desEO – DESIGN ENGINEERING SUITE FOR EARTH OBSERVATION

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ABSTRACT

desEO (Design Engineering Suite for Earth Observation) is a software toolkit to support mission analysis and preliminary system/subsystem design activities of Earth Observation (EO) missions.

desEO has been designed to be used by mission and system engineers throughout all phases of an EO mission (from Phase 0 to Phase E), whenever they need accurate and fast quantitative results to support design trade-offs and assessment analyses.

desEO has been designed to be a modular, flexible and self-standing application, to provide the user with a comprehensive set of mission-related and system-related computation modules and with visualization capabilities to yield meaningful numerical and graphical results.

desEO has been conceived as a tool in continuous evolution, suitable to be upgraded with further modules and capable to be interfaced with external software.

desEO currently embeds more than forty different modules in a Graphical User Interface (GUI), an EO mission data repository and a result visualization module (3D interactive visualisations, Gantt charts, Cartesian plots, cartographic maps representations and tables).

1. INTRODUCTION

The commercial market and the European Space Agency (ESA) offer a wide set of tools and libraries in order to help the space engineers in their everyday work, in both fields of mission and system analyses for EO missions. Nevertheless, none of the available tools merges together all and only those capabilities necessary for accomplishing the above-mentioned task.

The natural consequence for a user is the burden of dealing with a large set of different software tools, often supported by external post-processing instruments, and with clear drawbacks in terms of interface compatibility.

desEO is a DEIMOS (DMS) software toolkit, developed under an ESA contract, aimed at providing a unique instrument for supporting the work of system and mission analysts.

The underlying idea of desEO is to ease the user experience in its work, focusing the software design on the specific tasks it has been conceived for.

desEO thus collects more than 17 years of experience in system and mission analysis for EO missions, gathering in one tool the best practices consolidated in more than 30 mission studies, covering from Phases 0 to Phases D.

The objective of this paper is to describe the toolkit, both in terms of its capabilities and its field of applicability.

2. TOOLKIT HERITAGE

Mission and system analysis are continuously evolving disciplines, strictly connected with the technical evolution of the EO missions concepts.

In these disciplines a key asset is the analyst expertise: the expert shall be able to dynamically interpret new requirements and propose a feasible solution through effective analysis approaches.

A very solid background of analyses in those fields allowed the experts to define best practices and optimal approaches to face a large number of recurrent problems.

desEO is thus born as a software tool that aims at implementing all those best practices, in order to provide the analyst with assessment and design means tailored on the basis of his/her specific needs.

In order to consider this expertise in the user requirements definition, a comprehensive analysis of the DEIMOS analysts' know-how matured in more than 17 years of excellence in the EO mission analysis has been carried out. The result has been an exhaustive knowledge map that, opportunely filtered, has brought to the fore the impact and criticality level of more than one hundred possible analyses that could be executed in the fields of system and mission analysis. An attentive down-selection of all the possible analyses that could have been implemented in desEO led to the selection of the currently implemented capabilities. The main criterion for this selection has been creating a tool able to cover the most common and recurrent analyses that system and mission analysts deal with in their activities designing, developing and supporting EO missions.

Beside the above-mentioned inheritances converged in desEO, there is another extremely important component that defines the backbone of the toolkit. In fact, desEO collects the methodologies and algorithms retrieved from multiple DMS internal tools, the so-called "EO Mission Analysis and Simulation Suite". It represents a key added value for desEO: those methods and algorithms represent in fact the state-of-the-art expertise in the mission analysis field and at the same time they are very robust, since they have been applied and tested in a large number of analyses and in a wide spectrum of EO missions.

Moreover, desEO has been developed keeping in mind that the scope of mission analysis widens constantly at each new mission, therefore it cannot cover future needs that cannot be foreseen. In order to be an asset and not a bottleneck for future analyses, it has been designed to provide easy and flexible interfaces in order to be easily extended or integrated into a scripting environment and to be used as building blocks for fast prototyping and complex post-processing.

3. SOFTWARE ARCHITECTURE

desEO has been developed following the principles of flexibility and modularity, in order to guarantee reduced maintenance and upgrading efforts.

Moreover, since desEO inherited already robust algorithms from a heterogeneous set of different tools, a comprehensive work of re-engineering has been conducted in order to allocate a large number of different analysis concepts seamlessly in a unique but modular architecture.

The overall architecture has been designed in order to identify clear interfaces, both between analysis modules and GUI and among the modules themselves.

The design approach has been based on an Object-Oriented (OO) methodology, supported by the Unified Modelling Language (UML).

