy geometry is generated. Currently the prototype supports iso-latitude, iso-longitude, iso-altitude and iso-surface slices (Figure 18, bottom-left). This is useful to gain understanding for the currently selected dataset as it can be sliced interactively. Both, the volume rendering and the volume slicing can be enabled for time-dependent datasets.

Furthermore, the prototype supports rendering of time-dependent integral lines (Figure 18, bottom-right). The lines itself are precomputed beforehand. After this preparation step the lines can be loaded from disk. The line sets can be rendered with an animation. With this, the set will not be rendered as complete lines but as line segments. Furthermore, these segments are animated which helps to understand special relation and direction of the individual lines.

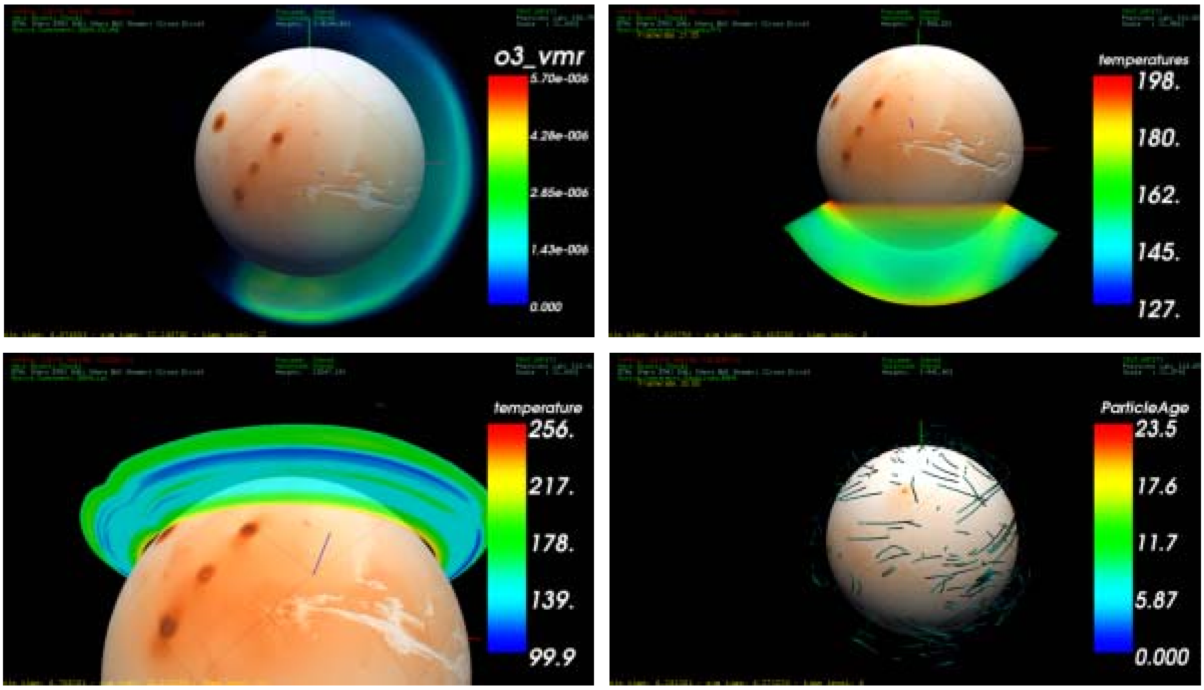


Figure 18: BGM4 Volume (top, left); Volume Rendering at south pole (top, right); BGM4 Iso Latitude Volume Slice (bottom, left); Integral Line Rendering (bottom, right)

Mars atmosphere and stars background for enhanced visual quality: For a virtual environment it is important to create a realistic context in order to increase the degree of immersion. Therefore a real-time light scattering model which simulates the atmospheric properties of Mars and a stars background has been implemented. While not being physically correct, the scattering model mimics the dusty atmosphere and its colors convincingly (Figure 19, left). For rendering the stars, the Tycho 2 and the Hipparcos catalogues are loaded (Figure 19, right).

Figure 19: Realistic rendering of the Martian atmosphere as seen from the Gale crater (left); SPICE based trajectories of Phobos, Deimos and Mars Express on 1st of February 2017 at 9:26 (right)

SPICE integration for time dependent positioning of celestial objects: NASA's SPICE library [9] has been integrated allowing for the simulation of correct lighting conditions. Given a specific point in time, all visible celestial bodies (Mars, Sun, and Stars) are positioned and rotated correctly in 3D space. In addition, the trajectories of various spacecrafts and of the moons of Mars, Phobos and Deimos can be visualized (Figure 19, right). The flow of time can be controlled in the user interface.

2.2.5. Rover Simulation with VERITAS

VERITAS (Virtual Environment Research in Thales Alenia Space) is one of the two selected Virtual Reality toolkits used during the CROSS DRIVE project. The VERITAS software consists of a series of libraries and applications that can be configured to run on complex PC clusters, CAVEs, or simple desktop PCs showing monoscopic or stereo images and to interface different interaction devices such as mouse and keyboard, 3D pointers, trackers, force feedback devices, and more. Through VERITAS, different VR scenarios can be built, shown and interacted with.

Before the CROSS DRIVE project, VERITAS was already used for different purposes like digital mock-up analysis, spacecraft design, trajectory visualization, astronomic datasets visualization, multidisciplinary analysis (like thermal, radiations, dynamics, …), ergonomics, cargo accommodation, virtual assembly and testing, simplified physics simulations, and more.

VERITAS was chosen for CROSS DRIVE because of its mentioned functionalities but, obviously, additional developments and customizations have been carried out in order to allow it to cope with the project needs. In particular, VERITAS was especially chosen to be used as a spacecraft and rover simulator for the third Use Case. Thanks to CROSS DRIVE, VERITAS functionalities have been greatly extended, and the following sub-chapters will summarize them all. Some functionality has a high maturity level, others still need some refinement. And TAS-I will carry out these ongoing researches in the next future. TAS-I greatly benefited from CROSS DRIVE both by improving its connections with the project partners, both by improving VERITAS software, and its new features will be helpful in a variety of future projects.

Figure 20: ExoMars rover 3D model (left), MASTCAM detail with panel showing the camera point of view (center), ExoMars TGO (right)

Spacecraft rendering: In terms of spacecrafts and other man-made objects visualization, a series of improvements have been carried on in terms of:

- CAD Extraction. TAS-I developed a web application (RAP – Retrieve cAd Parameters) that allows a semi-automatic extraction of CAD geometries, map them with multidisciplinary parameters and let VR tools like VERITAS to visualize them. Thanks to CROSS DRIVE, TAS-I developed a plugin to directly integrate RAP inside VERITAS and automatically extract geometries from the desired spacecraft baselines. CAD geometries can then be exported in the VOL file format. VOL (Veritas Object Library) is an internally developed file format using Blender modelling software as an authoring tool for VERITAS 3D models (along with materials, animations, …), and it has been improved significantly during the project.
- ExoMars Rover simulation. The CROSS DRIVE rover of choice for the Use Case 3 is ExoMars one. Thanks to RAP and the VOL files, ExoMars rover has been designed in terms of geometric representation, visual materials, physics behaviour (joints, wheels, dampers), locomotion system (the rover can be driven by applying torques to the motor wheels using two Nintendo Wiimotes) and virtual camera (the rover virtual camera is attached on top the rover MASTCAM, it can be rotated remotely, and its content can be shown on a panel on the screen).

- Spacecrafts. Just like the rover visualization, also some spacecrafts (ExoMars TGO, MEx, MRO, MSL) have been added to the simulation. Their visual representation has been obtained in the same way as the rover. And their trajectories are imported using NASA cspice library and kernels. These trajectories are also shown, as the complete trajectory or as the past trajectory.

Scientific data: TAS-I developed some new functionality regarding scientific data visualization, both in terms of terrain and atmospheric visualization:

- Terrain data coming from various sources have been added: DTMs (Digital Terrain Models) from HIRISE satellite instrument, terrain conical patches from Curiosity rover stereo camera, ALTEC MMTD facility DTM from laser altimeter scans.

Figure 21: HIRISE patch inside Gale Crater (left), terrain conical patches as reconstructed from Curiosity rover stereo camera (right)

- Planetary bodies meshes (Mars MOLA dataset, Phobos and Deimos 3D models reconstructed from pictures) and their trajectories (imported using NASA cspice library and kernels).
- Environment (correct Sun position and light direction, background Hipparcos stars).
- Scientific atmospheric datasets rendering through VTK library (2D, 3D or time dependant 3D data, volume rendering, iso-surfaces, slices, color scales, scalar altitude graphs, …).

