ROVER OPERATIONAL SIMULATOR FOR EXOMARS - TASK & ACTION PLANNING SIMULATOR (ROSEX-TAPS)

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ABSTRACT

ROSEX TAPS is the Operational Simulator of the Exomars Rover Module developed by TRASYS under TASI responsibility. It is intended to be integrated into the Rover Operation Control Centre (ROCC, under development in ALTEC) to support the daily preparation of the Exomars Rover operations in 2021 by proving the feasibility of the activity plans to be uploaded and executed by the rover and their consistency with the estimated associated resources (Power/Energy Consumption, Science/HK Data generated, Ops duration). This main objective calls for realistic resource determination and timing performance compliant with the daily activity planning and verification operations. This paper presents the modelling, the design, the development plan and the actual and expected results produced by the ROSEX TAPS Simulator.

1. BACKGROUND

ExoMars program is developed in a broad international cooperation between the European Space Agency (ESA) and Roscosmos, the Russian space agency, with important contribution from NASA. The programme comprises two missions: one launched in March 2016 and consisting of the Trace Gas Orbiter (TGO) and Schiaparelli, an entry, descent and landing demonstrator module, and a second (planned for launch in 2020) comprising a Rover and Surface Platform.

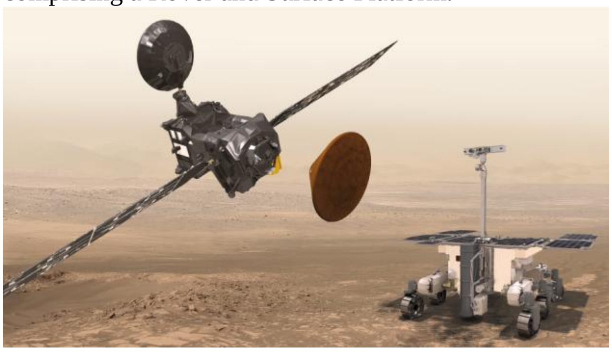


Figure 1. Exomars Mission

Roscosmos is providing the Proton rockets to launch both missions to Mars, along with contributions to the scientific payload (two of the four science instrument packages of the TGO are European-led and two are Russian-led). The 2020 mission comprises the European-provided Rover, and the Russian provided Surface Platform, both carrying European and Russian scientific instrumentation. NASA also contributes with some equipment and scientific payload elements to the missions. The prime contractor for the ExoMars programme is Thales Alenia Space Italia (TASI). The ROSEX TAPS (Rover Operational Simulator for EXomars - Task & Action Planning Simulator), subject of this paper, is an Operational Simulator of the Exomars Rover Module developed by TRASYS under TASI responsibility.

2. NEED FOR AN OPERATIONAL SIMULATOR FOR THE EXOMARS ROVER

Historically the need for an autonomous robot controller mainly comes from Planetary Exploration, where i) the communication capability is usually very limited, (for example on Mars like MERs [MER], Curiosity [MSL], ExoMars [EXM]), and ii) where the environment in which the rovers operate is unstructured and generally unknown. This limitation requires from the rover a degree of autonomy allowing to execute surface operations without human intervention.

ExoMars Rover operations are defined on-ground and uploaded to the rover in the form of a sequence of Activities, named “Activity Plans”. As explained above, these Activity Plans cannot be a simple list of time-tagged commands, but needs a mix of a more complex language and high level operational bricks allowing the Rover to cope with the environment uncertainties. Moreover these Activity Plans needs to be somehow validated from Ground in short time, not compatible with standard satellite simulator means (ATB, SVF). The following subparagraphs explains how these top level needs have been taken in account and solved for the ExoMars Rover, providing the rationale behind the creation of the ROSEX TAPS Simulator.

2.1. EXOMARS ROVER AUTONOMY CONCEPT: RAPD LANGUAGE, ACTIONS, TASKS & STATE DIAGRAMS

The ExoMars Rover is designed to implement E3 level of autonomy allowing the “Execution of adaptive missions operations on-board” (see Fig.2). It will be capable to adapt the execution of the plan to the available resources and equipments state and automatically switch to Alternative Plans prepared by Ground (e.g. lack of energy wrt the foreseen energy availability will induce the selection of an Alternative Plan).