For the interfaces definitions, an extended use of XML Schema Documents (XSD) has been done, making their modifications very agile.

The result has been a very flexible infrastructure, able to integrate in a unique paradigm a large number of different analyses, thus enabling an easy extension of the tool capabilities and, hence, being prone to future improvements and enhancements.

As depicted in Fig.1, the user can operate desEO both via a GUI and also via command line. Moreover, the analysis modules are integrated in the overall high-level architecture by means of well-defined interfaces, so that they can be extended (both in number and functionalities) with a plug-and-play approach.

The analysis modules have been coded in standard C++, while the GUI is based on Eclipse RCP. The file interfaces are either XML ASCII files (following XSDs) or NetCDF binary files.

desEO has been developed for Mac and Windows platforms, and its functionality has been already tested in Linux Operating System (OS).

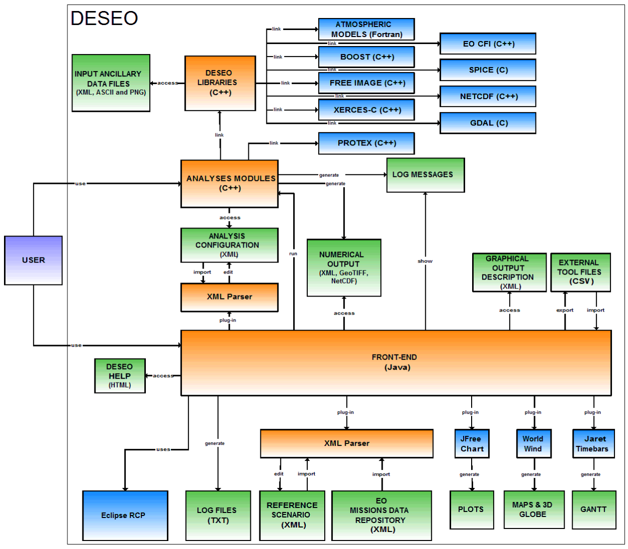

Figure 1. High-Level System Decomposition

4. ANALYSIS CAPABILITIES

desEO provides the mission and system analyst with a wide set of assessment and design tools, which span from complex simulation-based computations to fast auxiliary analytical models.

The different analysis modules embedded in the toolkit are intended to yield a powerful instrument for the analysis processes, as well as to support the analyst work by means of fast and precise computations.

The following sub-sections briefly outline the desEO analysis capabilities.

4.1. Orbit Propagation

desEO implements several propagation methods, which can be used as standalone analyses or as backbone for all those analyses that foresee orbit propagation. Moreover, the propagators can be used both for short-term propagations (e.g. for generating a reference orbit) and for long-term propagations (e.g. for studying the behaviour of a perturbed orbit). The available propagation methods encompass:

- **Numerical propagation**, aimed at short-term precise propagations (Fig. 2);
- **Semi-analytical propagation**, aimed both at short- and long-term propagations (Fig. 3);

Along with the orbit propagation methods, some other analyses relying on them are provided:

- **Attitude computation**, implementing different attitude laws (Fig. 4);
- **Atmospheric analysis**, computing atmospheric characteristics, using different atmospheric models (Fig. 5).

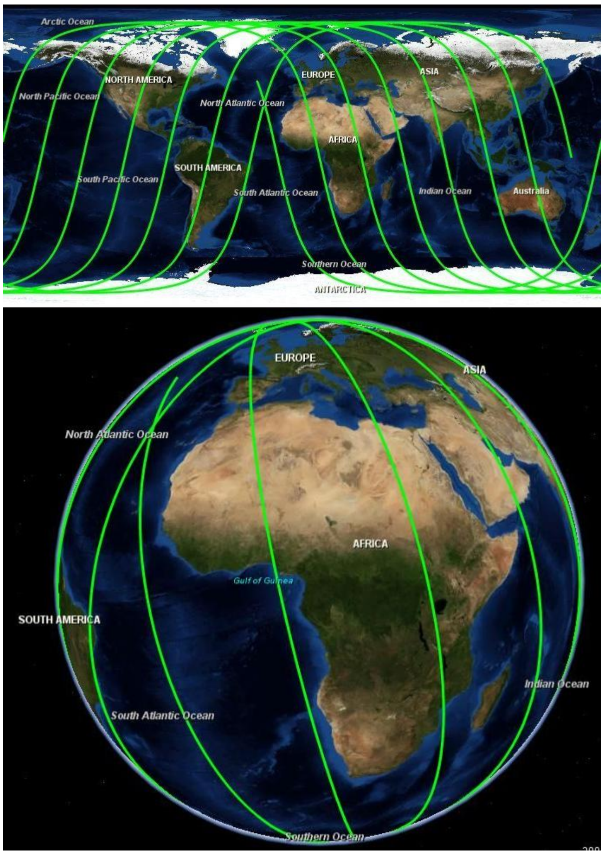

Figure 2. Propagated Orbit: Map Projection (above) and 3D View (below)