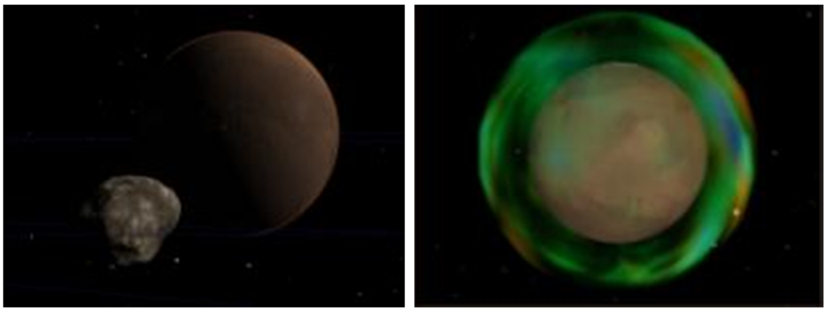


Figure 22: Mars and Phobos (left), Atmospheric visualization (volume rendering) around Mars (right)

Navigation and interaction: VERITAS is not only a visualization tool. It also allows interacting with the loaded virtual simulation. The features developed in the scope of CROSS DRIVE are:

- Annotation tools. A set of virtual tools have been added to allow annotations: the user can create (both from the desktop interface and in VR) landmarks (arrows), text annotations, ellipses and polylines.
- Telepresence. Each user inside the Collaborative Workspace (see Section 2.2.6) can be represented with a full body virtual avatar, moved with a motion tracked suit, or with a triplet composed by a virtual head, a name, and a line showing the avatar pointer. An avatar point of view can be shown in a dedicated panel, and avatars can also be targeted automatically in order to find them in the virtual space.

- MMTD (Moon and Mars Terrain Demonstrator) facility interactions. In Use Case 3 some calculations and data needed to pass through the Collaborative Workspace to VERITAS clients from the ALTEC MMTD facility. A specific interface has been implemented in order to exchange data with the MMTD facility, such as rover positions and status messages, rover paths created in VERITAS by driving the virtual rover, real rover camera pictures, map overlays, and so on.
- Atmospheric datasets interactions. Specific functionalities have been developed to allow simple interaction with atmospheric datasets: edit the volumes transfer functions and colors, rescale the values, make slices and extract iso-surfaces, show the altitude plot of a selected position and so on.

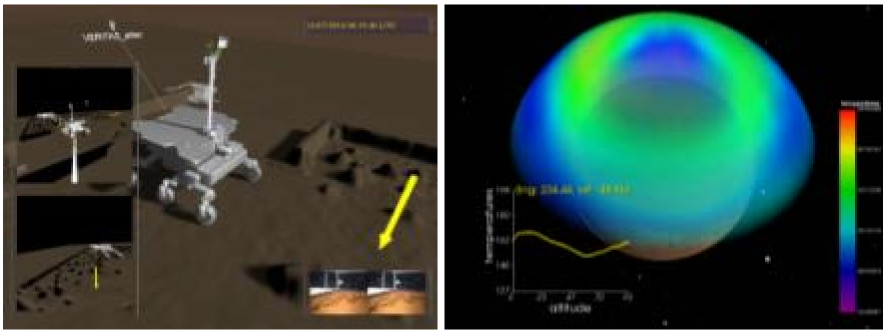


Figure 23: Landmark annotation tool, avatar, avatar point of view panel and real rover stereo picture (left), atmospheric datasets data extraction (right)

Collaborative Workspace integration: VERITAS, in order to allow remote collaboration with other facilities, users and software, has been interfaced with the Collaborative Workspace developed in CROSS DRIVE (for more details, see Section 2.2.6). Here we show a brief list of modifications made to VERITAS to allow remote collaboration:

- Collaboration Layer integration. TAS-I integrated the Collaboration Layer libraries in VERITAS in order to allow to connect it to the CROSS DRIVE Server, share the workspace and exchange data.
- Messages. CROSS DRIVE partners defined a common protocol to exchange the relevant information and keep the state of the entire system consistent, like objects creation and updates, commands, time synchronization, remote requests and responses, and so on. Not only the format but also the content is important, and some conventions and common network representations have been taken, like reference systems and date formats.
- Multi-scale layered rendering. In order to allow seamless transitions between planetary scales and local scales, VERITAS implements a layered rendering of sub-scenes of different scales, thus allowing users to see and navigate both the rover scene (on a 20 m patch) and the entire Mars with its surroundings (thousands of km).

2.2.6. Collaborative Workspaces

This section provides a description of the work carried out in the CROSS DRIVE project to allow collaboration, of the workspaces investigated, and of the telepresence techniques used. The Collaborative Workspaces provide a common framework for connecting heterogeneous simulations in a common space and allowing the execution of remote computations and the distribution of their results. Telepresence approaches allow people to join each other within a collaborative workspace without needing to travel to be together.

2.2.6.1. Workspaces

In order to allow different forms of collaboration in different contexts, three workspaces have been investigated in the CROSS DRIVE project: Core Collaboration Workspace for the core mission team, External Public Workspace for engaging selected scientists and Web Portal for broader dissemination and engagement of the scientific community and the general public.

Core collaborative workspace: The users of the core collaborative workspace are the scientists and engineers that are part of the CROSS DRIVE project. And their objective is to collaborate with other users by providing information about several topics of interest. One of them acts as the Mission Director, leading the collaborative session and ensuring that the expectations and objectives are met. After the introduction to the session, the users can explore the environment and execute different analysis in parallel and, later, get together to show their findings to the others and start discussing issues.

Figure 24 shows an overview of the core collaborative workspace and its components. It is composed of three remote sites connected via a private network to a central premise, the Mission Control Centre (MCC). The MCC is responsible for the coordination and supervision of a collaborative session. The remote sites represent the premises of two science teams (Science Home Bases SHB1 and SHB2) and the Engineering Support Centre (ESC). Each of these four existing immersive VR facilities has unique characteristics in terms of hardware setup and level of immersion. SHB1 is located at University of Salford, UK, and consists of two VR environments in two labs. One is based on a Powerwall with a 2-pipe active stereo rear-projection system. The other hosts the Octave, a reconfigurable multi-modal immersive display and capture space consisting of eight moveable active stereo rear-projection screens and six floor projection tiles. SHB2 is located at a VR lab in DLR in Brunswick, Germany, and consists of a Powerwall with a 3-pipe active stereo rear-projection system including floor projection. The ESC is located in the TAS-I COSE lab in Turin, Italy. It consists of a Powerwall with a 3-pipe active stereo projection system. The MCC is located at ALTEC, Italy. It consists of a large projection screen system with a single screen setup. These sites are equipped with motion capture to allow user interaction.

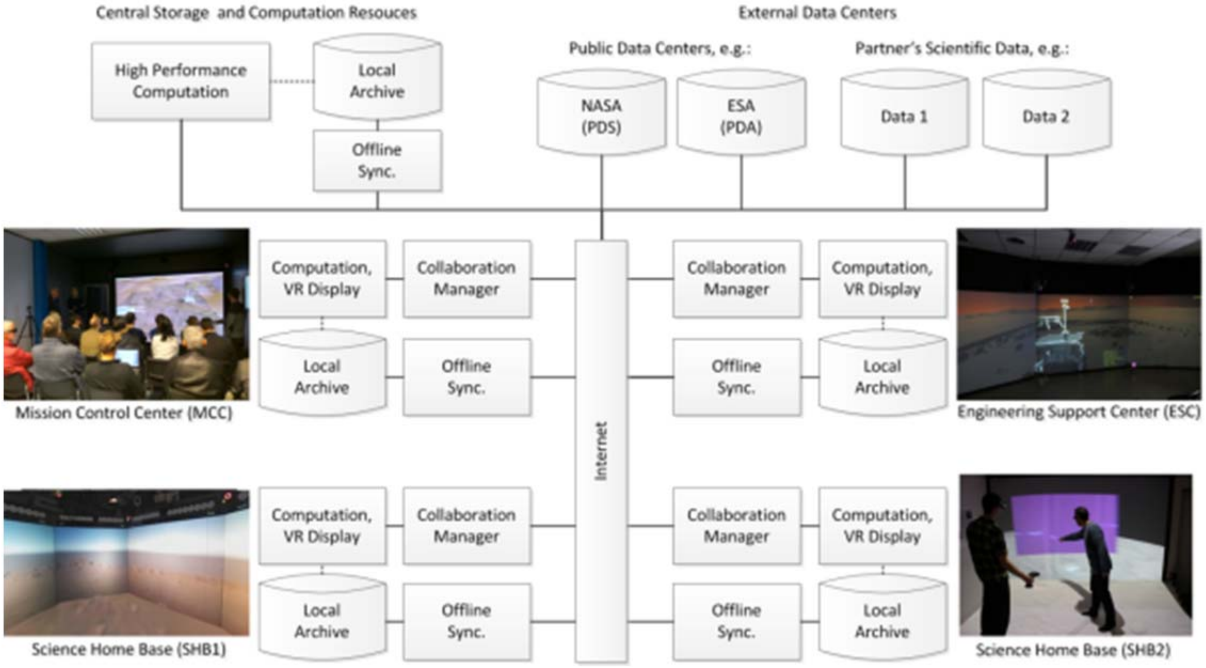


Figure 24: Overview of the core collaborative workspace and its components

Two main groups of data allow the communication in these facilities: datasets about Mars and real-time data exchanged by the users. The former group is available in a local archive at each site and relates mainly to the work performed in WP5 and 6, while the second is used to describe the real-time user interaction. Remote computation servers can be accessed to request for time or resource consuming calculations.

