

PlanetExp: a Framework for the Science and Engineering Operations of Exploration Missions

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The exploration of celestial bodies such as Mars or the Moon is relying more and more on the use of rovers for the surface operations. These have the advantage of a closer presence of the instruments to the scientific targets. In-situ operations pose very specific challenges, which are much higher than in orbit operation, mainly the uncertainty of the surface operations (e.g. rover-soil interaction and limited visibility of on-board cameras), and the fact that operations are limited to daylight. The planning cycle is therefore driven by the planet/Moon day duration and it is reactive to the outcome of the previous cycle activities (e.g. finding biological traces in a zone will most likely restrict the remaining mission to that zone). Furthermore, the amount of time provided to the ground segment to produce the plan for the following day ranges from 8 to 24 hours in the case of Mars which given the complexity of operations involved means a pretty tight schedule. The above reasons make mandatory the use of a specific approach for the selection and planning of scientific targets and activities. The application to be used for such operations must allow for a fast analysis (mainly visual, to provide situational awareness) of the rover surroundings as well as mission and internal status. It needs also to provide the means to plan and schedule the scientific and housekeeping activities of the following cycle. PlanetExp, the outcome of the MMI for Exploration Missions project, carried out by a GMV-led team for ESA during the last year, demonstrates different ways to implement these challenging requirements for the data analysis and planning tools. The project is focused mainly on the MMI and on the definition of data types and associated meta-data involved in the process, making re-use of existing ESA systems such as EGOS User Desktop.

I. Introduction

The exploration of celestial bodies such as Mars or the Moon is relying (or will rely) more and more on the use of rovers for the surface operations. These have the advantage of a closer presence of the instruments to the scientific targets (in fact opening new opportunities since we are no longer limited to orbital instruments, but we can actually drill, perform in-situ analysis, manipulate...). But there are also difficulties: the uncertainty of the surface operations is much higher than in orbit. Among the causes of this fact are: the interaction of the rover wheels with the soil cannot be estimated with accuracy (especially the slippage) and there is a high level of uncertainty in the accurate knowledge of the surroundings of the rover (the current on-board cameras only provide meaningful information up to 25 meters). Hence, the planning of operations for the following days will be highly dependent on the status and the results obtained by the experiments during the current day (for example, finding biological traces in a zone will most likely restrict the remaining mission to that zone or excessive slippage will cause an energy consumption higher than expected, there are no longer accurate celestial events or precise times of visibility of the

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scientific targets). Time is a very important constraint in this kind of missions in order to take the maximum advantage of the communication windows over the rover. The amount of time provided to the ground segment to produce the plan for the following day (including analysis of Housekeeping TM and basic product processing) ranges from 8 to 24 hours in the case of Mars (depending on the number of communication windows allocated to the rover) which given the uncertainty and the need for simulations could be a pretty tight schedule. The above reasons make mandatory the use of a different approach for the choice of future scientific targets and activities. The application providing support to the user must allow for a fast analysis (mainly visual, to provide the situational awareness) of the rover surroundings as well as mission (scientific products, progress of overall mission objectives) and internal status (based on Housekeeping TM analysis), so targets and experiments can be selected and proposed to the mission planning. It will also provide the means to help to plan the activities of the following period and execute fast simulations to check times and resource consumption under different circumstances (especially regarding soil characteristics). ESA is conscious of these needs and in 2010 launched the MMI for Exploration Missions project to study the different options and ways to implement these new requirements. This project is focused mainly on the visual analysis part and on the definition of data types and associated meta-data (along with their storage), but it also pays attention to relations with other entities of the ground segment (data processing, mission planning). An agile development approach has been chosen in order to maximize interaction with the future users, and to speed up the process of development and testing. The tight schedule and budget makes the reuse of existing components and libraries a must.

II. Planetary Exploration Mission Operations

The planetary missions under consideration may be rovers or static spacecraft operating on the surface of a planet or moon (e.g. Phoenix lander or the Beagle 2). Orbiters could also be considered as additional assets which support the surface craft as communication relays and/or providers of orbital images.

