The Mission Simulator of COSMO-SkyMed di Seconda Generazione: a valuable tool supporting the Developing, Verification and Operational Phases of the Programme

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ABSTRACT

COSMO-SkyMed is the Italian end-to-end satellite system for Earth observation, conceived by Italian Space Agency (ASI) and Italian Ministry of Defence (It-MoD) for both a civilian and a defence use. The first generation constellation (CSK) is composed of four high resolution X-band SAR (Synthetic Aperture Radar) satellites, launched from 2007 to 2010. A constellation of new generation, known as *COSMO-SkyMed di Seconda Generazione* (CSG), composed of two satellites, is now being developed aimed at ensuring operational continuity to the currently operating first generation and achieving a step ahead in terms of functionalities and performances. In the frame of CSG Programme, a system tool devoted to the end-to-end system modeling and simulation has been developed: the CSG Mission Simulator (CSG-MS). The CSG-MS is a SW application that replicates the CSK and CSG missions behavior in response to a given scenario. The main CSG-MS inputs are the system configuration, in terms of number of satellites, their characteristics and orbits, SAR beams, number of ground stations, their location, band and characteristics and finally the users requests handbook, i.e. all the information related to the target acquisitions requested by the users. The main output of the CSG-MS is the Mission Plan, containing details about the requests satisfaction, related statistics and a detailed execution log. Another important feature of CSG-MS is the capability to model the key performance aspects of the mission, such as system response time, user request satisfaction, resource usage profiles and loads. Thanks to the capabilities offered by the CSG-MS, an extensive usage of the tool has already been done during the developing phase of the CSG Programme. The tool has been used to verify, by analysis, time performances requirements imposed to the mission, confirming the achievement of the required revisit time, information age and response time. Moreover, considering the massive improvements made in the CSG Mission Planner and Harmonizer with respect to the CSK's one, the CSG-MS has been used to evaluate and confirm the effectiveness of these enhancements in a realistic operative scenario. In addition, the MS has been extremely useful in characterizing the benefits arising from the introduction of an additional acquisition mode (DI2S multi swath) in terms of reduced number of conflicts among requests. Further simulation campaigns will also be run to analyze and tune the Planner configuration parameters and the CSG mission

programming rights sharing policy. Thanks to the flexibility and the configurability of all the simulated subsystems, an extensive use of the MS is expected during all the CSG lifetime as well. Indeed, the CSG-MS can be fully representative of the real deployed system, thus allowing to simulate the system behavior both in a nominal condition and in a possible failure condition.

INTRODUCTION

COSMO-SkyMed di Seconda Generazione (CSG) is the follow-on mission of COSMO-SkyMed first generation (CSK), aimed to provide operational continuity to CSK, with increased performance, flexibility and capability to respond to updated civilian and defence user needs [1]. The programme has been commissioned and funded by the Italian Space Agency (ASI) and the Italian Ministry of Defence (It-MoD) and thus conceived for a dual use (civilian and defence). The first generation constellation, based on four satellites, has been fully deployed since 2010 and the second generation, based on two additional satellites, is currently facing the Mission Critical Design Review. CSG is designed to introduce both technological and architectural improvements to the system, to enhance the operational aspects and the user services portfolio. CSG primary mission objective is to promptly and effectively satisfy the heterogeneous user needs (institutional, scientific and commercial purposes) providing the Users with several end-to-end services, ranging from a new SAR image acquisition to image processing and distribution.

The CSG Space Segment (SS) is composed of two satellites, embarking a brand-new design of the SAR instrument, capable to reach space resolution of the “narrow field images” finer than CSK, while providing multi-polarization. The renewed Payload Data Handling and Transmission system (PDHT) shows improved performances in terms of on-board data storage capacity, space-to-ground data transmission throughput and data reception rate from SAR. Finally, the CSG SS will also achieve the capability to serve more products in a specified area by a state-of-the-art exploitation of both instrument and platform agility.