The network services are responsible for delivering this data to the participants of a session. A custom protocol to exchange real-time data was created defining different types of message for session, user and object management, geological and atmospheric visualization, rover messages and remote computations. The CROSS DRIVE system makes use of a hybrid network architecture approach in which all the user and session management messages are sent using a client-server architecture, while the user and object positions are sent using a peer-to-peer architecture. The former provides an additional level of security as the server checks every message and the latter allows every message to be delivered faster, making the system more responsive. Only selected IP addresses are allowed to connect to the server and the communication is encrypted using an asymmetric public-key cryptographic system.

External collaborative workspace: The users of the core collaborative workspace are invited external scientists that can contribute to the session with their expertise, discuss and provide off-line inputs about science results.

These external users make use of a simplified system to connect to the collaborative workspace. The main idea behind this is that they may not be used to manipulation and navigation in VR environments, especially using a keyboard and a mouse on a small screen, or maybe their computer is not powerful enough to run the whole system. In this case, the interaction and the visualization are designed for desktop users and common interaction devices (mouse and keyboard), as depicted in Figure 25. External scientists connected to the collaborative workspace using this interface are able to interact with core users and perform most of the interactions within the system in a simplified way.

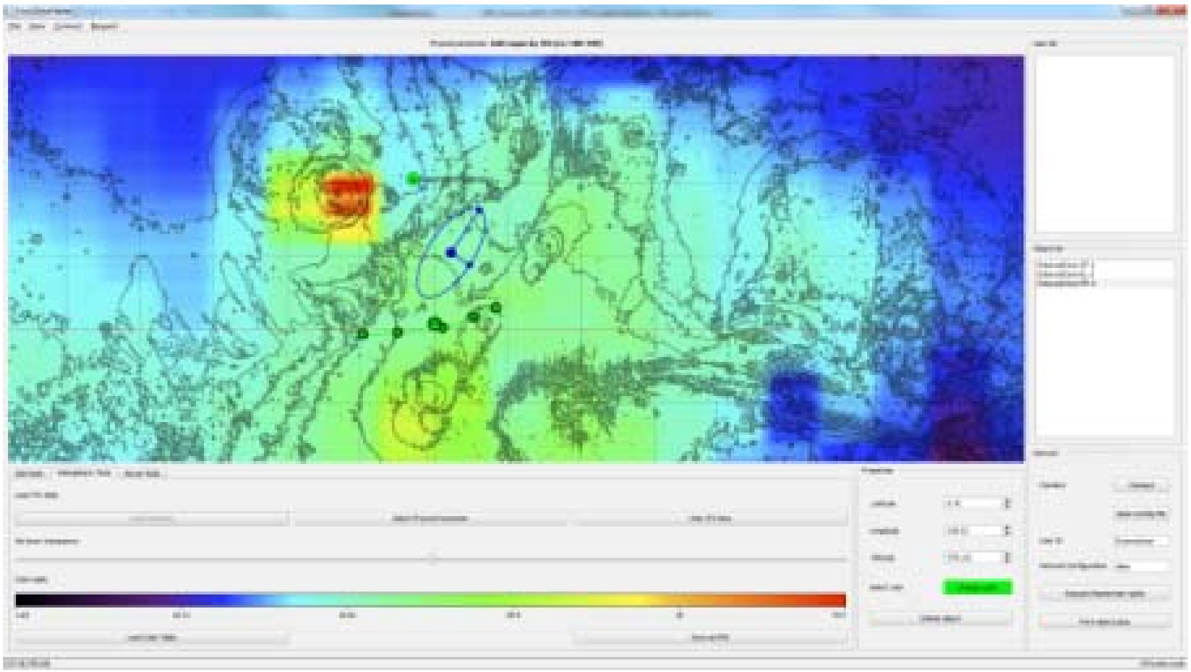


Figure 25: User interface for external users displaying TES data on top of MOLA 2D map

In order to make the external users able to connect to the session, a proxy (Figure 26) allows them to connect to the core system using a random IP address and provides an additional level of security for external connections, as the server can only be reached by the IP addresses of the members of the consortium.

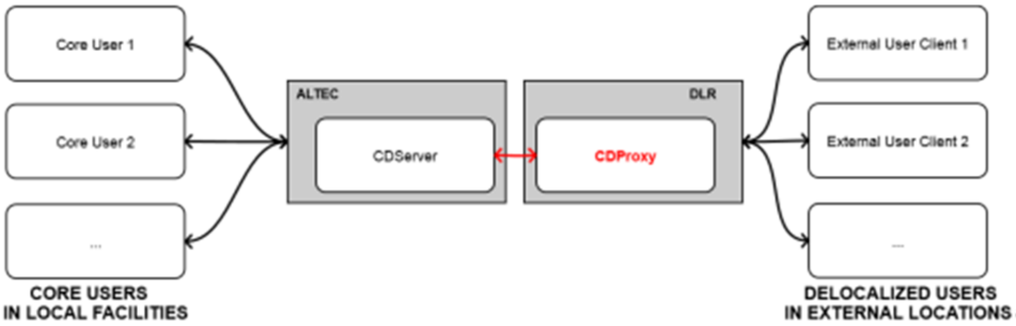


Figure 26: CDProxy to allow connection of external users from random IP addresses

Web portal: The users of the Web Portals are a broader scientific community and the general public interested in learning about Mars and space exploration missions. Two portals were created with the main aim of dissemination:

- Project Portal: This portal provides information on the CROSS DRIVE project as well as access to media resources and news for the general public.
- Scientific Community Portal: This web portal is designed to promote the interaction among scientists in order to contribute to the advancement in planetary science. The portal provides tools to collaborate using the web such as a data repository, forums, blogs, video/audio conference, etc.

A further description of the web portal is provided in section 2.4.

2.2.6.2. Telepresence

The vision for the telepresence aspect of CROSSDRIVE was to give collaborators the impression of "beaming" to the surface of Mars, along with simulations of the environment and equipment, to, for example, discus and step out together where a rover should land and move.

Aim: The main aim was to support simulation focussed social human communication. That is, to support verbal communication with non-verbal communication situated within the simulation. An important aspect of this was communication of both attention and appearance. This is important to communicate what aspect of the simulation someone is talking about and how they feel about it.

As an example, imagine a conversation between two scientists and an engineer that must end in a decision of which direction to send the rover. One scientist wants it to go to the West and the other to the East. The Engineer is concerned about the feasibility and safety of movement. Such conversations are made easier when the team is situated together within the simulation. At one level, we demonstrated how this could be achieved when the team were physically together (Figure 27, left). At another we attempted to reproduce the communicational semantics of this when they were apart (Figure 27, right).

Figure 27: Within Octave: co-located in a crater from ALTEC's MMTD (left); joined by an avatar in the Terrain Renderer (right)

Approach: The approach was to integrate telepresence research prototypes with the CROSS DRIVE simulation, across a diverse set of existing display systems at partner sites. Two research prototypes of immersive telepresence systems were incorporated together within the CROSS DRIVE simulation. Both situated people and, at remote sites, their avatars in respective copies of the simulation. One used a traditional Computer Generated Imagery (CGI) avatar driven by live motion capture of the stereo glasses and 3D wand of the user (on the right side of Figure 28, left). The other was a live 3D video based reconstruction, taking from surround cameras (waving in the centre of Figure 28, left, and viewed from different perspectives in Figure 28, right). Both allowed gestures such as pointing and head gaze to be faithfully communicated while retaining their target within the simulation. For example, if a person looked a crater, the remote user could follow their gaze to the same crater. The former, whoever, was clearly a pre-built model of a person and did not look like anyone apart from the person who had built it in their likeness. Furthermore, it could not express emotion through the face, hands or posture. The later looked like the person it was copying, reproduced eye gaze, facial expression including micro-expressions, posture and finger movement. For that matter, it also communicated what shirt they were wearing and if it had been ironed.