Level	Description	Functions
E1	Mission execution under ground control; limited capability for safety issues.	Real-time control from ground for nominal operations Execution of time-tagged commands for safety issues
E2	Execution of pre-planned ground-defined, mission operations on-board	Capability to store time-based commands in an on-board scheduler
E3	Execution of adaptive mission operations on-board	Event-based autonomous operations Execution of on-board operations control procedures
E4	Execution of goal-oriented mission on-board	Goal oriented mission re-planning

Figure 2. ECSS-E-70-11A Autonomy Level Definitions

At the basis of the design of the E3 Autonomy level are the concepts of Action, Task and the RAPD programming language.

- An Action represents elementary rover Activities such as MAST_Initialise and GNC_Initialise. The Actions implement functionalities of a single rover subsystem (e.g. Mast, Wisdom, etc).
- The Tasks are logical and temporal composition of Actions (e.g. the RV_Prepare4Travel Task embeds the MAST_Initialise and GNC_Initialise Actions in parallel). The Tasks, as composition of Actions control several subsystems in parallel.
- Finally, the need of an event driven Activity Plan has led to the definition of a new on-board mechanism in addition to the standard PUS services of Mission Time Line, Event Action tables, TC and DTC files, based on an evolution of the DTCF executor concept: the Activity Plan is contained in one (or more) text file(s), following the semantics of a specific **Rover Activity Plan Description language (RAPD**) and are interpreted on-board.

The RAPD language provides the following basic features, allowing for:

- The definition of the mission in terms of activities (i. e. actions and tasks)
- An actual event driven approach, i. e. no fixed timing ‘a priori’ established for TCs execution but the possibility of synchronization with events
- Concurrent execution of activities. Concurrency is needed both for the execution of parallel (long lasting) activities, (e. g. warm-ups) to save time, and for cooperation among tasks involving different subsystems (e. g. RV traveling and interaction with WISDOM instrument for measurements)
- Use of conditional execution, based on results returned by actions and/or tasks at execution time. This provides a possibility of adaptation of the current plan to predictable cases.

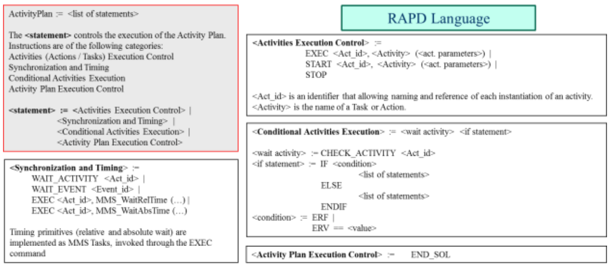


Figure 3. ExoMars Rover RAPD Language

The RAPD Language is used to trigger the execution of the ExoMars Rover **Actions & Tasks**, which represents the meaningful set of “operational bricks” to be used by Ground. These bricks are not just elementary operations (i.e. close LCL, enable thermal control), but covers medium/high level functionalities to ease Ground Planning. The difference between Actions and Tasks is mainly their “scope”: an Action is enveloped in one subsystem (i.e. Mechanism Move, Snap a photo) while a Task is a composition of Actions and other Tasks belonging to different subsystems (i.e. Prepare Rover for Travel Ops, Drill for X meters while using MaMiss). In Flight SW language, Actions are implemented through OBF (On Board Functions) while Tasks are implemented through OBCP (On Board Control Procedures).