The CSG Ground Segment (GS) is based on a multi-center and dual use architecture geographically distributed over a wide scale, including Fucino (S-band station), Matera (X-band station), Pratica di Mare (X-band station) and the foreign stations of Cordoba and Kiruna (X- and S-band stations). Significant upgrade to the GS have been done for managing a System with such an increased performance (i.e. rank based planner algorithm, definition of asynchronous requests, fairness criteria for resources sharing), for ensuring the full architectural integration between the first and the second generation and for implementing an increased interoperability, expandability and multi-sensors capabilities.

The need to model and simulate the functional characteristics and the performances of such a complex dual system raised from the very beginning of the program. For this reason, the customers ASI and It-Mod asked for a tool capable to simulate the system, in order to support the activity related to the international cooperation, to evaluate the effectiveness of the architectural design solutions with the aim of answering the user requirements, and to help in identifying possible strategies of resource sharing between civilian and defence users. The industrial team exploits such a tool as well, to support calibration and validation activities, generating feasible scenarios for Commissioning and Operative Phases. Since no conventional SW tool, such as the System Tool Kit or equivalent COTS was able to provide all the required features due to the complexity of the system, a dedicated tool has been developed in the framework of the CSG program.

MISSION SIMULATOR DESCRIPTION

The CSG Mission Simulator (CSG-MS) development activities have the main objective to deliver a mission specific tool, capable to simulate the innovative characteristics introduced by the CSG Mission both at GS and SS level, maintaining, at the same time, the ability to simulate the technical and performance behavior of the first generation CSK [2]. In the frame of the first generation mission, the MS is still being used for constellation maintenance and control, allowing to simulate specific acquisition scenarios.

CSG-MS is a SW application capable to replicate the end-to-end mission behavior in response to a given scenario composed of a mission configuration (at SS and GS levels) and a specific user requests handbook. Accordingly, CSG-MS is a comprehensive set of powerful software elements, each one devoted to represent and simulate some specific tasks, functionally and logically interrelated according to the real CSG System architectural design. The main CSG-MS inputs are the system configuration, in terms of number of satellites, their characteristics and orbit, number of ground stations, their location, band and characteristics and finally the user requests handbook, containing all the information related to the target acquisitions desired by the system users. One of the main outputs of the CSG-MS is represented by the achievable acquisition performance, the Mission Plan, containing details about the request satisfaction, related statistics and a detailed execution log. Indeed, one important feature of CSG-MS is the ability to model all the performance aspects of the mission, such as system response time, user request satisfaction, resource usage profiles and loads.

The CSG-MS is characterized by a high hardware and software portability, with an excellent automation level and user-friendly graphical functionality. Databases capabilities are exploited to configure satellites, platforms, subsystems and payloads. A 7th-8th order Runge-Kutta differential integrator is used to propagate satellites trajectories, setting the desired dynamical models.

The main CSG-MS tools, better described in the following sections, are:

- Flight Dynamics Simulator,
- System and Mission configuration;
- Access Computation (Target and GS);
- Planner;
- System simulator;
- Data analyzer;
- Time performance;
- Tool For Coverage.

Flight Dynamics Simulator

The Flight Dynamics module is mainly devoted to the propagation of satellites ephemeris over the selected time windows. The ephemerides database generated is an essential input for several functionalities of the CSG-MS, as for example, the computation of all the possible access times and geometries to the targets (Data Take Opportunities, DTOs, of the user requests) and the computation of satellite visibility times over a given ground station. All these computed “opportunities” will be automatically stored in proper databases, which will be then accessed by the planner.

The Flight Dynamics module allows also to generate some reports, as satellite eclipse times and nodal passes.

A dedicated window allows the user to select the dynamical models considered in the orbit propagation (gravity field harmonics, atmospheric drag, solar radiation pressure, etc.) and to set some integration parameters (i.e. integration step).