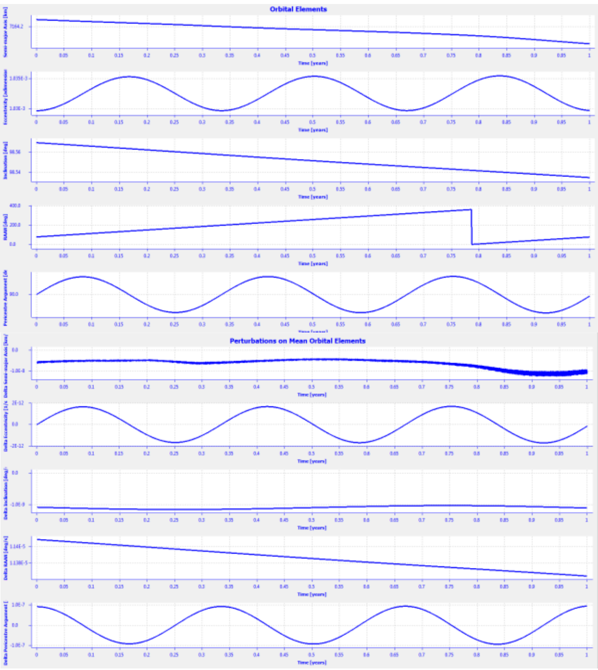

Figure 3. Propagated Mean Elements (above) and Relative Perturbations (below)

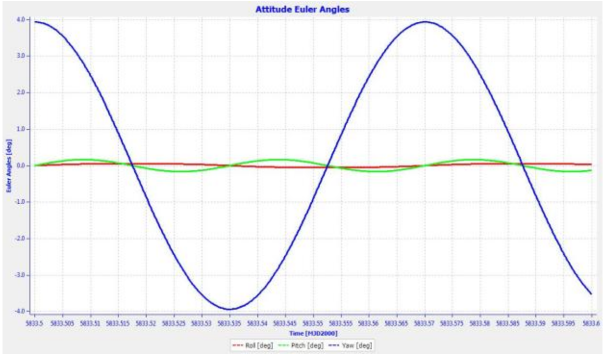

Figure 4. Attitude Computation

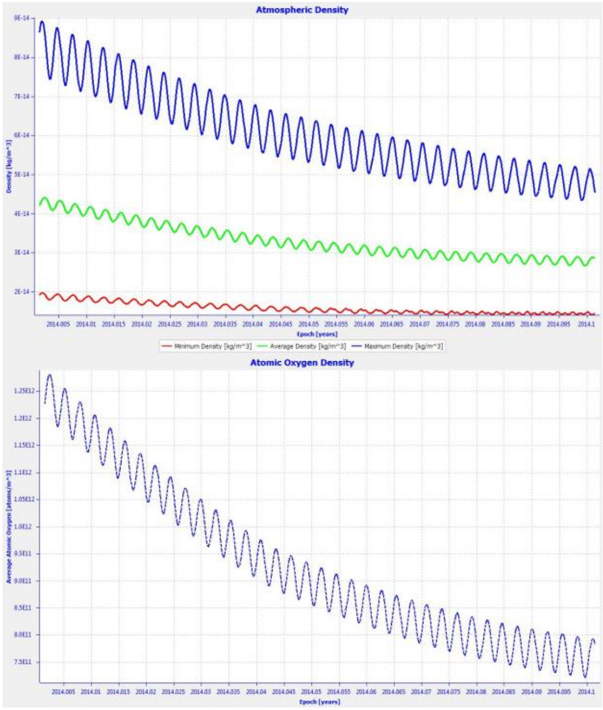

Figure 5. Atmospheric Density (above) and Atomic Oxygen Density (below)

4.2. Coverage Analyses

Based on short-term orbit propagation, desEO provides algorithms to compute information about the zones observed by a defined on-board payload (P/L). The coverage analysis is highly customizable, both in terms of payload and maps definitions.

The instruments can be designed taking into account classical constraints, for e.g. optical and radar instruments (e.g. field of view, incidence angles/observation-zenith angles, sun-zenith angle, sun-glint, etc.).

