GENEOS – The new ESOC Earth Observation Flight Dynamics Software based on GODOT – Design, Capabilities and Operational Validation

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Abstract

This paper discusses the transformative efforts undertaken by the European Space Operations Center (ESOC) to enhance the Flight Dynamics management of Earth Orbiting satellites through the development of the GENEOS (GEneral Navigation for Earth Orbiting Satellites) software package. Leveraging a unified astrodynamics library core named GODOT, GENEOS represents an overhaul aimed at modernizing ESOC's Earth Observation Flight Dynamics (FD) operational software, which has been foundational yet increasingly outdated over its two decades of use. The initiative seeks to consolidate disparate software subsystems — including Orbit Determination, Manoeuvre Optimization, Command Generation, and Telemetry Monitoring — into a cohesive and streamlined framework. This paper outlines the motivation behind GENEOS, its development process, the operational validation with currently flying missions, and its role in future LEOPs (Launch and Early Orbit Phase). GENEOS and its dependent libraries, GODOT and ODLIB, are made available under the ESA Community License, fostering collaboration and standardization within the ESA Member States.

I. INTRODUCTION

The Flight Dynamics (FD) team at the European Space Operations Center (ESOC), responsible for managing Earth Orbiting satellites, has successfully conducted multiple missions over recent decades. Currently, their fleet includes 15 satellites: XMM-Newton, Integral, Cluster-II, Swarm, Cryosat-2, and various Sentinels. The current FD operational software, which is crucial for these missions, is both reliable and has passed rigorous validation processes. However, it was initially designed over twenty years ago and has been expanding since.

The overall software infrastructure comprises different software packages for each subsystem, including Orbit Determination, Manoeuvre Optimization, Command Generation, and Telemetry Monitoring, developed independently. Each package utilizes its unique set of libraries and utilities, with only a few shared across subsystems, leading to redundancy in functionalities.

To modernize and streamline its software infrastructure for more efficient mission management, ESOC initiated the development of a unified astrodynamics library core named GODOT ([1] and [2]). This initiative aims to centralize tools and functionalities for general astrodynamics needs more effectively. Following this, the Earth Observation Flight Dynamics section began creating the GENEOS (GEneral Navigation for Earth Orbiting Satellites) software package, leveraging the GODOT libraries for enhanced mission preparation and development.

This paper presents an overview of the ongoing implementation and validation of GENEOS into currently flying missions as well as Launch and Early Orbit Phase (LEOP) for new missions.

GENEOS and its ESOC library dependencies (GODOT and ODLIB) are offered free of charge to any company within ESA Member States under the ESA Community License – Weak copyleft in the Space Codev ESA platform (https://www.space-codev.org).

II. GENEOS DESIGN AND ARCHITECTURE

GENEOS is being developed as a cohesive system comprising four distinct yet integrated modules, each utilizing a uniform interaction system and a shared library set. These modules are at various stages of progress:

- **Orbit Determination and Product Generation (ORB) module**: Orbit determination, propagation and product generation activities. This module is completed, with operational validation already finished. It is replacing the outgoing NAPEOS software [3].
- **Orbit Control and Manoeuvre Optimization (MAN) module**: Orbit control and general optimization activities. Currently in development phase, with the first operational validation steps being performed, this module will replace the MANTRA software [4].
- **Command Generation (TCS) module**: Generation of the parameters for commanding the satellite which FD is responsible for. This module is in the design phase with some initial implementations. This will replace the internal EOLIB software libraries.
- **Telemetry Monitoring (AMS) module**: Monitoring and feeding to the rest of the software the updates coming from telemetry. Development for this module has not yet started.

These modules are being combined into GENEOS, culminating in a comprehensive Flight Dynamics software solution for satellite operations. GENEOS, alongside its associated components, are fully licensable at no cost for use within the European industry, fostering accessibility and standardization across FD satellite operations.

GENEOS is developed at two different layers:

- **The User Interface**, which has been coded in Python 3 and includes the Framework, a base class which provides several functionalities to all the tools.
- **The Core**, which has been coded in C++11 and takes care of most of the processing of the software. This is a compiled numerical processing core which depends on GODOT and ODLIB.

The use of the python Framework base class enables several functionalities in all the tools: YAML configuration files, structure files (schema-like files to define the configuration files), variables, time handling helpers, references, command-line arguments and options, preconfigured templates and a standard python interface. More details can be found in [5] and [6].

III. TOOLS AND CAPABILITIES

GENEOS has been designed as a set of small independant tools, each being able to perform specific bounded tasks. In order to create a processing stream, several of these tools need to be concatenated into a sequence; several control flow mechanisms have been introduced in the controller tool, used for automation control.