System and Mission Configuration

The System can be configured in terms of:

- SS subsystems (Payloads, AOCS, TMTC, Power, BUS) parameters
- GS resources (Down/Up-link stations, User Ground Segments and Network) parameters
- User characteristics
- Planning settings

Different configurations can be saved in dedicated databases for each resource and subsystem.

At SS level several platforms can be configured combining different subsystems and finally, for each simulated satellite, the operator may associate a saved platform. This approach allows the user to save subsystems parameters related to the current design configuration, experimental configurations or real contingencies configurations.

The mission configuration involves the setting of the mission time window, the selection of the SS and the GS scenario and the preparation of the User Requests’ Handbook that consists in inserting the users and their acquisition requests.

Access Computation

Once the satellites ephemerides have been computed, Requests Handbook has been submitted and GS scenario has been configured, DTOs computation and GS visibility can be carried out. Specific databases will store the information computed and will be exploited by the Mission Planner.

It is important to note that the accesses computation algorithm will exploit an instance of the SAR PARameters Calculator (SPARC) tool, identical to the one deployed in the CSG real operative chain. SPARC allows to refine the DTO and to estimate the SAR Payload programming parameters, taking into account the real geometric topography of the scene to be acquired and the real satellite orbit altitude, leading to an optimization of the image quality features.

Planner

The mission planning execution is the function in charge of generating a feasible, conflict free mission plan, i.e. the exact chronological sequence of tasks that every space and ground subsystem has to perform in order to satisfy the mission objectives and user requests in the time window under analysis. In doing this, the planner function uses the data evaluated by the flight dynamics module and the access computation.

The Check Constraints function performs the feasibility of the requests against predicted orbits and system characteristics and resources of the CSG constellation considering:

- power and thermal constraints established for satellite platform and payloads;
- imaging operations and data download operations compatibility with the available onboard memory resources and ground station availability and visibility;
- maneuvering operations;
- conflicts for satellite activities overlapping;
- user quota limit usage.

A Harmonization function takes in input different requests lists of each Partner and automatically selects, iteratively, the next request to be submitted to the Planner function according to the rank value (i.e. priority index) of each request and the relevant Partner parameters.

The Planner uses a rank-based algorithm for prioritized requests and an optimization-based algorithm for unranked requests. Both algorithms satisfy the User needs (i.e. Requests) optimizing at the same time the system resources usage. Please note that the rank-based algorithm is based on a User Requests rank approach. That is, every time that a new request is processed by the Planner; it is performed a complete efficient search of a possible solution (i.e. try the different combination of DTOs of the previous requests) before eventually reject that new request. The core algorithm for this efficient search is based on the Conflict-Directed Backjumping (CDBJ) algorithm [4].

Finally, a Scheduler function translates the plan in a sequence of “events”, each one representing an elementary task for a given space and ground subsystem. Indeed, the resulting mission plan is stored in a dedicated DB and compiled to yield a command schedule to be submitted to the System Simulator.

System Simulator

The mission plan, in the form of a time-ordered list of tasks (events) to be performed by the space and ground systems, is the input to the System Simulator, that is in charge of decoding this list and forwarding the events to the involved systems. The System Simulator tool is devoted to simulate all the different satellite operational tasks considering the battery power charge status, memory load, attitude, on-board Telecommand load, on-board Telemetry load and profile, PDHT data rate, SAR payload Temperature and Data Rate, Ground Station loads. Also, the MS engine generates the complete execution log files and all information of importance in assessing the real capabilities and performances of *COSMO-SkyMed di Seconda Generazione*. Results are very helpful in the resource sizing or verification process of space and ground subsystems.

Data Analyzer

The Data Analyzer is composed of a set of tools which allow the operator to get a quick and fast access to most of the data generated by the various simulator functions. Several data can be shown on WorldMap:

- Location of targets and ground stations
- Satellites ground tracks, with the possibility to highlight ground stations visibility circles

- Feasibility analysis results in terms of target acquisition geometry and related parameters

The Mission Plan can be shown by a Gantt diagram, in which every single task of satellites is represented by a colored bar defined by its start and stop time (i.e. eclipse periods, maneuver duration, acquisition time, download period).