The maps identifying the areas of interest for data acquisition can be thematic (e.g. terrain, water, ice) or polygonal maps.

Among the wide set of computed outputs, there are **revisit time** (Fig. 6), **coverage** and **P/L duty cycle**.

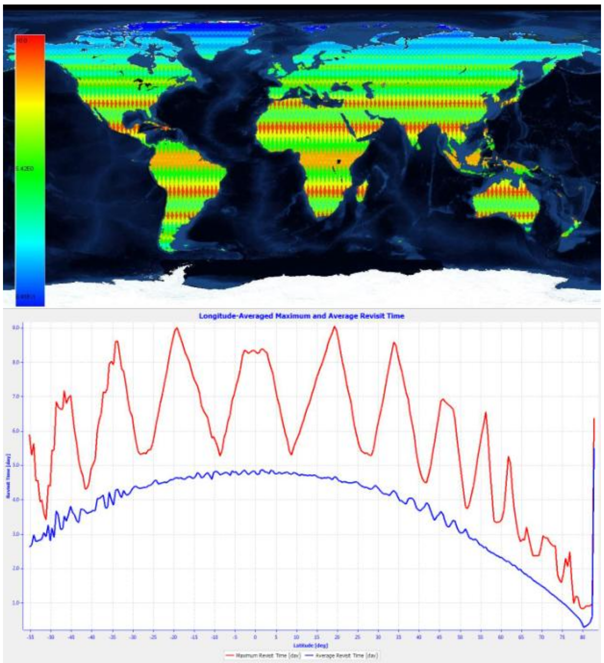

Figure 6. Revisit Time Map (above) and Revisit Time Longitude-Averaged Values (below)

4.3. Ground Station Contact Analyses

desEO provides a set of analyses focused on the relationship between the space and ground segments. It enables the computation of the visibility geometry and contact statistics of a spacecraft with respect to different ground stations. It is also possible to solve conflicts that arise when a spacecraft has contemporary access to multiple ground stations.

The timeliness analysis then provides a powerful instrument to compute the latency of acquired data, given a ground station (GS) network.

- **Ground station visibility**, computing the visibility intervals between S/Cs and GSs (Fig. 7 and Fig. 8);
- **Ground station conflicts**, solving possible ground station access conflicts (Fig. 7 and Fig. 8);
- **Timeliness analysis**, assessing the time from instrument data acquisition to their delivery as data product to the user segment interface (Fig. 9).

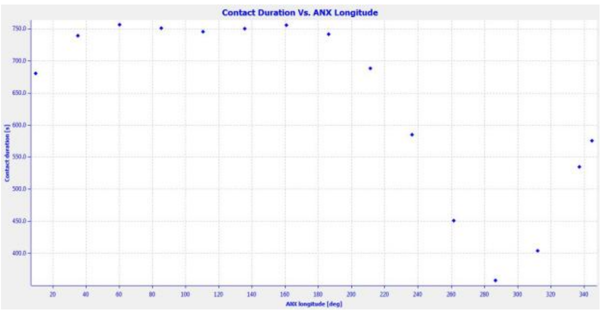

Figure 7. GS Contact Duration vs. Ascending Node Crossing Longitude

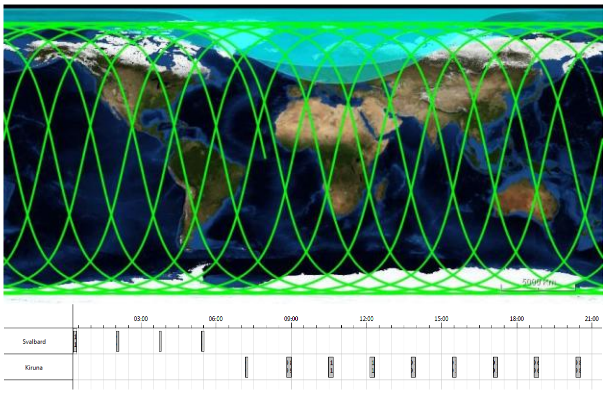

Figure 8. GS Visibility Map (above) and Contacts Gantt Chart (below)

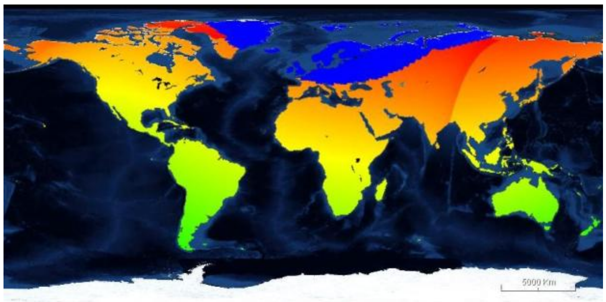

Figure 9. On-Board Data Latency Map

4.4. Orbit Control Analyses

A comprehensive set of analyses is dedicated to computing the ΔV and fuel necessary to maintain an orbit, given a control strategy. desEO provides several control laws, stand-alone or combined. It also implements an analytical formula for estimating the ΔV and fuel necessary to control a loose formation in a master-drone configuration.