Figure 28: Avatar created through live video based reconstruction: facing both a real person and a CGI avatar (left); viewed from different perspectives (right)

Integration: The 3D video based avatar was integrated with the Mars Renderer and a prototype simulation running a model of a crater from ALTEC's MMTD. This comparison proved interesting because of the very different scales of movement and observation. The crater simulation lent itself well to a group of life sized avatars populating at as they could stand together within the crater and did not need to move more than the confines of the display systems to undertake simulation focussed discussion (Figure 27, left). In contrast, discussions using the Mars simulator tended to involve moving huge distances within the simulation. For example, Mars was sometimes observed from a distance and then flown down to. This introduced interesting challenges in how to group together when one wanted to lead the others to a different place.

Four display systems were integrated. Three large displays used immersive projection technology (IPT). The fourth was a simple desktop. Two IPTs projected on both horizontal and vertical planes and one only vertical. One of the former could project on surrounding and a floor between them in an area large enough for a small group to move around. This set of displays proved interesting in that they afforded different degrees to which a simulation space could be shared. Initially, neither wall display had a projection floor. When connected together, this allowed people looking at one display to look through it at others and thus each group occupied a part of the simulation separated from each other as if through glass.

2.2.7. Use Cases and Validation

The use cases have been conceived and defined on the main characteristics of the ExoMars project, the ESA mission originally foreseen for 2016 to 2019, when a Mars satellite and rover will be jointly operated. Intensive real-time science analysis processes are expected during the rover operations. And in order to reduce costs, part of the science team would have to be remotely connected to the Mission Control Center (MCC). ExoMars missions would require specific systems for data exploitation and analysis. The rover's operators will have to process science data in a short timeframe. And therefore, the mission team will benefit from the support of remote scientists. Such a process will have to be executed in a few hours and repeated iteratively every day. At the rover's MCC, two separate teams, one with scientific skills, the second composed of technicians and engineers, will collaborate in a complex environment never experienced before in a European mission. After the first phase, when all the experts will be hosted by the MCC to simplify operations, a decentralised approach would be adopted and the rover's operators would be remotely supported by other scientists. Moreover, the mission's results will be disseminated worldwide within the science community and generic users to increase the returns of such a complex and important mission. The capability of the proposed approach and framework has been assessed through the execution of three different use cases. They have the main objective to demonstrate the effectiveness of the developed concepts and the collaborative environment, focusing on different aspects of a space exploration mission.

Use Case 1: The storyboard of Use Case 1 has been planned to include the visualization and analysis of relevant data for landing site selection of past (i.e. Spirit), current (MSL) and future (Insight, ExoMars) Mars robotic missions. The data involved in this Use Case concerned few separated areas of ~50x50 km with a maximum resolution of 1 m. Individual archives, storing the same information, have been considered for this phase. In particular each user had access to a local computer storage system (basically represented by the dataset available for the integration with the Virtual Reality tools).

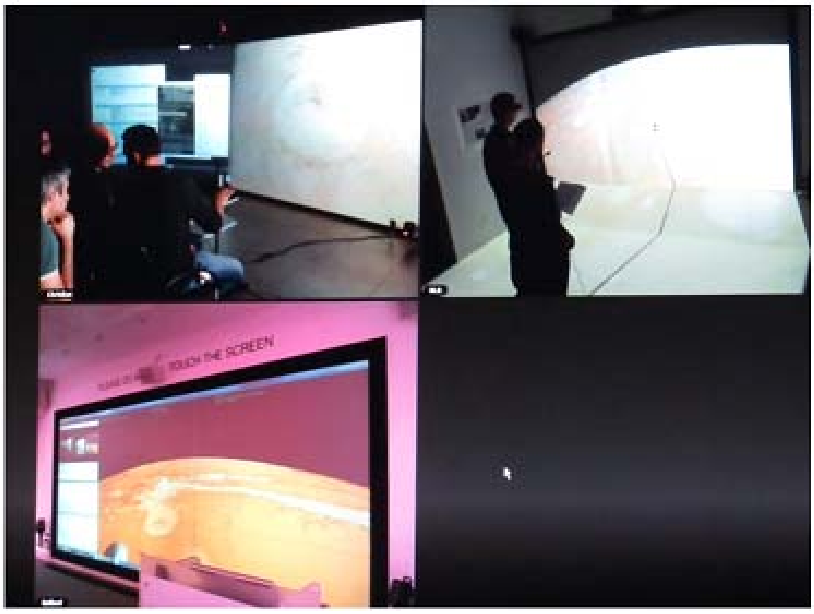


Figure 29: Collaborative session during the execution of the first Use Case

The Use Case 1 main focus was the feasibility assessment and testing of the connection among different Virtual Reality infrastructure. It involved four core users (users interacting from the main Virtual Reality facilities). The science session considered for this first Use Case concerned the analysis of terrain features and geological datasets. The Use Case has been executed following a planned series of activities which have been defined to better exploit the functions available from the Virtual Reality tool. Adobe Connect service has been set-up by DLR to support the internet streaming of the event. This solution allowed the partners, which were not directly involved in the Use Case 1, to follow the demonstration. The execution involved the following environments:

- 3 Sites (DLR, USAL, TAS-I).
- 4 users (DLR, USAL, TAS-I, ALTEC)

The Virtual Reality tool used (Terrain Renderer) was available among all the facilities. The dataset that has been exploited during the session is stored locally and delivered by DLR-IPR. The execution demonstrated that the developed prototype performed properly, supporting the interaction among users. The connection across different facilities has been managed successfully without particular issues. The CROSS DRIVE Server performed without problems and it ensured the right communication among the Terrain Renderer clients installed at each facility.

Use Case 2: The main aim of the second Use Case focused on the visualization, analysis, and discussion related to state of the art research on Mars atmosphere. In particular, this Use Case exploited global views of Mars to analyse concepts related to the atmospheric temperature fields, suspended dust and ice, global circulation, and dynamics. Regional and global planetary coverage of dataset with a maximum resolution of about 100 km has been used, in addition to few separated areas with a higher resolution (e.g., Gale Crater and Hellas Basin). Individual archives, storing the same information and datasets, have been considered for this use case. In particular each operator involved in the execution of the second use case had access to a local computer storage system. A data model (VTK format) has been developed to manage data among partners in a more effective way. The corresponding data structure has been updated and delivered by the partners. This Use Case basically involved four core users and three external users. Two external users used a desktop version of the Terrain Renderer, to test both the communication with the main platforms, the integration with a desktop machine, and the visualization capabilities that can be provided by the machine itself. One external user used the External User Client.

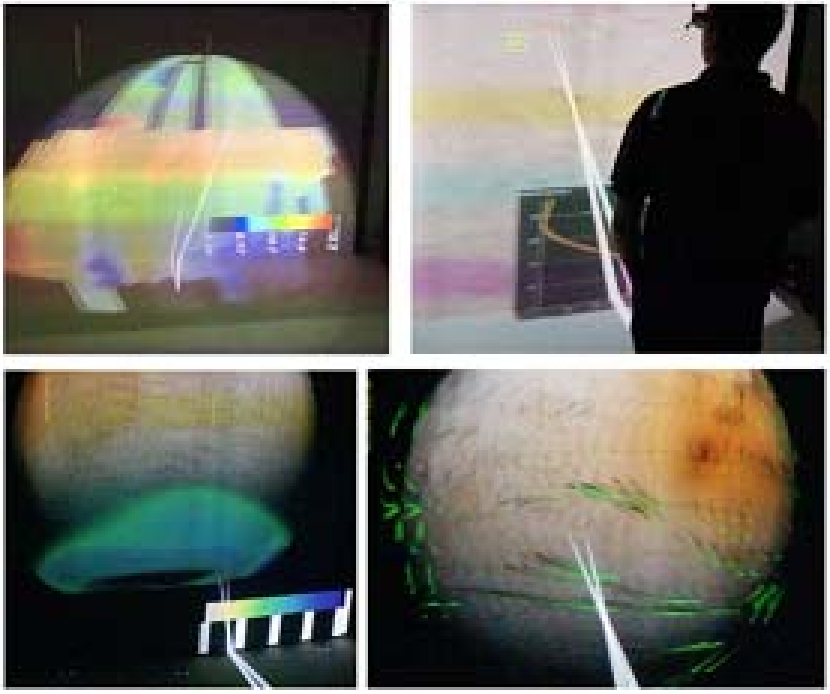


Figure 30: Collaborative session during the execution of the second Use Case

The Use Case has been executed following a planned series of activities. The execution involved the following environments:

- 6 Sites (DLR, USAL, TAS-I, ALTEC, INAF, BIRA).
- 4 core users (DLR, USAL, TAS-I, ALTEC)
- 2 external users with desktop version of Terrain Renderer (INAF, BIRA)
- 2 external user with the External User Client (TOHO, USAL)

Complex orbiter data from spectrometer and observation data from Earth were combined with global circulation models and high-resolution terrain data and images available from Mars Express, MRO, and MGS instruments. Leading Mars research institutes evaluated the leverage of insight into data interdependencies by means of Virtual Reality techniques. Scientists interactively extracted features from datasets and changed visualization parameters in real-time in order to emphasize findings.