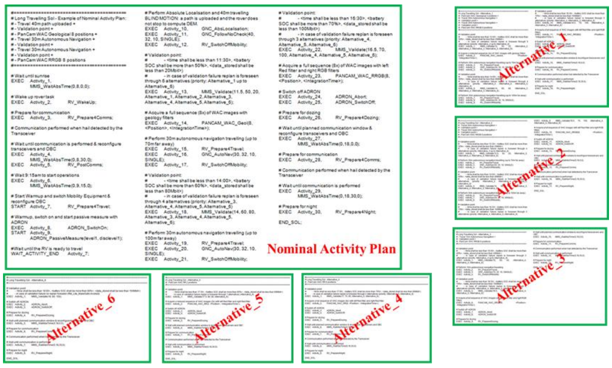


Figure 4. Example of an ExoMars Rover Activity Plan

The identification of the Actions associated to each subsystem is intimately linked with the model of this subsystem. Briefly speaking, an Action can be triggered when the subsystem is at a given state, during its execution sets the system at a new state and finally, at completion, leaves the system at a final state.
For the ExoMars rover and mission, a significant work has been performed in close collaboration between the TASI (the prime of the mission), the scientists responsible of their instruments and the rover platform responsible to model all the rover subsystems as Finite State Machines driven by the Actions.
In addition, at each state of the model is associated a set of information indicating the resources consumed by the given subsystem at this state. It includes, the Duration time (sec) (when applicable), the Power Consumption (Watt) and the Critical/Non Critical Data generated

(bps) (see Fig.5).

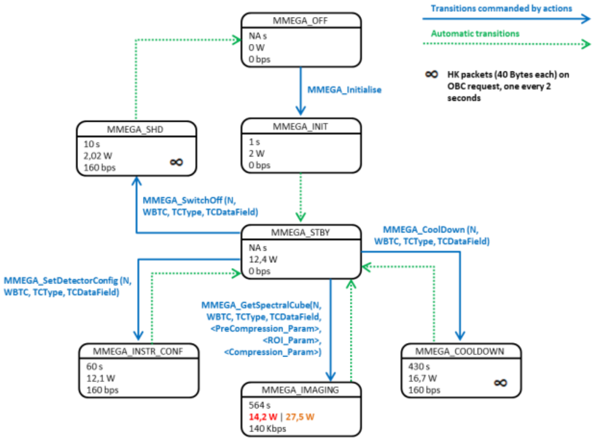


Figure 5. Example of the Micromega subsystem State Diagram & Actions

All the concepts, the models, the Actions and the Tasks described so far are instantiated for the ExoMars Rover implementation in the TASI Functional Architecture Document [FUNC]. In particular, 18 subsystems are identified with 154 associated Actions and 40 Tasks.

The ROSEX TAPS Simulator implements the TASI Functional Architecture Document providing a mean to execute an Activity Plan translated in a RAPD program and quickly estimate the associated resources consumption. Moreover ROSEX TAPS Simulator implements a set of environmental and support models to estimate the resources availability (e.g. power generation capability through the Atmospheric and Solar Array model, data upload/download capability through the Orbiter model) providing so closed loop simulations with the environment in which the rover operates.

Figure 6. Example of ROSEX TAPS Simulation output

Summarizing: the ExoMars Rover “understands” Activity Plans made by Actions and Tasks organized in RAPD Language programs. Activity Plans can be validated vis-a-vis the expected resources availability thanks to the ROSEX TAPS Simulator, which exploits the link between Actions and Subsystem FSM Models (containing resources consumption).

2.2. EXOMARS ROVER AUTONOMY CONCEPT: PLANNING CONSTRAINTS AND FIDELITY

The main objective of ROSEX TAPS calls for realistic resource determination and timing performance compliant with the daily rover activity planning and verification operations. To fulfil such objective two main characteristics are needed:

- Since for Exomars Rover the time for the ground tactical planning (time from reception of Rover telemetry till the production of a new plan to be uploaded) is four to ten hours, the Rosex TAPS shall be sufficiently fast to allow iteration with the planner for the optimisation of the Activity Plan to be uploaded to the Rover every sol (from 10x to 100x real time, that is one to two orders of magnitude faster than standard SVF and ATB test platforms)
- The ROSEX TAPS Simulator is intended to reproduce as faithfully as possible the Rover behaviour considering the operational environment known with the level of detail available during the activity preparation phase and complying with activity planning operational constraints. The target is to quickly estimate (see above) the resources associated to an Activity Plan with an accuracy up to 95%

For these two reasons ROSEX TAPS Simulator is an all software configuration running on one Linux Machine/s (portable on all OS by Virtual Machines technology). No hardware units are foreseen to be integrated. The ROSEX TAPS Simulator will not include any real time processor emulator (such as TSIM) and therefore it will not host or run any part of the real time on board software. This does not exclude that specific algorithms and part of OBSW source code are integrated in order to increase the simulator fidelity. This allows to run fast simulations obtaining a very good accuracy in resources estimation. Since the ROSEX TAPS is not a part of the flight SW (which is robust to erroneous Activity Plans), its SW Criticality Category is set to D according to ECSS-Q-ST-80C.