The results of the Orbit Control analyses could be further used to compute the overall mission ΔV and fuel budget, along with other orbit manoeuvre contributions.

The set of orbit control analyses encompasses:

- **Altitude control** (Fig. 10)
- **Inclination control**
- **Equator ground track control**
- **Altitude and inclination control**
- **Equator ground track and inclination control**
- **Master-drone control**

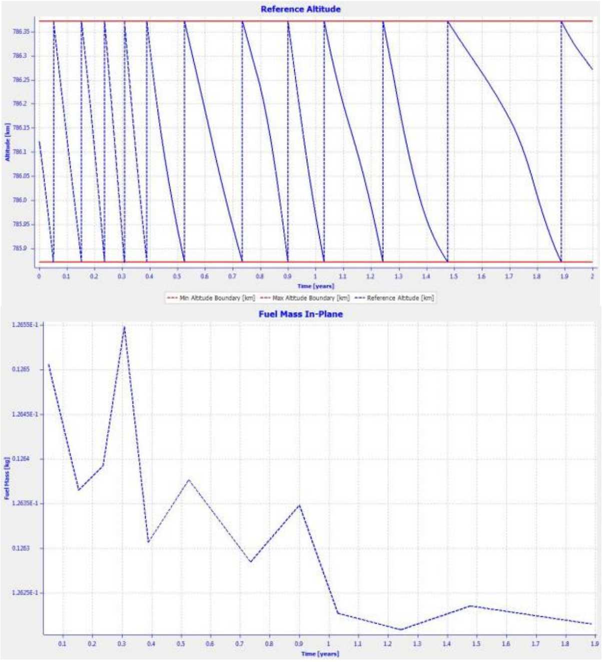

Figure 10. Altitude Control (above) and Firing Fuel Mass History (below)

4.5. Delta-V and Fuel Budget Analyses

This system analysis is aimed at providing the user with a powerful instrument for evaluating the overall mission ΔV and fuel budget.

- **Injection errors correction**, computes the ΔV for correcting launcher dispersion errors;
- **Collision avoidance**, computes the ΔV for the collision avoidance manoeuvres estimated over the mission lifetime (to avoid collisions with catalogued debris objects);
- **Orbit transfer**, computes the ΔV for possible orbit transfer manoeuvres;
- **End-of-life (EoL) decay analysis**, computes the ΔV for the EoL re-entry manoeuvre (Fig. 11). This analysis fully implements the ESA guidelines on ΔV and fuel budget calculation [1].

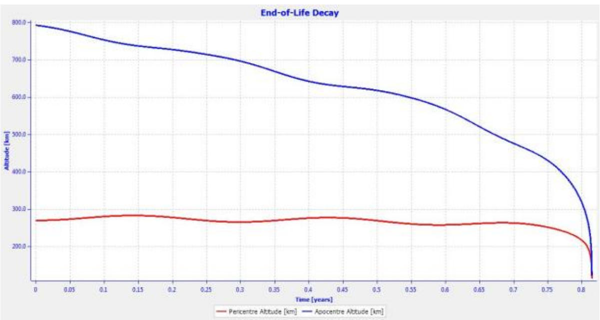

Figure 11: Apogee and Perigee Evolution during the EoL Uncontrolled Re-Entry Phase

4.6. Power Budget

The Power Budget analysis is a complex system analysis that can be exploited both for sizing the power subsystem (by means of a parametric approach) and for assessing S/C sub-system design.

This analysis takes into account the S/C attitude, the orientation of the solar panels (that can be fixed or with a degree of freedom) and a model of the losses both in terms of batteries and solar panels (Fig. 12).

Figure 12. Battery Status (above) and Power Fluxes (below)

4.7. Mass Memory Occupation Analysis

This system analysis couples the information conveyed by the payload duty cycle with the GS visibility contacts, generating the timeline of the on-board mass memory occupation (Fig. 13).