Use Case 3: This Use Case had the scope to visualise, analyse, prepare, execute and discuss about operations of planetary rovers and satellites by using the Collaborative Workspace. In particular the system allowed the analysis of geologic features of terrain as viewed by the on-board cameras of the rover as well as the comparison among rover images/DTM and satellites' images/DTM. Analysis of the morphology of the terrain in correlation with the expected landing trajectories represented another interesting aspect of the Use Case. The collaborative session included also the provision and review of the commands sent to a rover mock-up (on terrain simulator facility). Computing of traversable areas and optimal path evaluation has been considered to show the capability to support rover operational scenarios. Use Case 3 focused on the visualization and analysis of the engineering data related to the operational phase of a robotic mission. Data on Mars atmosphere and geology have been also considered to characterize the area near the rover location. Global and regional coverages of Mars have been considered in addition to a few separated areas with a higher resolution. Virtual Reality tools managed different levels of spatial resolution on the data. In particular the Terrain Renderer has been used to navigate data from global to regional resolution. Areas with very high resolution, with patches of the order of 20x20 meters, have been navigated with the support of VERITAS. In the latter case, the use of VERITAS is related to the virtual model of the rover within an area with a high level of details. The execution involved the following sites:

- DLR-SST: VR-Lab
- University of Salford: THINKlab facility
- TAS-I: COSE VrLab
- ALTEC: VR-Lab and MMTD facility
- INAF, DLR-IPR: connection from Adobe Connect through the CROSS DRIVE client applications

The execution of the third Use Case demonstrated that the developed prototype performed properly, supporting the interaction among users. ExoMars Rover mock-up performed as expected, demonstrating the capability to keep the real hardware in the loop. At the same time, it has been demonstrated how the operational activities, both short and long planning, can be performed and supported with a higher level of fidelity thanks to the Mars terrain simulator facility and real hardware.

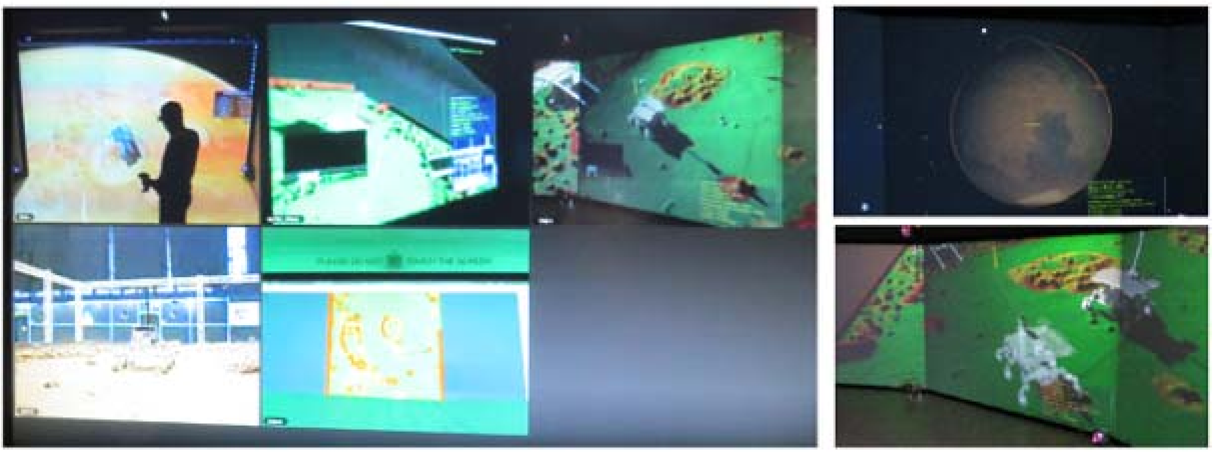


Figure 31: Collaborative session during the execution of the third Use Case

2.3. Potential Impact, Dissemination Activities, and Exploitation of Results

The main goal of CROSS DRIVE has been to procure a valuable understanding concerning design and management of space exploration missions for the European scientific and engineering communities, providing relevant added values to actual and future space projects. It provides a platform for extracting value out of space data and broadening the engagement of the scientific community in contributing more effectively to space science and future missions. The final results:

- Provide easy access to otherwise distribute recent science data of Mars and the possibility to view, interpret and compare them.
- Give remote access to complex algorithm developed in INAF and IASB-BIRA to analyse the Level 1 data (mainly spectra).
- Offer innovative 3D visualisation and interaction systems in support to science analysis and space operations to explore:
  - Mars geology and geodesy data,
  - Mars atmospheric data and
  - Rover target selection and its operations.
- Enable collaborative workspaces that can connect with main scientific and engineering teams to engage in space mission planning and operation by means of:
  - Distributed virtual environments that “teleports” scientists as avatars to a “Virtual Mars” for immersive discussion sessions,
  - External Public Workspace that can bring external leading scientists to support data analysis, mission planning and operation on demand,
  - Community Portal that allows a broad range of scientists to support space missions by collectively analysing data and contributing their findings.

The successful outcome of CROSS DRIVE has a significant impact on:

- How future missions, such as ExoMars, will be designed and validated,
- The way space scientists will conduct space science research in the future,
- The mobilization of the best expertise in various fields of science for the analysis and interpretation of space data,
- How distributed scientists and researchers will work together to engage in data analysis and interpretation.

The outcome of CROSS DRIVE makes space science data exploitation available to a larger group from academe, the public sector and industry. Together these contribute significantly to the development of the European economy and maintain Europe’s leading position in the exploitation of space mission findings.

The CROSS DRIVE project allowed the definition and development of a collaborative environment that can improve the current practises of data exploitation and exchange among scientists and engineers. A distributed workspace represents a very interesting solution when information needs to be processed by groups of people with different expertise and backgrounds. In particular during operational scenarios there are a lot of scientific teams involved on a common space exploration programs. Robotic exploration missions, like ExoMars, are often characterized by a set of payloads with different principal investigators spread worldwide. A distributed system, exploiting web technologies and infrastructures, is an effective solution when the science teams are located on different remote centres. A common collaborative platform can widely reduce the number of persons needed on site to elaborate data and support the decision process of rover operations.

The visualization on the same environment of datasets coming from various data source, for example coming from both atmospheric science and geology, showed how the actual mission status can be analyzed in a more effective way. This ensures a better support for both long and short planning activities of rover operations. The visualization on a common framework of all the available information and a common set of tools and capabilities (landmarks and annotation creation, landing ellipses and path lines drawing, etc.) can widely reduce the possible misunderstandings among users.

The proposed methodologies and related tools can have interesting applications in the context of project like ExoMars where a large number of scientists and engineers are involved. The Terrain Renderer and the VERITAS tool, connected through the CROSS DRIVE server, can also help activities like troubleshooting since all the information is formalized and provided within a common 3D scene.

One of the main scopes of the CROSS DRIVE project was also represented by the enhancement of the groups' expertise with respect to the knowledge not directly belonging to their corresponding fields. In particular the dissemination of the results was conceived to improve the expertise of the partners across the different disciplines involved in the project.

During the project execution it was expected that people gain additional expertise across the following fields:

- Mars geology
- Mars atmosphere
- Virtual Reality and Virtual Presence
- Collaborative Workspaces
- Spacecraft's operations

In particular it is expected that such collaborative environment helps scientists to gain a greater familiarity about the topics that generally characterize Engineering. A greater confidence with respect to design alternatives, Engineering solutions and technical choices can help to better understand all the aspects of a particular project. This approach can also provide a clearer overview of the current status of a project, highlighting potential issues and achieved results, driving the decisions concerning the scientific aspects in a more effective way.

In the same way engineers can gain a greater confidence with the scientific data available from a mission. In this way they can better understand the reason related to specific design solutions or the requests coming from the scientists themselves. In certain cases the design solutions directly affect the scientific results and it is always not so easy to find a common point of view.

A deeper interaction between engineers and scientists can widely improve the effectiveness of the overall mission, reducing possible issues and errors. The main scope of such an approach and the related platform is in fact to provide a clearer overview of the systems and the elaborated data.

The results to be disseminated mainly regarded the availability of scientific data in an aggregated manner, allowing a better navigation also to persons not belonging to a specific field. Such a capability ensured a better exploitation of the data coming from different sources and they have been used also by engineers with no particular confidence on the details regarding the datasets.

The integrated visualization of data is one of the main achievements that have been shared across the partners to disseminate the knowledge related to scientific information. In this way, engineers can navigate more effectively the resources made available from the scientific partners, avoiding or at least reducing the distance that characterize the expertise of people with different skills and backgrounds. In this way, they can better understand the focus of their work, helping them in the process of system design and exploitation.