3. ROSEX TAPS SIMULATOR FUNCTIONAL DESCRIPTION AND BREAKDOWN

This section presents the top-down description of the logical breakdown of the Rosex TAPS Simulator highlighting the main models and the main data sets exchanged.

The Exomars ROSEX TAPS Simulator is constituted by the following main components:

- The **Rover model** simulates the rover and payloads behaviours. It includes all rover subsystems, the payloads and the rover control logic reproduction. It aims at proving the feasibility of the commanded activity plans by reproducing the conditions expected to occur during its progress and by realistically identifying all the resources needed and available;

- The **Environment model** is in charge of the simulation of the environment which interacts with the Rover. This task encompasses real time reproduction of planetary and orbiter ephemerides as well as ground stations positions, real time provision of planetary atmospheric data, preparation of terrain related data, co-registration of test scientific data associated to local conditions to feed payload models;
- The **Terrain model** produces the input for the environment model creating a mesh of the terrain faced by the rover enriched by soil properties and possibly enriched by test scientific data to be used by payload models. Terrain generation could be based on real data gathered on Mars or on fully/partially synthetic reconstruction. The complexity of the representation is tuneable with respect to the fidelity selected;
- The **MMI simulation supervisor** is a set of MMIs allowing the operator to control the simulator and to understand its results by means of 2D visual displays and variables monitoring;
- The **3D visualisation environment** shows the kinematics of the rover and its moving parts acting in the proper environment;
- All the models are connected and run by the underlying **Simulation kernel** in charge of managing the scheduling of the models execution and realising the data flow between models. It acts as the simulation timekeeping and provides the means for the simulation execution control and monitoring.

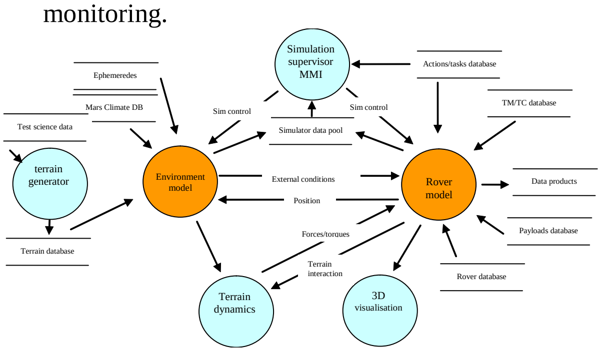


Figure 7. ROSEX TAPS building blocks

3.1. ROVER MODEL

The rover model is a complex model composed by several other sub-models (including Rover Platform, Payload Support Function and Payloads behaviours). It includes all rover mechanisms kinematics simulation, the rover subsystems, the payloads, the rover control logic reproduction. It aims at proving the feasibility of the commanded activity plans by reproducing the conditions expected to occur during its progress and by realistically identifying all the resources needed (consumption) and available (generation).

ROVER VEHICLE (RV)	PASTEUR PAYLOAD (PPL)
ADE(s) s/s	ADRON s/s
Data Hnadling s/s	CLUPI s/s
Mast Assembly s/s	ISEM s/s
Mobility s/s	MicrOmega s/s
Power s/s	MOMA s/s
Thermal s/s	RAMAN s/s
TT&C s/s	PanCam s/s
Solar Arrays s/s	WISDOM s/s
Controller s/s	

PAYLOAD SUPPORT FUNCTION (PSF)	GENERATION MODELS
Drill & MA-MISS s/s	Solar cells Model
SPDS s/s	Battery Model
	MPPT Regulator Model

Figure 7. Rover Model building blocks

Let us briefly discuss two rover models:

- The **Power model** reproduces the Rover PCDE behaviour in terms of resources consumption, by implementing a FSM "driven" by the Controller model (e.g. Day <-> Night transition);
- The **Controller model** reproduces the behaviour of the on-board controller. It implements all the identified Actions and Tasks including an interpreter of the RAPD programs.