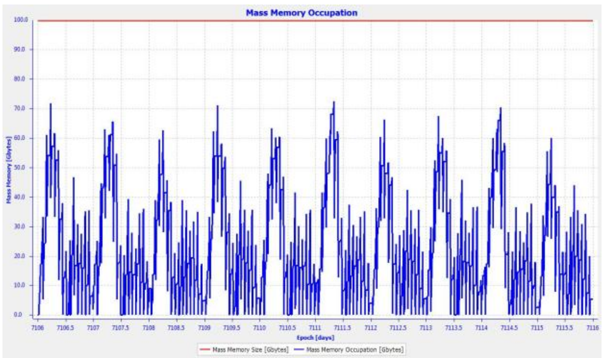

Figure 13. On-board Mass Memory Occupation

4.8. Orbit Selection

The Orbit Selection analyses embed a series of tools aimed at helping the mission analyst in identifying the candidate orbits for a specific mission.

- **Orbit wizard**, provides an orbit state vector based on high-level orbit definitions;
- **LEO selection**, provides a set of orbits given certain requirements, along with ancillary information for the reference orbit selection (Fig. 14);

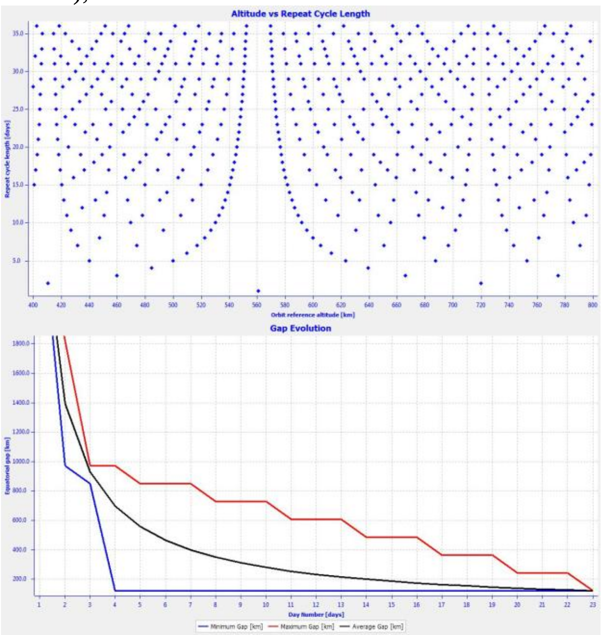

Figure 14. Altitude vs. Repeat Cycle Map (above) and Gap Evolution Graph (below)

- **SSO inclination**
- **Frozen eccentricity**
- **Right Ascension of Ascending Node (RAAN) drift rate**

4.9. Generic Geometric Analyses

The Generic Geometric Analyses collect a series of analyses providing geometric information about a space system.

- **Ground illumination**, provides a map or 3D view of the Earth illumination at a given epoch;
- **Time transformations**, implements transformations between different time reference frames;
- **Coordinates transformations**, implements transformations between different coordinate reference frames and coordinates systems;
- **Basic swath geometry**, computes geometrical information of a simple swath model;
- **Geodetic distance**, computes the geodetic distance between two points on ground;
- **Sun-zenith angle**, computes the sun-zenith angle within a swath generated by a space-borne sensor;
- **Observation-zenith angle**, computes the incidence angle within a swath generated by a space-borne sensor;
- **Swath computation**, computes the geometric characteristics of the swath generated by a space-borne sensor (Fig. 15);

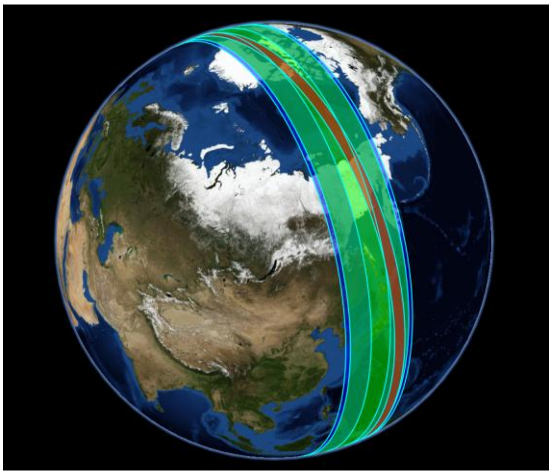

Figure 15. Swath 3D View

- **Pointing analysis**, performs parametric analyses, applying constraints on the orbit segments;
- **S/C topocentric coordinates**, visualises the spacecraft orbit in a topocentric coordinates system (Fig. 16);

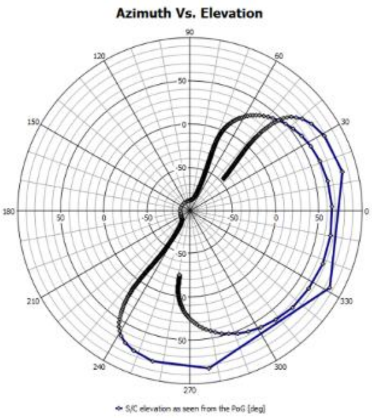

Figure 16. Azimuth-Elevation Polar Plot

- **Sun-synchronous beta angle**, computes the Sun β-angle during a year for a sun-synchronous orbit;
- **Sun-synchronous eclipse**, computes the eclipse durations during a year for a sun-synchronous orbit (Fig. 17).