Another key element is represented by the visualization capability that has been developed for the analysis and design of space missions. In particular the workspace provides useful tools for the visualization of engineering data in a more structured way that can help scientists to navigate such information. This approach has been demonstrated through the development of the Collaborative Workspace. These results have been disseminated through the project teleconferences, meetings and the final workshop. Some details are also available from the Official Web Site which has been also used to support the knowledge sharing.

The details regarding the spacecraft operations are however available through the same platform and such results can be disseminated through the Collaborative Workspace itself. A wider spreading of such results has been achieved through the participation to specific conferences or with dedicated publications.

Undergraduate students, postgraduate students, public and standards organizations can access high level data on framework capabilities on the project public website. A limited set of information, but however representative of actual scenarios on Mars data, is accessible through the developed platform. This data are provided to show the basic capabilities of the framework but nothing prevents the use of a larger number of datasets.

Space missions' operators can be involved in scientific discussions and science analysis to better understand the processes that drive the Science Working Groups during definition of science missions' objectives and the planning of operations. This is an important task because during space robotic science missions it is fundamental to achieve a common understanding among engineering and science teams.

The knowledge directly related to the project results and achievements can be accessed through different means on the basis of the stakeholder role and resources availability. In particular, information can be accessed by one of the resources listed below:

- Official Web Site
    - CROSS DRIVE Project Portal.
    - CROSS DRIVE Scientific Community Portal.
- Project Site
- Collaborative Workspace

In the previous list we have also included the Collaborative Workspace that has been developed to show and assess the main concepts of the proposed methodology and environment. Such infrastructure represents one of the resources that can be used to enhance the interaction among partners, allowing a better experience of information and knowledge sharing. The prototypes have been tested during the execution of all the Use Cases as well as during the Final Workshop.

The Official Web Site represents one of the main instruments used to ensure a proper exploitation of the information of the project. In particular the Official Web Site is used with different purposes, a list of which is summarized in the following.

- Access to selected and relevant datasets (on the basis of user credentials and roles)
- Access to simplified tools for visualizing filtered datasets
- Access to publications, conference proceedings, research papers, forum discussions, etc
- Access to tools for visualizing complete datasets
- Ability to engage in blogs
- Links with scientists
- Link with engineers
- Links with other projects (e.g. EU-FP7 PRoViDE)

- Ability to upload raw and processed data
- Access to recent news, simplified information and aggregated data
- Access to images, videos related to the project or simplified information (for example low details view of a 3D model)

The CROSS DRIVE Project Portal is mainly conceived to provide information about the CROSS DRIVE project for the general public (external audience). In this case the site mainly provides access to media resources and news about the most important achievements of the project. Such interface is basically considered as an instrument to spread information about the project also to a non-scientific community. For this reason such platform does not include a detailed representation of the available datasets.

The CROSS DRIVE Scientific Community Portal is instead oriented to the dissemination of project results to a more specific audience. In particular such platform is designed to promote the dissemination of the project results to a broader scientific community and the interaction among the scientists.

Project results are reported within the Community Portal through a dedicated news section directly linked with more detailed pages, describing for example the main achievements of the scheduled demonstration scenarios as well as the status of the project developments. Brief descriptions of the performed activities have been provided to the Community Portal administrators (University of Salford) that consistently update the Community Portal. This approach helped to populate the sections related to the ongoing activities and news.

The projects results have been disseminated not only through the Community Portal but also with the participation to specific conferences and workshops. The publication of papers on the project main achievements helped to show CROSS DRIVE results to a wide audience.

The dissemination of knowledge has been also pursued through dedicated events that helped to enhance the information exchange with the external audience. Some events have been followed on the basis of the available information and consistently with the conferences deadlines. Different approaches have been considered for the dissemination of results, taking into account the various stakeholders that are involved by the project. For this reason two main audiences have been identified:

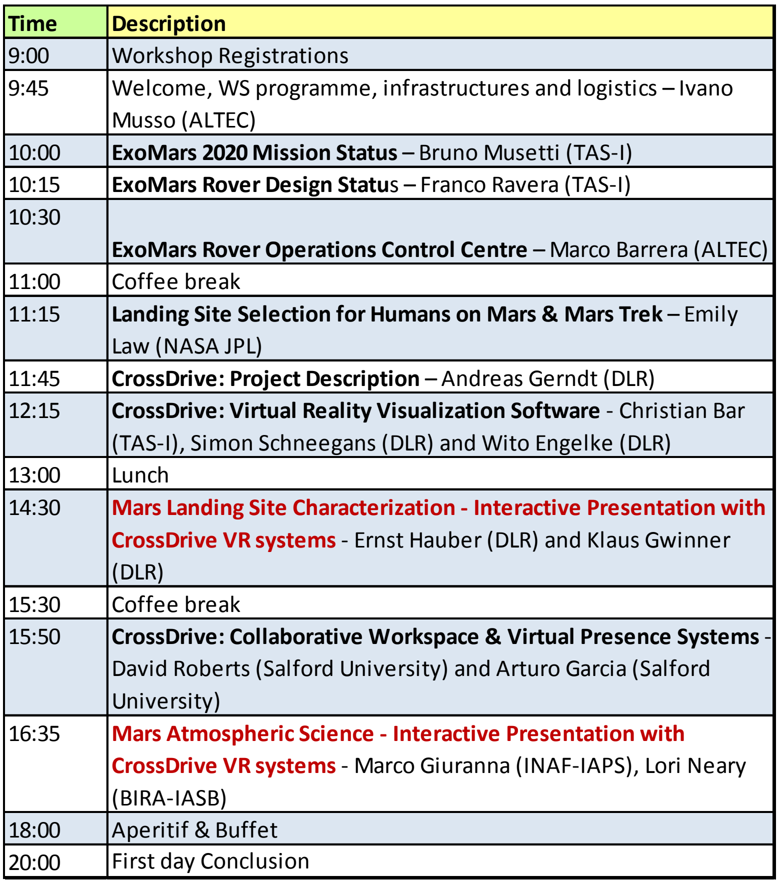
- Mars experts
    - Planetary Scientists
    - Computer Vision & AI Scientists
    - Industry
    - Mission Designers / Operators
- General public, schools and students
    - Undergraduate and Postgraduate Students
    - Public
    - Public Organizations

The CROSS DRIVE final workshop has been hosted in ALTEC on 29-30 November 2016. At that time, all three Use Cases have been executed and the CROSS DRIVE systems are completely ready for use. A specific Virtual Reality projection system has been rented for the workshop in order to provide a complete view of the systems during the event.

The event lasted a total of two days, from 9 AM to 8 PM on November 29 and from 9 AM to 12 PM on November 30. It hosted people from CROSS DRIVE team as well as external ones, both represented by invited academic and industry representatives.

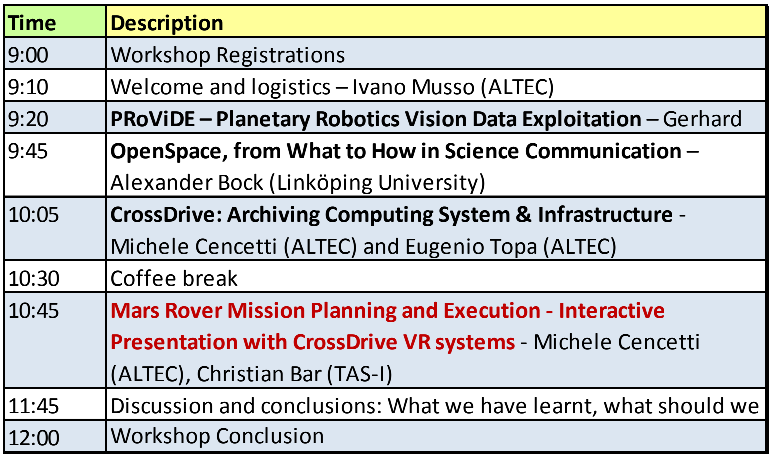
The preparation of the main infrastructure for the Final Workshop started about three weeks before the event. This activity regarded the set-up and configuration of the network areas and physical integration of all the systems involved in all Use Cases executions. The 3D projection system allowed the people in the auditorium to get involved with interactive presentations through the use of active glasses in an immersive environment. All the three Use Cases have been reproduced with the main objective to demonstrate the actual capabilities from a user point of view.