Time Performance

The Time Performance tool allows the operator to evaluate time performances of selected satellites over an area of interest and visualize related color maps and statistics. The performances evaluation can be realized by setting the area of interest, maximum and minimum incidence angle, operative mode and side looking. The results of time performances estimation are accessible to the user by means of color maps (maximum, minimum and average), as well as statistics reports and graphs of the following figures of merit:

- Revisit Time, that is the time elapsed between subsequent observations of the same point on Earth,
- Response Time, that is the time interval between request deposit and product delivery,
- Information Age, that is the time interval between data take acquisition and product delivery.

It is worth to note that the CSG-MS can also compute the Minimum, Maximum and Average Time Performances for the constellation that integrates both CSK and CSG satellites.

Tool For Coverage

A dedicated area coverage planning algorithm is implemented in a user-friendly tool inside the CSG Mission Simulator Tool For Coverage (TFC). TFC allows to obtain the optimal acquisitions list that satisfies the total coverage of a particular area selected by the user. It exploits both the Flight Dynamics Simulator and the Access Computation function of the Mission Simulator. TFC offers the best compromise between computation time and optimal solution providing an acquisition plan schedulable by real mission and practical kml files to navigate into the solution.

USE OF THE MISSION SIMULATOR

Considering the maturity of the CSG-MS and its capability to simulate the end-to-end behavior of the System, an extensive use of the tool has already been done. In the following sections, an overview of the use that has been made of the CSG-MS and of the future planned activities are provided.

Time performances analysis

The first application of the CSG-MS concerns the verification of the requirements of time performances for the CSG system. At this aim, the simulation time has been carried out along a CSG orbital repeat cycle, lying CSG in a Sun-synchronous repeating ground track orbit. The following GS scenario has been set, according to the actual GS configuration:

- User Ground Segments: Matera (Civilian Users) and Pratica di Mare (Defence Users);
- X-band stations: Matera, Pratica di Mare, Kiruna, Cordoba;
- S-band stations: Fucino, Kiruna, Cordoba.

To evaluate the time performances, the CSG-MS requires the definition of a grid of requests distributed in space and time, the setting of the minimum and maximum incidence angle, the SAR looking mode and the setting of the CSG chronology parameters, such as, for example, the duration of the feasibility, ranking and harmonization phases.

The figure below shows an example of colorimetric map, reporting the CSG average revisit time in the world map, considering a relative anomaly between the satellites of 180°. The analyses showed that all the time performance requirements are met and the relevant budgets have been properly allocated.

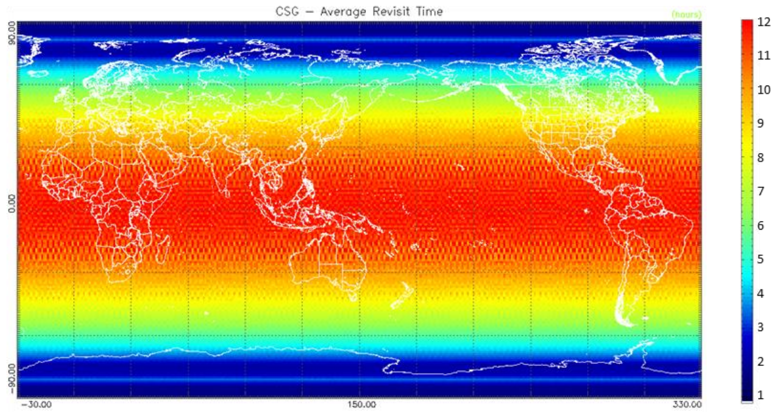

Fig.2: CSG constellation average revisit time (hours)