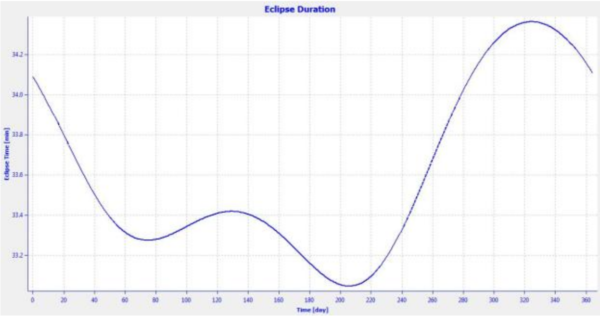

Figure 17. Eclipse Yearly Evolution

5. desEO SUCCESS CASES

5.1. Mission Analysis

As introduced in Section 2, one of the drivers in the desEO user requirements definition was creating a tool able to cover the most common and recurrent analyses a system and mission analyst encounters in his/her daily activity.

An opportunity to prove the applicability of desEO to a classical mission analysis study was provided by the role that DEIMOS covers in the Mission Analysis (MA) for EO: desEO developer and MA responsible of several Phase A/B1 studies, e.g. in the ESA Earth Explorers (EEs) programs, GMES, Copernicus Space Component Expansions and other mission and system studies for commercial customers, ESA and the European Commission.

A traceability matrix between the desEO implemented analyses and the Mission Analysis Reports (MAR) produced by DEIMOS has been generated (Fig. 18). The outcome of this exercise has highlighted that desEO has been able to cover almost all the analyses required for the chosen EO missions.

A very interesting aspect of the analysis of desEO applicability to the EEs Phase A/B1 studies is the inverse traceability matrix, i.e. detecting which analyses performed in the scope of a Phase A/B1 study are actually covered by desEO and which not: almost all the analysis necessary for the EO MARs are covered by desEO. In few cases it has been necessary to use desEO embedded in a scripting environment to perform some refinement/dedicated post-processing.

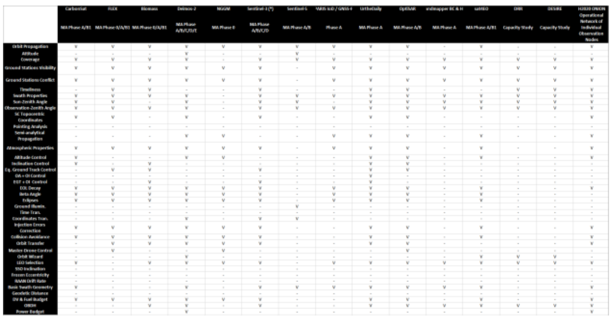

Figure 18. desEO Capability vs. MARs Matrix

Moreover, the only analyses of the whole assessment conducted on the Phase A/B1 studies under consideration not covered at all by desEO are associated with very specific computations that had to consider not-generic characteristics of the payload or the mission. Nonetheless, some of them could be handled with an opportune post-processing of the available data generated by desEO (e.g. formation, GS interference, duty cycle and complex data latency analyses) and the remaining ones with very simple extensions of the toolkit capabilities (e.g. sunglint and orbit control analyses, interferometric acquisition optimization).

5.2. Advanced Complex Tools

As introduced in this paper, one of the objectives in designing desEO was to achieve a high-level of modularity in order to use its low-level components as building blocks for specialized and complex tools.

This modularity serves primarily desEO itself since many of its most powerful components are built compounding simpler modules. A clear example is shown in Fig. 19 which graphically explains how low-level desEO components (blue boxes) interact to produce a complex processing chain to simulate the behavior of the On-Board Data Handling (OBDH) subsystem.