The agenda of the two-day event proceeded as reported below:



Time	Description
9:00	Workshop Registrations
9:45	Welcome, WS programme, infrastructures and logistics – Ivano Musso (ALTEC)
10:00	**ExoMars 2020 Mission Status** – Bruno Musetti (TAS-I)
10:15	**ExoMars Rover Design Statu**s – Franco Ravera (TAS-I)
10:30	**ExoMars Rover Operations Control Centre** – Marco Barrera (ALTEC)
11:00	Coffee break
11:15	**Landing Site Selection for Humans on Mars & Mars Trek** – Emily Law (NASA JPL)
11:45	**CrossDrive: Project Description** – Andreas Gerndt (DLR)
12:15	**CrossDrive: Virtual Reality Visualization Software** - Christian Bar (TAS-I), Simon Schneegans (DLR) and Wito Engelke (DLR)
13:00	Lunch
14:30	**Mars Landing Site Characterization - Interactive Presentation with CrossDrive VR systems** - Ernst Hauber (DLR) and Klaus Gwinner (DLR)
15:30	Coffee break
15:50	**CrossDrive: Collaborative Workspace & Virtual Presence Systems** - David Roberts (Salford University) and Arturo Garcia (Salford University)
16:35	**Mars Atmospheric Science - Interactive Presentation with CrossDrive VR systems** - Marco Giuranna (INAF-IAPS), Lori Neary (BIRA-IASB)
18:00	Aperitif & Buffet
20:00	First day Conclusion

Figure 32: Final Workshop – first day



Time	Description
9:00	Workshop Registrations
9:10	Welcome and logistics – Ivano Musso (ALTEC)
9:20	**PRoViDE – Planetary Robotics Vision Data Exploitation** – Gerhard
9:45	**OpenSpace, from What to How in Science Communication** – Alexander Bock (Linköping University)
10:05	**CrossDrive: Archiving Computing System & Infrastructure** - Michele Cencetti (ALTEC) and Eugenio Topa (ALTEC)
10:30	Coffee break
10:45	**Mars Rover Mission Planning and Execution - Interactive Presentation with CrossDrive VR systems** - Michele Cencetti (ALTEC), Christian Bar (TAS-I)
11:45	Discussion and conclusions: What we have learnt, what should we
12:00	Workshop Conclusion

Figure 33: Final Workshop – second day

During the first part on the first day, after the Welcome, the status of the NASA and ESA missions, in particular ExoMars, MRO and MEx have been presented. Members of the CROSS DRIVE team provided the status of the instruments they have supported (FHS, SHARAD, NOMAD, HRSC, PanCam, CASSIS, etc.) and the operative infrastructures they host (e.g. ExoMars Rover Operations Control Centre). During the second part of the first day, the CROSS DRIVE systems have been presented providing an overview of the team, infrastructures, datasets, interfaces and facilities involved during the project. The systems have been described as an initiative to address the needs for current and future exploration missions discussed during the first part of the event. The scope was to show directly the systems of the Virtual Reality laboratories used during the project and the Terrain Demonstrator. Use Case 1 and Use Case 2 have been repeated during the first day, addressing specific science and operative topics and presenting them to the audience in the Auditorium. During the demonstration, some external people were invited to use and test the tools.

The third Use Case has been performed on the second day during an interactive session when the focus was on engineering operations of rover planning activities. Additional presentations, regarding in particular the status of visualization and exploitation tools of rover data products, have been allocated within the same day.

The event ended with a final presentation by the team leaders addressing the results and future works on projects topics.

The demonstration involved the following facilities and systems:

- 3D-VR projection system in the ALTEC Auditorium
- HTC Vive (HMD, head-mounted display)
- ALTEC 3D VR-Lab
- TAS-I 3D VR-Lab (COSE VrLab at Cose Centre)
- ALTEC MMTD Mars Terrain Demonstrator
- External User from INAF machine through a desktop application (to show the capability that a client can connect to the same infrastructure without the need of a 3D visualization facility)

The infrastructure and the visualization tools can potentially be used to support data exploitation and analysis on actual research activities. It was an effective approach to show the tools capabilities on real use cases. This helped to show the real benefits that can be achieved through such collaborative environment. The CROSS DRIVE network infrastructure showed interesting capabilities for the connection of distributed visualization and simulation environments. Nothing prevents from the possibility to use the same approach and integrate additional tools. The visualization tools, Terrain Renderer and VERITAS, can be further developed to include different scenarios with little or no changes with respect to the actual network library and server application. The same infrastructure can be used to share information about other mission scenarios or focus on the exploitation of Earth data. In both cases, the results can be further disseminated within other engineering domains, paving the way for an effective demonstration of the tools and prototypes.

The core application of the network library has been also conceived to ensure minor or no changes when new simulation tools or additional datasets are exchanged among the connected clients. This represents one of the main achievements of the proposed architecture and one of the elements that can improve the dissemination of the project outcomes.

2.4. Project Web Site and Contact Details

The CROSS DRIVE project web site was set up during M1 of the project and can be viewed at:

www.cross-drive.eu

The web site aims at providing a platform to disseminate the results of the CROSS DRIVE project as well as to encourage collaboration among the scientific and research communities. For that, two main sections were developed in parallel, the Public Portal and the Scientific Community Portal.

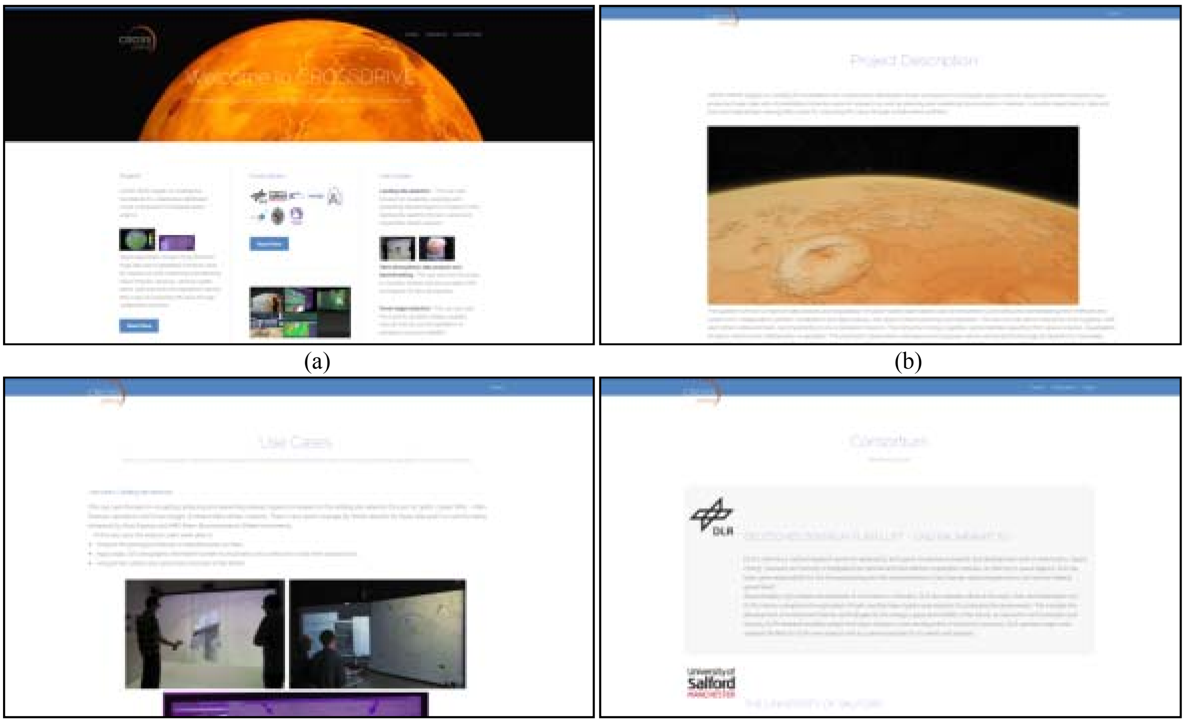
The web site is designed, managed, and maintained by Prof. Terrence Fernando from University of Salford, United Kingdom.

Figure 34: Project logo (left: default; right: for dark background)

2.4.1. Public Portal

The Project Portal contains information about the CROSS DRIVE project as well as materials for the public. It provides the following information for the general public and other interested parties:

- CROSS DRIVE Project Information: the background, objectives and a summary of CROSS DRIVE and presentation of use cases.
- Partners: CROSS DRIVE Partner organisations (with links to personal pages or to the pages of the institutions).
- Publications: Access to non-confidential internal reports, publications etc.
- Media Assets: multimedia files such as images and videos generated from the project and other sources.