ROSEX initial developments and architecture are based on the 3DROV planetary operations simulator ([3DROV]). The detailed analysis and RM functional decomposition have been performed by TASI as part of the Functional Architecture definition.

3.2. ENVIRONMENT & TERRAIN MODELS

The environment model is in charge of providing all the external stimulation and environmental conditions as experienced along the Rover activity on the Martian surface. This model encompasses:

- Real time reproduction of planetary and Orbiter ephemerides, to allow reconstruction of geometrical conditions including illumination, visibilities, relative velocities, accelerations
- Real time provision of planetary atmospheric data (fluxes, temperatures, winds, etc), based on Mars Climate Database [MCD] and the LMD1D Tool allowing to compute power generated by Solar Arrays from incident and diffuse illuminations.
- Preparation of terrain related data (shape and terra-mechanics characteristics)
- Co-registration of test scientific data associated to local conditions to feed payload models (e.g. subsurface soil compactness).

It is constituted by the following main components:

- Terrain Model,
- Atmospheric Model, and
- Orbital Model.

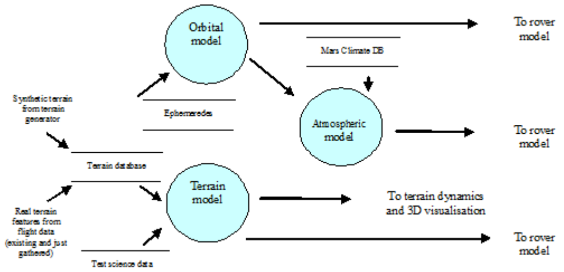


Figure 7. Environmental Model building blocks

3.3. MMI SIMULATION SUPERVISOR AND 3D VISUALISATION MODELS

The MMI simulation supervisor represents the interface of the simulator towards the operator. It includes a set of MMIs providing the operator the means to specify Activity Plans, to translate them in RAPD programs, to control the simulator and to understand its results by means of 2D visual displays and variables monitoring. It allows to define all the preliminary and initial conditions for the simulation and to retrieve the final states. It allows stopping and restarting the simulation from any previously recorded state. The main features of the simulation supervisor are:

- Initialise the Simulator providing a scenario (rover initial conditions, environmental initial conditions, activity plan incorporation)
- Select and adjust the fidelity level by allowing switching between models
- Inject failures and environmental anomalies
- Control the simulation execution (start/ pause/ resume)
- Monitor the simulation execution allowing the operator to observe the evolution of the Rover operations and to alert him in case of anomalies detection
- Monitor instantaneous resource utilisation and margins
- Log events and most significant model variables

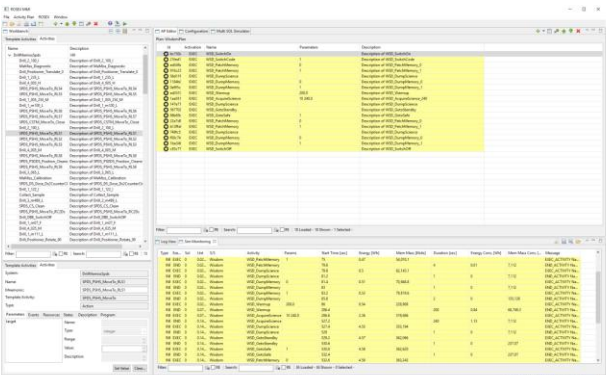


Figure 8. ROSEX TAPS MMI general view

The 3D visualisation environment, integrated in the MMI, shows the kinematics of the rover and its moving parts acting in the proper environment and generates realistic images to possibly feed image based control algorithms.