Currently the following tools are available:

- **General functionality**: FTP/SFTP tools, orbit file updates, manoeuvre calibration, tracking data preprocessing, Orbit Determination, propagation, automation tools…
  - controller: Handle sequences of tools and automation.
  - ftpget: Connect through FTP and SFTP and download files based on rules.
  - ftpmonitor: Similar to ftpget, but to monitor when new files appear.
  - manCal: Compare two manoeuvre files and extract calibration factors.
  - manUpd: Merge manoeuvres and manually add them to a manoeuvre list file.
  - massUpd: Merge and copy mass files.
  - odp: Orbit Determination program. Created to be easy to use, but with extended functionalities for advanced users. It handles as well regular propagation without any orbit determination.
  - orbUpd: Copy and merge orbit files.
  - prepro: Preprocess tracking data.
- **Product generation**: Event finding (for station visibilities, eclipses, ascending nodes crossing, interferences, angles, altitudes…), OEM, OPM, NDM, TLE among others…
  - closeApproach: Generate Collision Warning Reports.
  - cpfGen: Generate CPF files.
  - eclipseProfile: Generate eclipse profiles.
  - eventCounter: Count events (to keep track of absolute orbit numbers).
  - formatter: Format json files into ASCII reports.

- generator: Create generic json files.
- injectionReport: Generate the injection reports.
- ndmGen: Merge OEMs and OPMs into an NDM.
- stdmGen: Generate STDM ESA ground stations prediction files.
- oemGen: Generate OEMs.
- opmGen: Generate OPMs.
- orbEvents: Create an events database.
- predOrbGen: Generate predicted and reconstructed orbit files.
- tleGen: Generate TLEs based on an orbit file.
- tovEstim: Estimate Time Offset Value to compute the time difference between two orbits.

- **Analysis**: Plotting, compare orbit files, propagate TLEs, plot accelerations along a trajectory…
  - gtDev: Compare the ground track of an orbit with a reference.
  - manInfo: Display information on manoeuvres.
  - obsView: Inspect a prepro database.
  - orbAcc: Compute and show accelerations of dynamical models along a trajectory.
  - orbComp: Compare two orbits generating results in ASCII or a plot.
  - plot: General plotting tool.
  - plotTab: Plot process noise files.
  - tleProp: Generate an orbit file based on a TLE.
  - tubeDev: Compare an orbit with a reference in a cross-track/radial frame.
- **Utilities**: Interpolate orbit files, state vector conversion, time conversion, tracking data simulator…
  - ascii2ipf: Transform ASCII files to IPF binary ones.
  - asciiUpd: Merge ASCII files.
  - cleanCases: Helper tool to clean out old case directories.
  - czmlGen: Generate czml files, which are the input of genVis (below).
  - eopGen: Tool to generate Earth Orientation Parameter files.
  - example: Example on how to use and create tools.
  - eventDump: Dump events for inspection from an events DB (generated by orbEvents).
  - geneosInfo: Uses the framework to extract information, like variable values, log location or validity of configuration files.
  - genVis: Web tool to plot orbits and stations in an Earth Map.
  - ipf2ascii: Transform IPF binary files to ASCII ones.
  - ipf2json: Transform IPF binary files to JSON format.
  - ipfedit: Edit IPF binary files.
  - ipfInfo: Dump headers and records of an IPF binary file.
  - json2ipf: Transform JSON format files to IPF binary ones.
  - notifier: Distribute products.
  - obsSim: Generate synthetic tracking data measurements.
  - opmProp: Propagate an OPM file.
  - orbInfo: Dump headers and records of an orbit file.
  - orbInterp: Orbit interpolation tool.
  - prepareAccount: Script to prepare an account from scratch to use GENEOS.
  - pnUpd: Update Process Noise files (like drag coefficient history files).
  - solmagUpd: Create solar and geomagnetic indices for NRLMSISE00 drag model.
  - svConv: Transform state vectors between reference frames/representations.
  - timeCalc: Transform between time representations and compute delta times.

IV. TESTING AND VALIDATION

GENEOS and GODOT have been extensively cross-validated during their development and are currently being deployed and further validated in operations. As part of the GENEOS development a large numbers of unit tests (around 2900) and regression tests (around 550) are run continuously on the software to ensure its correctness through the development cycle. In order to assure the correctness and backward compatibility of any change, all commits to GENEOS are validated through a Continuous Integration (CI) process in a gitlab repository. More tests are added as new functionalities and features are implemented.

Details on the cross-validation activities of GENEOS against the legacy software performed during development can be found in [5].