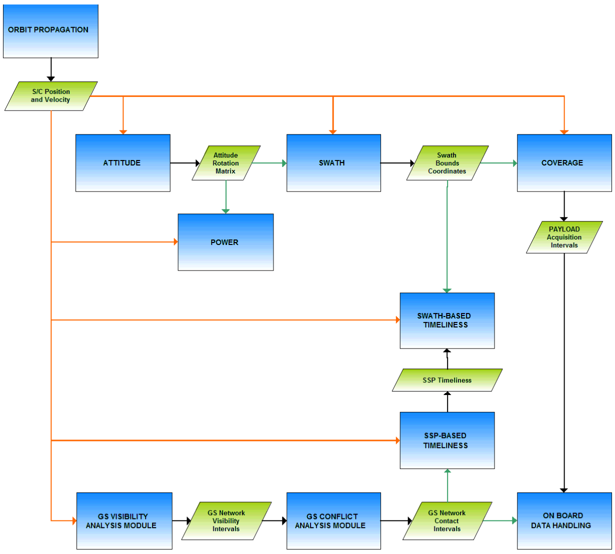

Figure 19. OBDH Analysis Functional Diagram

Nevertheless, the desEO building blocks can be used in external tools to provide fundamental functionalities with an easy integration procedure. A significant case in which desEO components have been used in such a manner is the Capacity Analysis and Mission Planning (CAMP) Tool [2]. In the CAMP, desEO analysis modules have been integrated in a wider tool able to simulate and optimize, by means of a genetic algorithm the acquisition timeline of an agile EO satellite, considering several operational constrains (e.g. power availability, stabilization after maneuvering, memory evolution).

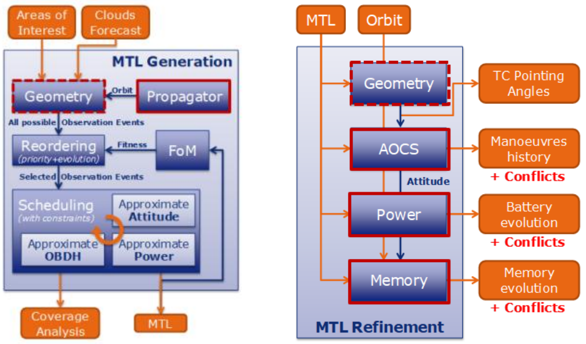

Figure 20. CAMP High-level Context Diagrams [2]

Fig. 20 shows in red boxes the desEO component embedded into the CAMP tool.

6. FUTURE DEVELOPMENTS

desEO is a toolkit in continuous development, following the increasing needs posed by the expanding EO institutional and commercial markets.

The most relevant feature currently under development is a Constellation Design model that, given high-level mission requirements, will be able to provide a set of possible constellation designs compliant with them.

Moreover, the inclusion of statistical cloud databases is foreseen, in order to perform coverage analyses considering the impact of cloudiness.

7. CONCLUSIONS

desEO is a powerful toolkit, designed to supply an exhaustive set of functionalities and cover the most common and frequent analysis needs that a mission/system engineer faces in his/her everyday work.

desEO can be used by analysts whenever they need accurate and fast quantitative results to support trade-offs and analyses. Nevertheless, desEO is also able to manage large analysis campaigns, as a complete EO mission Phase 0 or Phase A study.

desEO has been designed considering progressive future developments. For this reason, a modular and generic architecture has been implemented, paving the way for future extensions. Moreover, the desEO implementation allows its use via GUI, command line or as building blocks for fast prototyping and/or complex post-processing in a scripting environment.

The outcome is a very generic and modular software toolkit that is undertaking incremental upgrades minimising the integration effort for new capabilities, both in terms of analysis modules and GUI functionalities. The wide margin of extendibility of desEO covers both the increase of computation capabilities (especially the system analysis modules) and the consolidation of GUI for improving the user experience when operating it.

The desEO development has been based on a comprehensive overview of the possible necessary analyses to be handled by the end-user in the frame of current and future EO missions outlining a large number of possible use cases. Many of them have been already integrated in the current toolkit version. Nevertheless, the other use cases represent a solid basis for starting the design of further upgrades, both in terms of implementation of new analyses and consolidation of the current ones.

The ESA EE mission analysis activities, the Copernicus Space Component and Space Component Expansion, as well as the DMS commercial activities are showcases for the functionalities provided by desEO and their reliability throughout all the phases of an EO mission (from Phase 0 to Phase E).

desEO is available for both Windows and Mac OS X platforms, and its functionality has been already tested in Linux OS.

8. REFERENCES

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[2] Tonetti S., Cornara S., Vicario de Miguel G., "Fully Automated Mission Planning and Capacity Analysis Tool for the DEIMOS-2 Agile Satellite", 67th International Astronautical Congress (IAC), Guadalajara, Mexico, 26-30 September 2016.