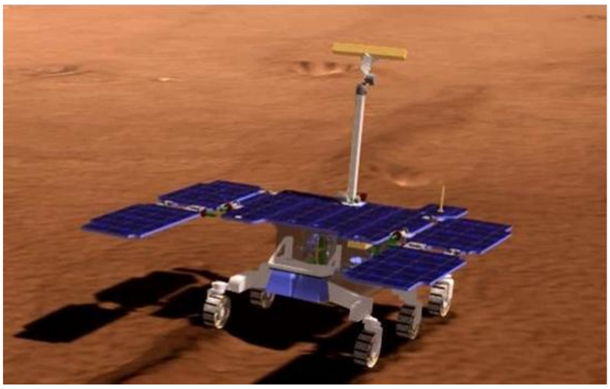


Figure 9. ROSEX TAPS 3D visualisation environment

It should be noted that the ROSEX MMIs are developed in a harmonized way with the ROCS [ROCC] developments in order to maximize the coherency in concepts, tools and interfaces. They are provided therefore as plug-ins of an Eclipse RCP environment.

3.4. SIMULATION KERNEL

In order to take advantage of the technology and know-how developed within the Agency on spacecraft simulations, it was initially decided to adopt the SIMSAT 4.0 framework [SIMSAT]. Developed at the European Space Operation Center (ESOC) in collaboration with European industry, SIMSAT is used for spacecraft and ground segment simulations and training. To be used within this framework, the models under development must comply with the Simulation Modeling Portability 2.0 standard (SMP 2.0). This standard was introduced by ESA to aid the portability of simulation models developed within the European Space Industry. The above choices also aimed at making the ROSEX TAPS compatible with other groups within ESA (e.g, Operations, the Concurrent Design Facility, etc.).
During the development stages it was however decided to keep the compliancy to the SMP 2.0 standard, but developing a proprietary Simulation Framework with the aim of optimizing the simulation speed and awareness. Thanks to the SMP 2.0 compliancy, ROSEX TAPS Models can be fully reused on SIMSAT.

4. ROSEX TAPS DEVELPOPMENT CYCLE AND EXOMARS PROJECT DEPENDENCIES

As already explained, the main and final objective of the ROSEX TAPS simulator is to support the ROCC daily activities of activity plan preparation and validation. However several other objectives are pursued during the Exomars program phases. For this reason ROSEX TAPS will be continuously updated with a scalar approach according to the Exomars Rover development phases needs. During the Design Phase (ongoing phase at the time of writing), models are implemented by TASI / TRASYS using the inputs (state diagrams, Actions and Tasks) derived from subcontractors documentation. This allows the introduction of all the need Operational I/F and models to assess the feasibility of the Reference Surface Mission. ROSEX will provide all the interfaces to ROCS in order to be integrated during the AIT Phase. Operational Sequences and Activity Plans will be prepared and validated in view of the Operation Phase, when ROSEX will be used daily to select the more suitable set of operations to be executed by the Rover on the Mars surface.

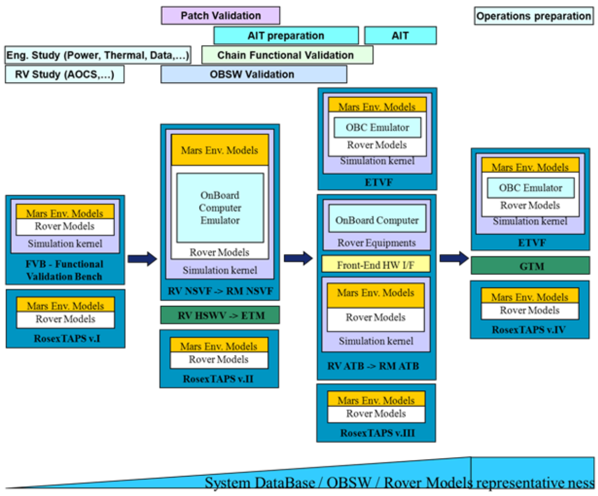


Figure 10. ROSEX TAPS ExoMars Incremental Development Process vs ExoMars development phases