Surface missions have particular features that are drivers for the mission design and in particular for the operations concept, namely:

- Operation in an uncertain environment
- Impossibility of real time operations due to the propagation delays
- Limited communications

One of the major mission design issues is the level of autonomy on-board the spacecraft. The drivers mentioned above call for high levels of autonomy in order to maximize the operational time (i.e. maximize the science return) as autonomy allows:

- The rover to operate without ground control for a certain amount of time due to communication delays and limited windows
- A flexible adaptation of the rover to the uncertainties imposed by an unknown environment, and with which has a high degree of interaction

The operations team may not always want to rely on the autonomy of the rover to identify science targets or do some engineering activity; sometimes ground may want to have the control. We can talk then of high/low autonomy operation mode rather than high/low autonomy rover.

A typical operations concept mainly derived from the MER experience is explained next. Exomars operations concept is under definition and may differ in some aspects.

The surface operation of the rover involves a series of complex ground and on-board activities with different timescales and which are closely inter-related. Typically we can consider two timescales in which operations are defined: strategic and tactical. While the “Strategic Operations Process” can be defined as the set of operations for planning the mid-term Rover activities to ensure the high level scientific objectives of the mission are satisfied, the “Tactical Operations Process” can be defined as the set of operations to achieve the execution of rover activities in the short term (one to a few ‘days’). The level of autonomy determines which and how operations are done on-ground and on-board.

The Tactical Operations Process can in turn be considered composed of the so called “downlink” and “uplink processes” which are supported by the rover operations control system.

The TM Acquisition and Processing is the first part of the “downlink process”. The housekeeping and science telemetry is received in the form of files or packets. The evolution trends for the planetary exploration missions promote the adoption of file-based operations making the downlink operation as well the distribution to the end user through the many nodes involved (orbiters, stations, control centers) easier and more reliable.

Either way, telemetry is extracted, validated, and processed to derive engineering housekeeping values, science products, and also products like Digital Elevation Models (DEMs) and terrain models. The latter are derived in a

complex process where first local DEM relative to the rover is produced from stereoscopic images and then georeferenced and inserted into a general DEM which contains the rover environment as it traverses. Both, raw and processed data is stored.

In rovers implementing on-board planning capabilities the TM also contains information about the activities executed on board in form of an activity log, an extended event concept.

All the TM data is assessed by the engineers and scientists teams making use of proper assessment tools:

- The engineering assessment focuses on:
 - Platform and instruments monitoring by analysis of housekeeping TM,
 - Planning assessment: verification of the execution of the plan commanded and corresponding expected parameters evolution (e.g. from a simulation) with respect to actual plan/activities performed and system evolution
 - Localisation calculations through different methods
 - Navigation assessment, e.g. for assessing the actual traverse paths and calibration,
 - Identification of new engineering activities needed to be plan
- The science assessment focuses on the analysis of images and science products used in supporting the identification of new scientific targets (e.g. areas or specific locations). In addition to this “operational” science assessment other science exploitation may be carried out by specialised organisations using their own tools remotely. Like engineers, scientists will propose new science activities to be taken into account by the planning process.

During the “uplink process” the immediate future operations are planned. Independently of the level of autonomy, the Tactical Operations Process can be considered as “reactive” if the operations planned or goals defined are based on the latest known status of the rover and its environment as assessed from telemetry (which due to the impossibility of near real-time monitoring is not the one at plan/goal uplink or execution). This was the case of the MER rovers, but is one of the points open for ExoMars where a blind commanding is also being discussed.

The uplink process can be considered performed in two steps:

- In a first one, different groups of engineers and scientists establish their own proposals concretised in activities or goals. This is done using planning tools integrated with the assessment tools which allow for activities/goal specification.
- In a second stage, a subset of proposals, engineering and science, are consolidated in the final plan/goal(s) to be uplinked. This second stage requires specific planning, scheduling and command generation tools out of the scope of this project.

In a low or intermediate autonomy operations mode the uplink process implies the definition of a plan containing engineering and science activities. This plan consists on a sequence of activities to be executed by the Rover that fulfills all constraints, namely flight rules and resource limitations (power, memory, thermal) and at the same time meets the science requirements. Commands or activities at different levels are then generated and commanded.

In a high autonomy operations mode, the plan will be only defined at high level or even the final goals to be uplinked, which highly reduces the operational load on ground. In this case the rover will dynamically develop the goal or high level plan into concrete activities that will depend on the logic implemented on board, the actual environmental conditions and the evolution of the rover itself. The plan cannot be considered failed because there is no pre-defined plan but the goal can be only partially achieved which can be evaluated based on certain parameters. Before uplinking the consolidated plan (commands or goal based) shall be validated on a simulator.