(a)

(b)

(c)

(d)

(e) (f)

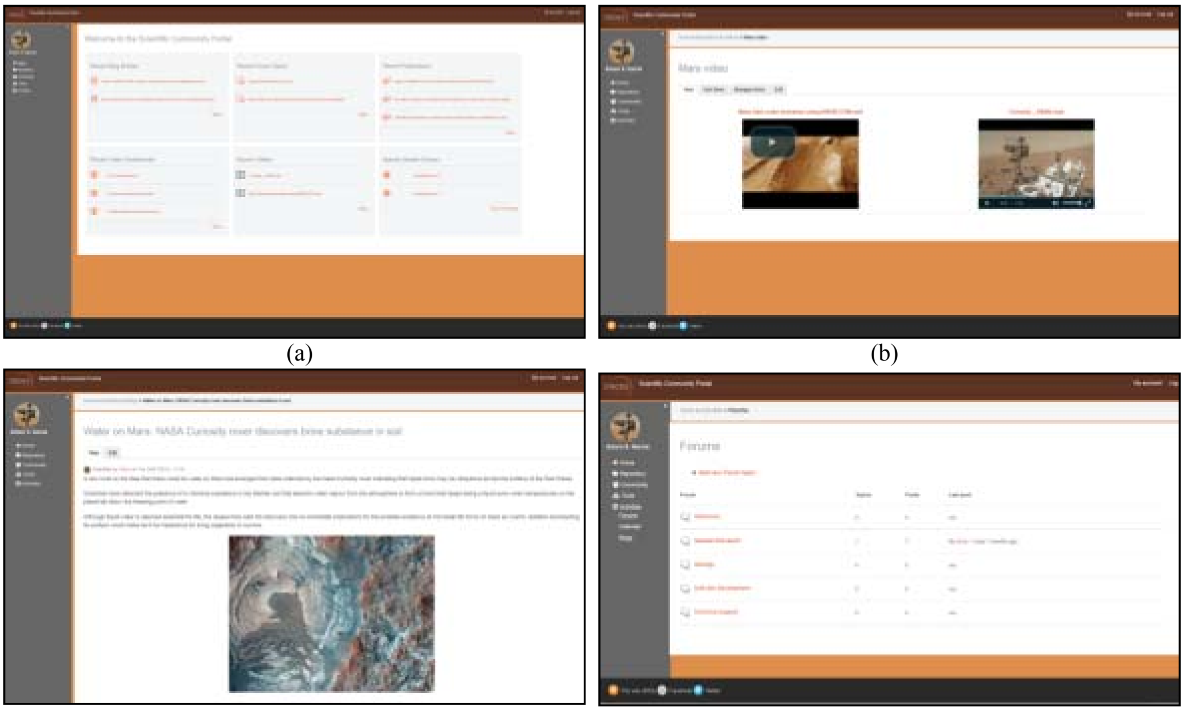
Figure 35: Sections of the Public Portal. (a) Main page, (b) Project Description, (c) Use cases description, (d) Consortium, (e) Publications summary, (f) Media gallery

2.4.2. Scientific Community Portal

The Scientific Community Portal (http://www.cross-drive.eu/sportal/) has been designed to promote interaction among scientists in order to contribute to the advancements in planetary science. Registration is needed to access this portal.

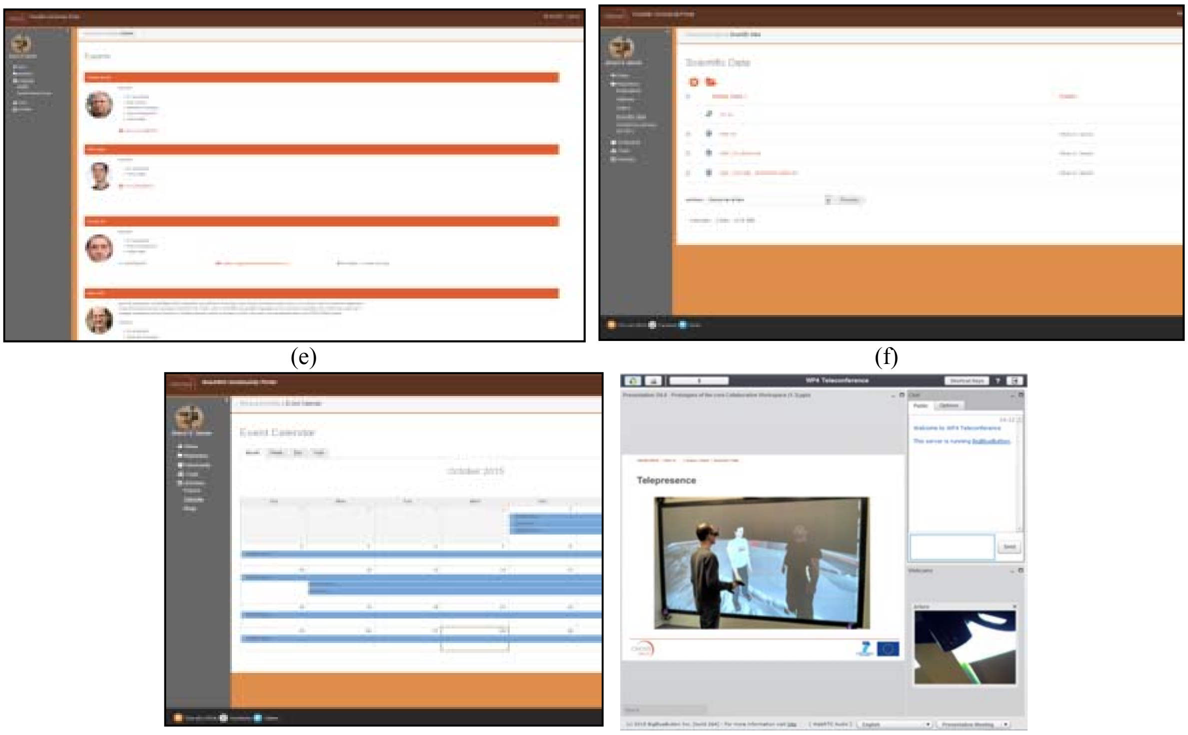
The features provided within this area in order to allow collaboration are:

- Access to Mars datasets, images, videos, relevant research papers, leaflets
- An expert community database (registered users)
- Ability to initiate online discussions using audio/video conferencing tools
- Ability to write blogs and create forums to discuss various topics
- Ability to conduct webinars on special topics



(a) (b)

(c) (d)



(e) (f)

(g) (h)

Figure 36: Sections of the Scientific Community Portal. (a) Dashboard, (b) Gallery, (c) Blogs, (d) Forums, (e) Experts, (f) Repository, (g) Calendar, (h) Videoconference and webinar tool

Additional functionality was added in order to:

- Execute algorithms and analyse Mars datasets (ASIMUT);
- Collaborate with other EU funded projects (PRoViDE);
- Connect to the CROSS DRIVE archive (ALTEC).

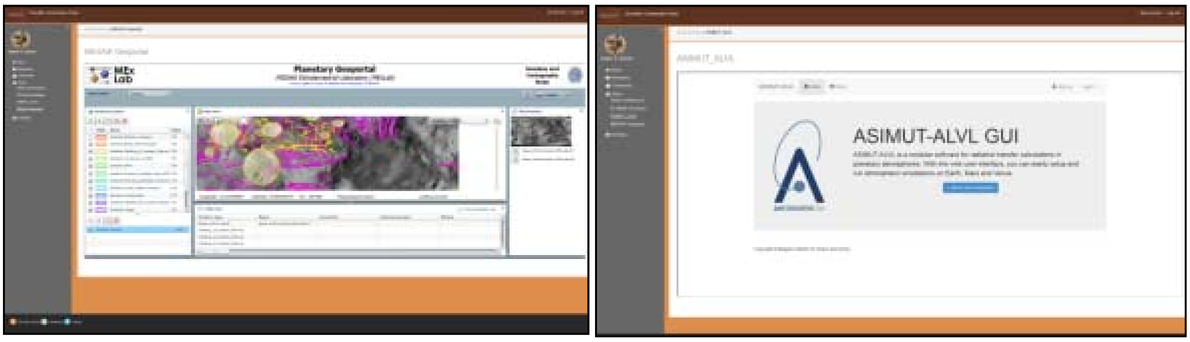


Figure 37: External tools included in the Scientific Community Portal. Collaboration with the PRoViDE project (left), ASIMUT tool (BIRA) (right)

3. References

[1] Scientific Specification (1/2), Project Deliverable 2.1.

[2] Scientific Specification (2/2), Project Deliverable 2.2.

[3] Requirements of Scientific Tools, Project Deliverable 2.9.

[4] ViSTA VR Toolkit. Online http://www.itc.rwth-aachen.de/cms/IT-Center/Forschung-Projekte/Virtuelle-Realitaet/Infrastruktur/~fgmo/ViSTA-Virtual-Reality-Toolkit/lidx/1/

[5] OpenSG Scenegraph Online http://www.opensg.org/

[6] Deliverable D2.4 System Architecture Specification M6, CROSS DRIVE Project

[7] GDAL - Geospatial Data Abstraction Library Online http://www.gdal.org/

[8] Gorski, Krzysztof M., et al. "HEALPix: a framework for high-resolution discretization and fast analysis of data distributed on the sphere." The Astrophysical Journal 622.2 (2005): 759.

[9] The SPICE Toolkit Online https://naif.jpl.nasa.gov/naif/toolkit.html