Afterwards, another time performances analysis has been conducted for the CSG System, with the aim of investigating different orbital configurations, in terms of relative phasing between the satellites. Indeed, different phasing corresponds to different interferometric configurations and, considering the importance of the interferometric applications for the CSG Users, an analysis has been performed to help in selecting the best configurations considering together both interferometric and time performance needs. Several orbital configurations have been evaluated. The analysis results have been recapped in colorimetric maps and summarizing tables to find out the best possible configuration. The results showed that the unique compliant configurations are those having satellite phasing equal to 180°, 157.5° and 135°, whereas all the others have a revisit time greater that the required value, even if the performances are better in terms of response time (phasing of 112.5° and 90°). If relaxing CSG Mission Requirement on Revisit Time (increasing of 2,4%), the Orbit Configurations with a phasing of 90° and 112.5° give a remarkable improvement in terms of Response Time.

This analysis will be extremely useful to select the orbital configuration that best fits the Users needs in terms of interferometric applications, being at the same time compliant to the time performance requirements.

Evaluation of the effectiveness of mission planning improvements

Several significant improvements have been made, with respect to the first generation, in the CSG Mission Planner and in the subsystem devoted to the Harmonization of the Acquisition Requests coming from the large and heterogeneous community of Users. The main drivers of the renewed design were:

- the increase of the user request satisfaction;
- the strengthening of the priority concept linked to the Acquisition Requests;
- the increase of the fairness of the System, with the aim of ensuring that, in a reference time window, at least the most important Acquisition requests of a Partner having low access rights are planned.

For more details about the architectural design, see [3].

During the development phase, an extensive simulation campaign has been carried out with the CSG-MS to assess the effectiveness of the improvements designed. Eight days of mission have been simulated, considering four international partners having different System access rights. The analyses showed that:

- for all the partners, 100% of the rank 1 Acquisition Request were planned;
- the percentage of satisfied Acquisition Requests of each Partner is fair, considering also the access rights of the partner;
- the simulated mission plan is capable to fully exploit the programming rights of each partner, meaning that each partner will be satisfied due to the exploitation of all his available System resources;
- the constraints imposed to the System are correctly implemented in the Mission Planner and the Mission Plan is consistent with all the System constraints.

DI2S Spotlight effects

The MS has been extremely useful in characterizing the benefits arising from the introduction of an additional acquisition mode in terms of reduced number of conflicts among requests. The new acquisition mode, known as DI2S (Discrete Stepped Strip) Spotlight Multi Swath, allows to achieve a couple of images simultaneously picked up, increasing the number of acquirable images on a given area otherwise not feasible for time gap violation [5]. In particular, DI2S Multi-Swath Spotlight solution can provide two images with the same azimuth position or two images shifted (but still overlapped) in azimuth or two images with same range shifted in azimuth (but still violating the time gap constraints of standard Spotlight modes). The DI2S is based on performing two almost simultaneous (half a Pulse Repetition Interval apart) acquisitions, which can be used to imagine two different sites (in Spotlight or Stripmap mode) or to improve the resolution of a Stripmap acquisition. Two DI2S Spotlight Multi-Swath acquisition modes have been foreseen in CSG: the DI2S Spotlight 1 Multi-Swath and the DI2S Spotlight 2 Multi-Swath.

A preliminary simulation campaign has been conducted by means of the CSG-MS to investigate the effects of the introduction of the DI2S Spotlight Multi-Swath mode on the final mission plan. Indeed, when executing the planning function, in case a conflict arises between two requests and before the final rejection of one of the two requests, the DI2S algorithm tries to couple the requests, solving their conflict. The DI2S algorithm, efficiently embedded in the MS Planner, has to verify the following constraints:

- requests and DTOs characteristics compatibility (e.g. sat, looking side, SAR mode, etc);
- SAR payload constraints;
- Temporal and system constraints with the rest of the plan.

The DI2S algorithm implementation, when activated in the CSG MS, showed always an improvement in the de-conflicting capability. In particular, in the simulated scenario, it has been observed an amount of DTOs taken with DI2S corresponding to the 10-20% of the total DTOs in the final mission plan, meaning that 10-20% of conflicts have been resolved, significantly increasing the satisfaction percentage of the users.