The Tactical Operations Process, encompassing downlink and uplink processes, takes place between consecutive communication windows including activities for the next few sol(s) activities. The level of autonomy and the planning of context-independent activities will help to alleviate the operational ground load. In this reactive operations concept, the availability for communication (orbiters and Direct To Earth availability, pass frequency, duration and bit rate) and selection of communications strategy (i.e. the use of the communication assets) is a major operational issue.

Once the activity plan/goals are commanded and executed the spacecraft will send back to Earth housekeeping telemetry and also a special type of information summarizing the execution on-board: the Activity Execution Report that is a detailed execution log possibly including the on-board events.

The future activities are only known once the planning is finalized, and will be stored in a data structure we might call Activity Plan. Depending on the autonomy mode the Activity Plan will be more abstract (goals) or specific (activities, tasks). In the former case the detailed activities may only be estimated from a simulation.

III. Overview of the Application

Since almost all the data can be geographically referenced, and a very intuitive interface was one of the main targets of the project, a GIS-like application was thought as a clear solution from the beginning: it offers a very intuitive way of accessing data and launching applications, and the users are familiar with this kind of approach, so the training would be relatively easy for the personnel involved in the operations of the spacecraft.

The look and feel of the application is defined by the use of Eclipse RCP as framework for the development and execution of the program. The different components of the application appear as views in the framework. Figure 1 shows the main functionalities: the Context View (which is the main entry point for the GIS functionality), a TM display (directly from the EGOS User Desktop libraries; this software is a recent development carried out by ESA-ESOC to serve as the framework for future MMI developments) and a 3D View in another tab (the one labelled Cell View).

The functionality is available by means of one or two clicks trying to make the use as efficient and as simple as possible. For the sake of commonality with standard GIS programs and reuse of existing libraries (MapServer) standard methods/functionality of this type of applications have been imported into PlanetExp, such as centring, panning, redrawing, the layer concept for filtering information and so on...