V. GENEOS OPERATIONAL USAGE

Several active missions are currently undergoing a crucial phase of operational validation through the execution of parallel runs with the ORB module. This entails maintaining the operational use of NAPEOS, while simultaneously deploying a secondary, independent processing stream using the GENEOS suite to duplicate outcomes and produce identical deliverables. Both processing streams undergo rigorous testing and validation by a dedicated Test and Validation team. However, at this stage, NAPEOS-generated products continue to serve as the primary output for distribution.

The implementation of this parallel processing approach is instrumental in the final stage of validation, providing a comprehensive verification that GENEOS meets all mission requirements and can reliably generate the necessary products across all operational scenarios. This strategy not only facilitates a seamless transition by allowing operational teams to acquaint themselves with GENEOS, but it also offers training opportunities by troubleshooting issues or performing any detailed investigations when needed.

One of these missions, **Sentinel-1A** has already performed the switch (as of 10th of April of 2024) and has already transitioned to GENEOS as the primary system moving NAPEOS to the secondary one.

Currently, two more missions are engaged in these parallel runs, each with anticipated timelines for fully transitioning to GENEOS as the primary system:

- **Cryosat-2**: Expected to switch to GENEOS in Q3 2024.
- **Swarm** (3 satellites): Anticipated GENEOS switchover within 2024.

In addition to these missions, all new developments related to the ORB module are being conducted exclusively on the GENEOS platform. Notably:

- **EarthCARE**: ORB development done purely on GENEOS. The MAN module is also being used for the EarthCARE mission, and its use cases and requirements are leading and steering the development of that module. EarthCARE is currently ongoing the simulation campaign for the launch preparation. Launch is expected on the range of 25th -31st May 2024.
- **BIOMASS**: The ORB development for BIOMASS is conducted entirely within GENEOS, with its launch expected in December 2024.

Beyond these mission-specific applications, GENEOS is also exclusively employed in a variety of auxiliary activities within our group. These include support for third-party missions, analysis, and preprocessing of new tracking data formats (in Integral, Cluster II and XMM-Newton). Such a diverse range of applications confirms GENEOS's capability to handle an extensive array of tasks, ensuring its scalability and flexibility for future requirements and enhancements.

VI. CONCLUSIONS

This paper has detailed the development, integration, and operational validation of the GENEOS Flight Dynamics software package within the context of Earth Orbiting satellite missions managed by the European Space Operations Center (ESOC). GENEOS represents a significant leap forward in the Flight Dynamics domain, offering a modular, integrated suite of tools designed to replace legacy systems with a modern, flexible, and scalable architecture.

Key conclusions and insights from the implementation of GENEOS include:

- **Successful Modular System Integration**: The design and architecture of GENEOS consolidate various Flight Dynamics functions into four main modules: Orbit Determination and Product Generation, Orbit Control and Manoeuvre Optimization, Command Generation, and Telemetry Monitoring. This approach not only enhances system manageability and efficiency but also enables targeted updates and scalability.

- **Rigorous Operational Validation**: The deployment strategy involving parallel runs with existing software like NAPEOS has proven crucial for validating the operational capabilities of GENEOS. This step-by-step validation ensures that GENEOS can meet all mission requirements and produce reliable outputs across various operational scenarios. This has already been validated by the first operational mission to run GENEOS ORB end to end, Sentinel-1A.

- **Facilitation of Smooth Transition**: The methodical implementation and validation process allows operational teams to gradually familiarize themselves with GENEOS, ensuring a seamless transition from legacy systems. This approach minimizes disruptions to ongoing missions and builds confidence in the new system's reliability and effectiveness.

- **Extensive Testing and Validation Framework**: The development of GENEOS has been supported by a comprehensive testing and validation framework, which includes thousands of unit and regression tests. This rigorous testing regime is critical for ensuring the software's reliability and readiness for operational deployment.

- **Adoption and Future Prospects**: The adoption of GENEOS across several missions, including Cryosat-2, Swarm and Sentinel-1A, and its exclusive use in the development of new ORB mission-specific applications, highlights its potential as a standard for Flight Dynamics Earth Observation operations within ESOC and potentially beyond. The open licensing under the ESA Community License further encourages its adoption across the European space industry.

- **Broader Implications for Satellite Operations**: GENEOS's development and implementation reflect a broader trend towards standardization, modularization, and efficiency in satellite operations. Its successful integration into ESOC's operations could serve as a model and encouragement for companies and agencies looking for Flight Dynamics operational solutions.

In conclusion, GENEOS represents a significant step forward for ESOC in enhancing its capability to manage and operate Earth Orbiting satellites. Its successful development, validation, and integration into existing missions not only demonstrate its operational viability but also set a new standard for future Flight Dynamics software systems.

VII. REFERENCES

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