"MapItaly" coverage comparison

The "MapItaly" project, originally born in 2009, has been developed by ASI and the Department of Civil Protection, with the support of e-GEOS. The purpose of the project is to provide an interferometric mapping of the entire Italian territory with the StripMap HIMAGE (HH polarization) mode of the COSMO-SkyMed constellation, both in Ascending Right and in Descending Right passes. In order to test the Tool For Coverage capabilities of the CSG-MS, a comparison of the solutions found by the TFC with respect the "MapItaly" project was carried out. Given the constraints imposed on system parameters and beams usage, the TFC solution complete the coverage in 16 days like in the "MapItaly" project. Moreover, the scheduling obtained in the TFC simulation is equivalent to the "MapItaly" one. The following images show the overlay of both solutions, the small differences are due to slightly different area borders definition or selection of a same beam over the area by a different satellite (case of interferometric satellite pass in a different day).

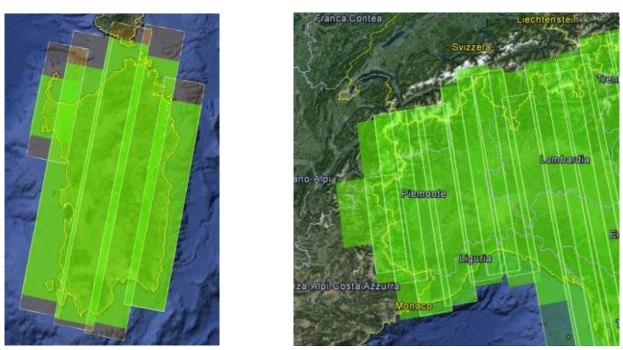

Fig. 3: Overlay of Mission Simulator TFC solution and current "MapItaly" project.

With the aim of designing the prosecution of the MapItaly project with the CSG satellites, a simulation has been performed imposing as constraint the use of the same current MapItaly beams for the two CSG satellites. The analyses showed that, using only the two CSG satellites, 32 days are needed to complete the ascending and descending coverage foreseen by the MapItaly project.

Future exploitation of the CSG-MS

In addition to the usage of the CSG-MS that has already been done, many other activities are foreseen in the future CSG Programme phases. First of all, an additional simulation campaign will be run to properly set the parameters that allow to perform the pre-ranking of the Acquisition Requests. Indeed, the algorithm devoted to sort the Acquisition Requests is quite complex, taking into account a variety of contributors, each of them expressed by a mathematical function with some tunable parameters. Such parameters should be properly set to combine together all the needs underlying each contributor; however, the high number of parameters to simultaneously consider makes this activity extremely complex if not supported by a simulation tool. The CSG-MS will answer this request, allowing to simulate many different scenarios, each of them characterized by a different set of parameters values, enabling the capability to quickly assess the effects of these parameters values on the final mission plan.

In general the MS represent a strategic tool to show the CSG System behaviors to potential new Partners, allowing to simulate how the Planning functionality can manage complex Scenarios fulfilling exigencies of different Users.

Thanks to SPARC tool exploitation, the feasibility and planning analysis performed by MS is fully aligned to the System that will be deployed. This advantage will be exploited during Commissioning activities, designing at the best all scenarios useful to both system requirements verification and calibration processes.

CONCLUSIONS

This paper provides a description of the Mission Simulator, designed and developed in the frame of the *COSMO-SkyMed di Seconda Generazione* Programme. An overview of the usage of this tool up to now and a forecast of the activities for the next phases of the Programme have been also presented. The main past, present and future simulation campaigns are relevant to the time performance analysis, the evaluation of the Mission Planner design improvements, the characterization of the benefits arising from the introduction of an additional acquisition mode. It’s worth to notice that the CSG-MS represents also a useful tool to perform the cross-validation between the Mission Planner and the planning algorithms implemented in the simulator itself. Moreover, thanks to the high configuration flexibility, all the simulations can be performed considering the actual sub-system status, being fully representative of the end-to-end system.

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