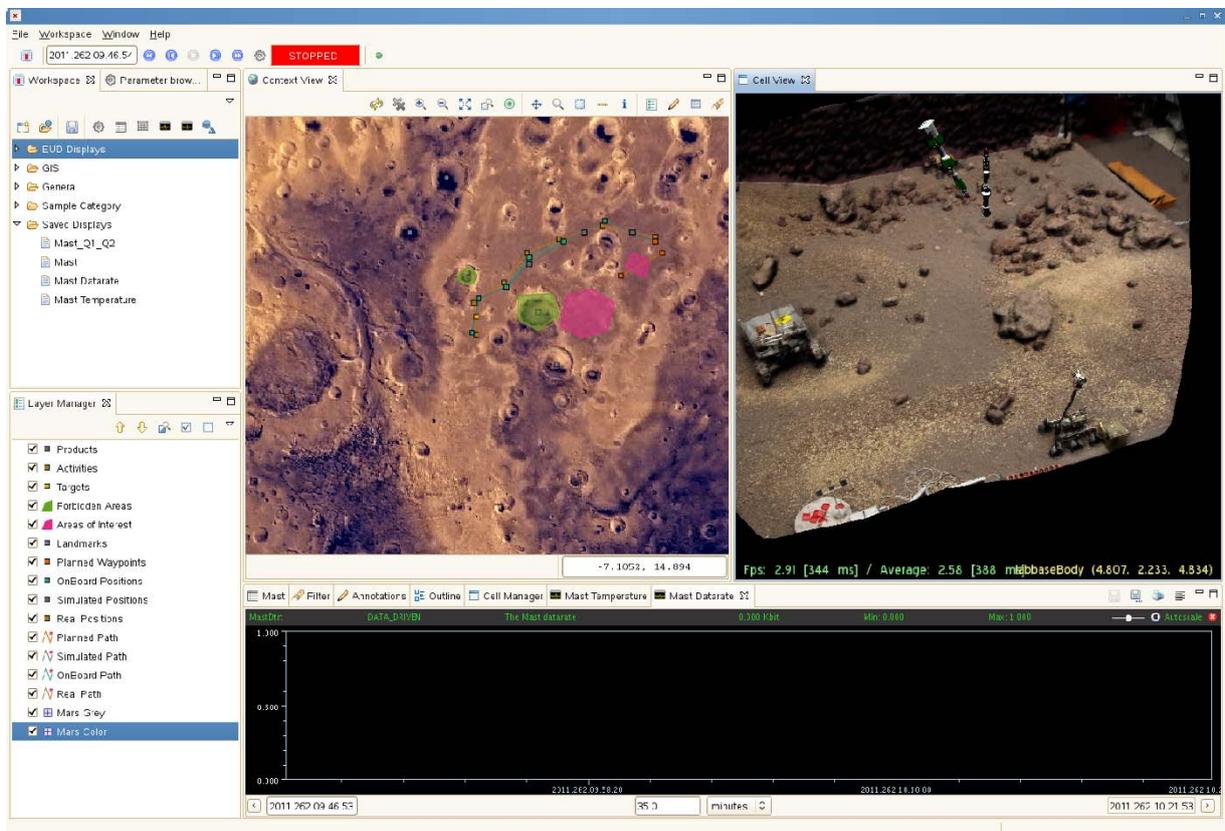


Figure 1. General View of PlanetExp.

There are 4 main types of functionalities grouped in what is termed "view":

- Context view: it groups the GIS functionality (including data queries in the databases). Its distinctive feature is the orbital image that serves as "locator" for the different products available within the system.
- 2D view: it will provide a viewer for the images (2D). The user can add information to the image such as targets, waypoints, landmarks or interest/forbidden zones...In an operational application the user could also apply different levels of image processing.
- 3D view: One of the most attractive features is the possibility of accessing 3D information. The surface missions use to have lately (the ones involving a rover at least) stereo cameras as one of the payloads, so 3D information is available, and the mission has access to DEM of the surroundings of the rover. By means of the 3D View the user can access this information and "navigate" through it. The 3D information can be

rotated in 3 axis, displaced, zoomed (in and out) and annotated (waypoints, target, zones...). This provides the user a high level of knowledge of the rover surroundings that allows identifying potential hazards such as rocks or slopes.

- TM view: it groups the different TM displays available. It is a EUD plugin for Eclipse. The different displays are configured by the user by dedicated tabs in the main user interface. The data can be exported to ASCII files, easily readable by external applications which make their integration within PlanetExp very easy.

Although the normal way to access the data stored in the databases would be by means of the mouse, PlanetExp also keeps classical ways of accessing the databases: queries.

Apart from the previous core functionality, the application can launch 2 complementary applications:

- Plan Editor: the user will be able to create activities and plans that schedule these activities. In real application they will be used to plan the activities of the spacecraft based on the analysis performed with the science data accessed through this type of applications.
- Mathematical application: in real life, the users will access the data and achieve environmental awareness by means of applications like PlanetExp, but the scientists will want to analyse the data in depth, with their own algorithms and programs. PlanetExp provides a launcher for this type of applications so the user can run it directly from the MMI (although it will not be another view in the Eclipse environment, unless it is explicitly developed in that way, which is not the typical situation).

IV. The Context View

It is the main entry to the application. From this view the user could access to all the products and data stored in the databases. It offers the standard features of a GIS application like zooming, pan, annotate, access to viewers etc...In the case of this application the image corresponds to a Mars orbital image (in colour or in B&W, the used memory is different, and hence the speed of the application varies).

The Context View could display the following items:

- Path: reconstructed path (both on-ground and on-board computed) for the past, and planned path for the future (including simulated path to check the correctness of the numerical models), shown as a sequence of locations at a given separation.
- Targets/features: objects/points, areas or other items on the surface identified by the operations teams shown as icons, areas, etc.
- Geographical planet features with their names (landmarks)
- Rover activities by instruments shown where they took place
- Forbidden Areas: areas the Rover should avoid to traverse through due to the soil conditions (slopes, soft terrain, rocky terrain, soft sand terrain...)
- Interest Areas: the opposite of forbidden areas, areas especially suited for explorations.
- Selection of generated products by instruments

In addition to viewing, the user would interact with above items. E.g. access to the items details in newly opened displays could be accessed by different click actions. Some examples include:

- Displaying of position of a point on the path
- Opening of a specific image/product viewer when clicking on an image/product icon
- Opening of a activity details viewer when clicking on an activity icon

The user can annotate the orbital image by adding the forbidden and interest zones, defining waypoints for the commanded path, defining landmarks, and targets (in the form of geographic positions) for further science investigation. The other items, i.e. the information coming from the spacecraft, have been injected in the application database in a previous step (out of the scope of the application) by the data processing function of the control center.