From the SW development point of view, the starting point was represented by the ROSEX TAPS specification, covering all the needed high level functional and performance requirements, which has been baselined at the EXM 2018 System PDR (Oct 2014). The "macro SW cycle" will be covering the standard development of the cat.D SW and will end up in 2020 with the validation of the Rosex TAPS version v.IV against such specification. Meanwhile five releases (ROSEX TAPS versions v.I, v.IIa, v.IIb, v.IIc, v.III) are expected to feed the engineering design process. Each intermediate release is being and will be used by TASI to support the Rover design process (e.g. support trade-offs, RFW/NCR evaluation, Change Requests processing, etc) and produce system budgets. The resulting "micro SW cycles" (every ~6 months) will use as target specification the Functional Architecture document, that is an instantiation of the Functional Reference Model (FRM) prepared by the Robotics Section of ESA's Technical Directorate in 1991-1992 [CT2-ES].

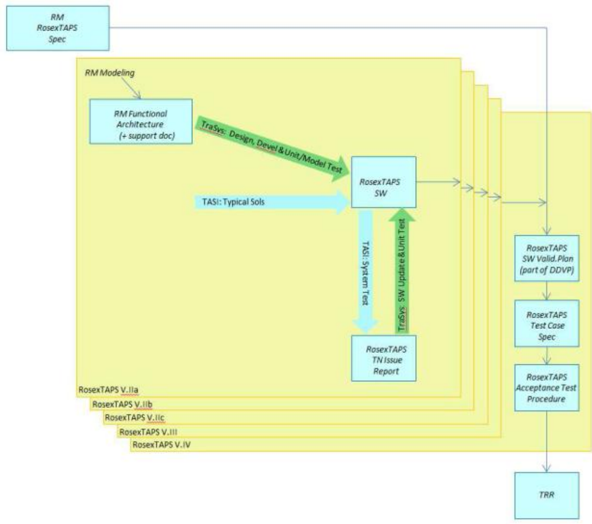


Figure 11. ROSEX TAPS Macro and Micro SW cycles

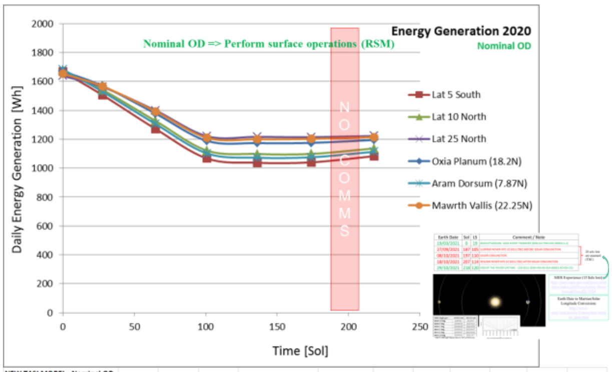
5. CURRENT STATUS AND RESULTS

At the time of writing three versions of ROSEX TAPS have been formally issued and have been used as engineering design tool by the Exomars Rover Team, namely ROSEX TAPS v.I, ROSEX TAPS v.IIa and ROSEX TAPS v.IIb.
The main objective of ROSEX TAPS during the Design Phase has been and is to:

- provide System Budgets VS Ops (i.e. provide an estimation of the Time, Power and Data generated by the execution of a specific Activity Plan in open loop)
- provide a feasibility assessment of the operations required by the mission VS the boundary environmental conditions defined by the ESA Environmental Spec (i.e. closed loop simulation of the logical sequence of Activity Plans)
- support trade-offs, RFW/NCR evaluation, CR processing (i.e. provide a simple-to-change simulation platform to change resources associated to States)
- provide 3D simulation in support to reviews to ease ops understanding

ROSEX TAPS v.IIa has been used to support the Exomars System PDR. Results can be found in [SIMRES].