V. 3D View

In order to improve situational awareness it is important to have a 3D representation, which we call "3D View", of the spacecraft environment (see Figure 2). This is represented with a reconstruction of the terrain which requires a DEM and a terrain model. They are incrementally constructed on top of a pre-existing DEM and improved as the rover takes images (with stereoscopic information) along its traverse.

As in the Context View, the user would need to see all georeferenced items stored in a database on top of the 3D representation: features, targets, paths, areas, other images/products, activities, etc. Again as in the previous cases there are associated actions to the selection of each of them.

The user can rotate, move and zoom the displayed scene as in a typical OpenGL applications. It has basically the same functionality provided by the context view, although limited to the surface covered by the DEM (much smaller than the orbital image used by the Context View). The information shown in this view is the same that the one shown in the Context View. Both views have access to the same data, and the difference is the way in which it is displayed, being the geographic position the key to the coherence between the two of them.

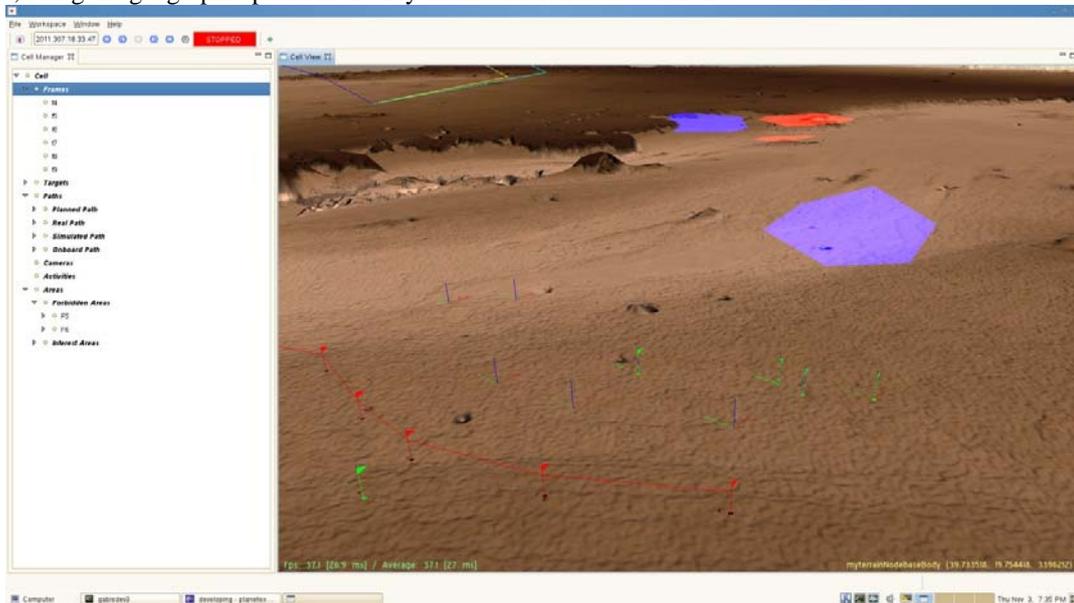


Figure 2. 3D Views.

VI. 2D View

Once a 2D image is selected, e.g. with the queries mentioned above, it shall be visualized in a dedicated image viewer we will call "2D View". This is the main scientific assessment tool as the raw and processed images are displayed without distortion, i.e. show the data as taken by the camera.

As in the previous cases, the user sees superimposed on the image all georeferenced items stored in the form of icons: landmarks, targets, paths, waypoints, areas, other images/products, activities, etc. As in standard GIS applications (including the Context View) the different types of annotations are classified per layers, and its visualization can be filtered by activating or deactivating the corresponding layer.

A basic task in this view is the ability to define targets, features, waypoints, and areas to be subsequently used in different planning activities: activity planning, path planning, etc. Given the potential collaborative operations, the targets and features being defined are immediately available to any other user displays (the database is common to all the users, so they have access to the same information).

VII. TM View

PlanetExp allows the access to the stored TM by means of four types of displays (see Figure 3). It provides the means to create them (which is basically defining the parameters to be shown), and save their configuration so they can be reused or reloaded.

The stored TM can be replayed by the user using the controls that appear in the upper left part of the main window. The application provides the basic controls of a media player with the play, stop, fast-forward, rewind... Besides the controls, the user finds two extra fields:

- To the left the TM epoch: while playing the TM it shows the latest epoch displayed. It can be used also to set an epoch, and the displays will show the data corresponding to that epoch.
- To the right the status of the TM ingestion: in this project stopped or retrieval (when the data is being replayed).

The available types of displays are:

- Alphanumeric (AND): for any given time, the values and ancillary information of a set of TM parameters is provided to the user (at one time, there will be one value per parameter)

- Scroll: for different times, the values corresponding to a pre-defined set of parameters are displayed (there will be several values of a parameter at a given time, each one corresponding to a different epoch).
- Graphic (GRD): graphical display of parameters values vs. time
- X-Y: graphical display of parameters values vs. parameters values.

These are directly inherited from the EGOS User Desktop, and they have been directly integrated into the application, making use of the Eclipse RCP framework.

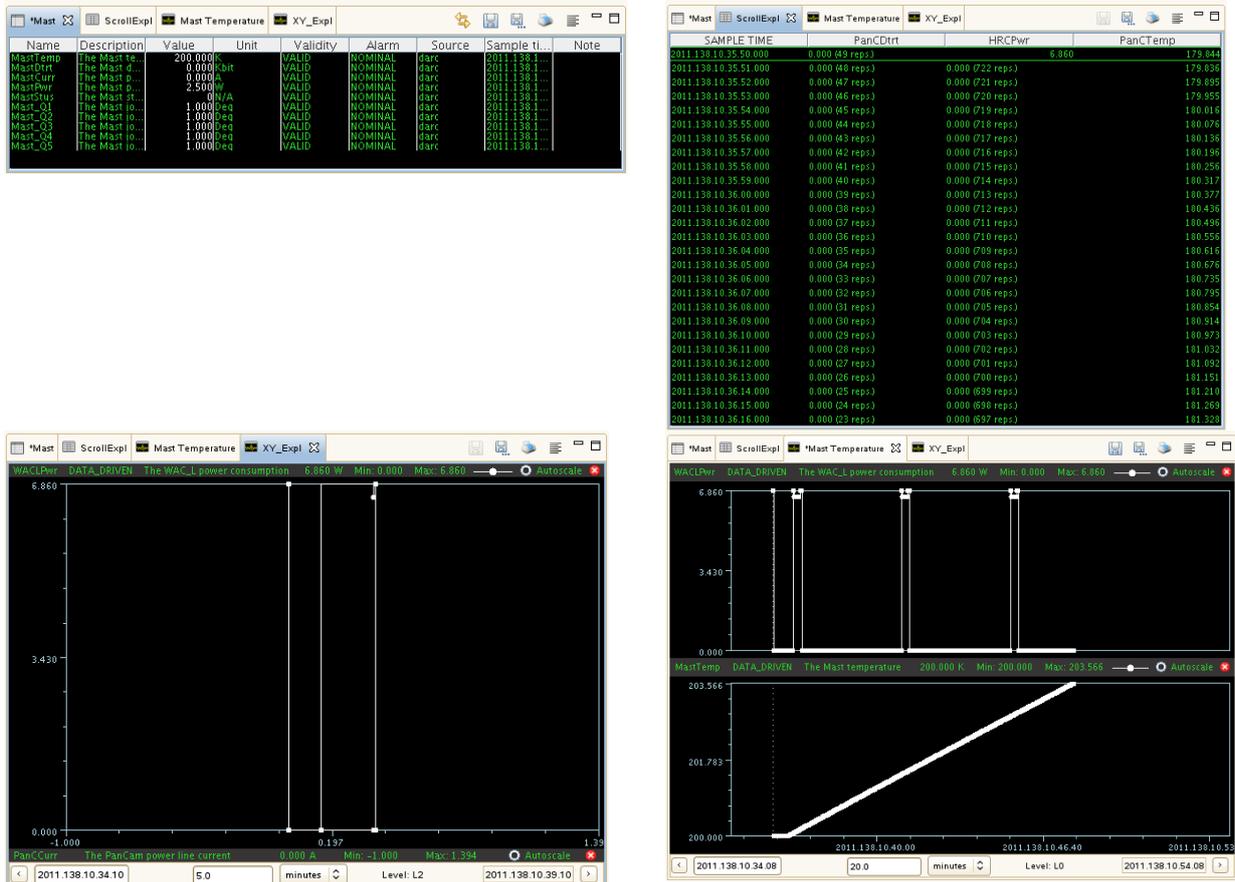


Figure 3. TM Displays; clockwise, starting from upper left corner, AND, Scroll, Graphic and X-Y.