***Aknowledgement**: this work has been done and the paper has been prepared with our TAS-I colleagues Andrea Merlo, Chiara Legnani and Gian-Paolo Zoppo; purely administrative reasons prevented us to include them as co-authors of this paper.*



NEW TASI MODEL - Nominal OD

Earth Date	Sol	LS	OD	Dust Degradation [%]	Shadowing [%]	Latitude: 5	Aram Dorsum 7.87	10	Oxia Planum 18.2	Mawrth Vallis 22.25	25
19/03/2021	0	19	0.65	0.0	10	1668	1683	1680	1670	1654	1639
17/04/2021	28	33	0.5	8.4	10	1504	1529	1541	1568	1566	1561
24/05/2021	65	50	0.5	19.5	10	1271	1305	1326	1377	1393	1399
30/06/2021	101	66	0.5	30.0	10	1067	1102	1121	1188	1210	1221
06/08/2021	137	82	0.5	31.1	10	1037	1072	1098	1174	1200	1217
12/09/2021	173	99	0.5	32.2	10	1040	1076	1099	1175	1203	1214
28/10/2021	218	120	0.5	33.5	10	1083	1114	1137	1195	1215	1223
					Daily Generation avg. [Wh]	1197	1228	1248	1303	1320	1327

Figure 12. ROSEX TAPS Output – Energy Generation

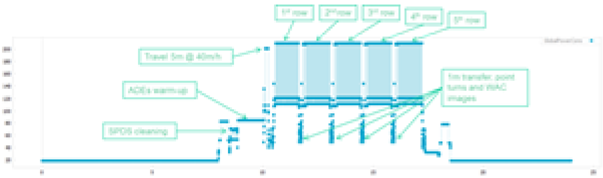


Figure 13. ROSEX TAPS Output – Power Consumption profile

Figure 14. ROSEX TAPS Output – WSD Grid image

Sol	Typ	Peak Power w/o 20% System Margin [W]	Ops Duration excluding Comms [hh:mm]	Global Energy w/o 20% System Margin [Wh]	Global Data Gen w/o 20% System Margin [Mbit]	Description
MC#1	Typ #1	87.2	02:28:34	710.3	74.3	Survey-Panoramic images
MC#2	Typ #2	199.0	04:47:13	944.4	53.7	Site Survey-outcrop approach and outcrop survey
MC #3	Typ #3	196.4	04:52:08	767.8	117.9	Site Survey-outcrop target approach and survey
MC #4	Typ #4	202.5	04:53:20	894.3	114.4	SM-Drilling site approach and surface sample acquisition
MC #5	Typ #5	100.1	05:54:45	997.3	214.3	SM- First sol of ALD analysis: MICR and RLS
MC #6	Typ #6	142.1	02:23:42	832.8	28.8	SM- Second sol of ALD analysis: MOMA LD-MS Broad Survey
MC #7	Typ #7	150.0	04:01:56	938.3	152.5	SM- Third sol of ALD analysis: MOMA GC-MS plus 6 WAC Stereo Images
MC #8	Typ #8	227.3	05:46:47	1067.4	63.0	DM drilling region approach and first sol of drilling region mapping
MC #9	Typ #9	241.9	04:41:56	1005.1	62.8	DM second sol of drilling region mapping
MC #10	Typ #10	234.2	09:09:06	1239.6	108.8	DM drilling site approach and first sol of drilling plus 10 WAC Stereo images
MC #11	Typ #11	108.3	09:12:08	1256.8	75.6	DM second sol of drilling
MC #12	Typ #12	115.1	14:05:23	1587.8	92.3	DM third sol of drilling and sub-surface sample acquisition
MC #13	Typ #5	100.1	05:54:45	997.3	214.3	DM- First sol of ALD analysis: MICR and RLS
MC #14	Typ #6	142.1	02:23:42	832.8	28.8	DM- Second sol of ALD analysis: MOMA LD-MS Broad Survey
MC #15	Typ #13	142.1	02:24:22	833.6	32.3	DM- Third sol of ALD analysis: MOMA LD-MS Detailed Analysis
MC #16	Typ #14	150.0	03:09:47	911.0	125.0	DM- Fourth sol of ALD analysis: MOMA GC-MS
MC #17	Typ #15	69.6	00:41:27	636.4	9.6	Refillable Container and Dosing Station unloading

Figure 15. ROSEX TAPS Output – Resources Consumption Summary

6. FUTURE WORK

ROSEX TAPS is in the process of being updated to version v.IIc, in support to the incoming Exomars System CDR. This is going to be the last version fully demanded to engineering design support, since the future version (III and IV) will be formally integrated in the ROCS SW environment.

7. REFERENCES

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