VIII. Math Application and Planning Editor

The application was designed to be able to launch external tools. It is understood that on top of the basic functionality provided (which at the end is the access to mission data), the users, either scientist or engineer, will want to apply their own algorithms. So the application shall allow the execution of external software that can be configured by the user. A launch button is provided for what is termed “Math Application” that generally identifies this external tool containing the specific algorithms. For testing purposes we have used Octave and Scilab to demonstrate its feasibility. Following the same philosophy (and mentioned above), the TM data is exportable in ASCII files easily parsed by external programs.

Although planning was out of the scope of the project, it was identified from the beginning that the assessment of the previously up-linked plan and the generation of proposal for future observations are among the main targets of the engineering/scientific assessment. To this end, a dedicated tool has been added to check the nominal plan (so it can be compared with the actual one), and to provide proposals for future activities based on the results of the performed analysis. Hence a basic application for the creation of activities templates and edition of plans was provided as well (see Figure 4).

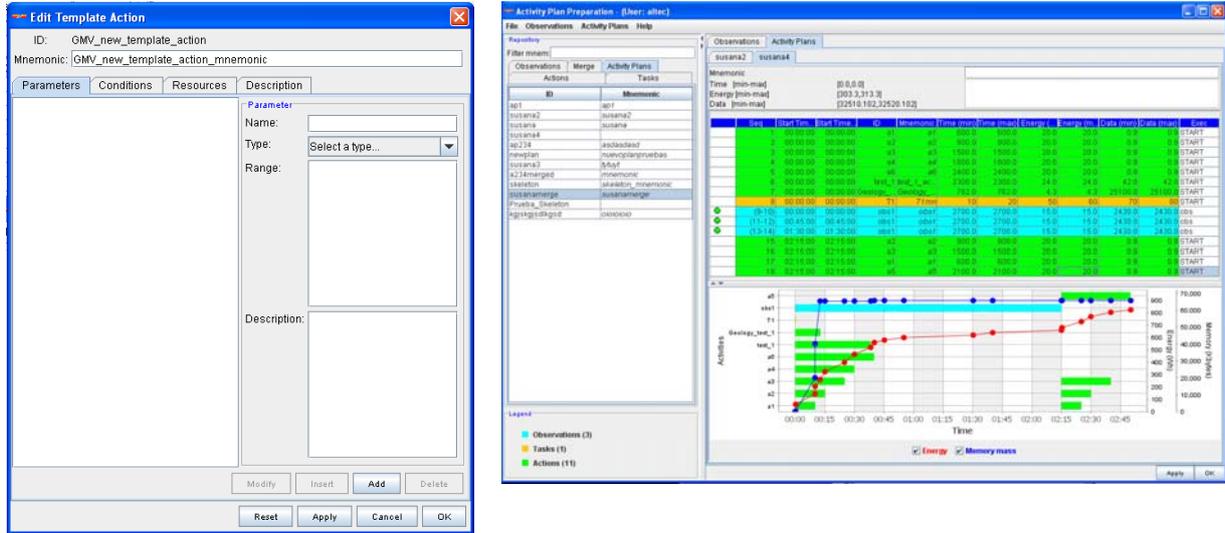


Figure 4. Activity Template and Plan Editor

IX. Conclusion

The application has shown the possibility of using geographic information systems as the main access to space missions data, providing an easy-to-use approach to the problem of accessing data and analyzing it in surface exploration missions (although the concepts could be easily applicable to more standard orbital missions, an adding the location of the targets to the typical access through time windows or orbit numbers). It also provides the means to explore the surroundings of the rover and provide the necessary situational awareness required for this type of mission in which the conditions of the environment are not well-known, and potential hazards are only discovered when the rover is a few meters away. Based on this knowledge, the on-ground model can be modified accordingly, and a safe plan generated and simulated. This is also applicable to science: it is expected that rich sites can only be detected when the instruments are relatively close, so the application provides the means and the desired flexibility to analyze the data and explore the close surroundings so the scientific proposals are generated based on the latest and most accurate information, in the available time, providing a higher scientific return.

References

- ¹ECSS, "Space Engineering: Space Segment Interoperability" ECSS-E-70-11A, 5 Aug 2005.