

AOCSim: a Tool for Rapid Analysis of Satellite Dynamics

During the Early Phases of a Project

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INTRODUCTION

The idea behind the Attitude and Orbit Control Simulator (AOCSim) is to provide the Future Missions Division (EOP-SF) of the Earth Observation Programme, responsible for the preliminary phases of a mission (feasibility study, pre-phase A, phase 0), with a tool tailored to their analyses.

A number of engineering tools for Attitude and Orbit Control Sub-system (AOCS) design and analysis are available, such as AGI's STK™, probably the most popular one in commerce, or like DCAP and ADS produced by Thales Alenia Space, and many others developed on ESA behalf by industrial contractors, plus all the *ad hoc* simulators developed for specific missions or applications.

The above tools, however valid and efficient, present several limitations. The most specialised tools can cover a narrow spectrum of missions. For others, the problem is the available support, since some of the tools are poorly documented and sometimes no longer maintained by their developers. Any attempt to solve problems or add new functionalities tends to be frustrating and time-consuming. Finally, for the commercial ones, there is the issue of the related costs: licenses and upgrades call for a sustained economical effort.

The AOCSim was developed at low cost and in a widely known environment such as Matlab/Simulink™, implementing a solid architecture and with the objective of being easy to use by the average user, with the additional features of being constantly maintained and upgraded as a result of its utilisation. Developed initially for missions in Geo-stationary Orbits (GEO), its capabilities were eventually extended to Low-Earth Orbit (LEO) as well.

OBJECTIVES AND SCOPE OF THE AOCSIM

The AOCSim was conceived as a supporting tool for the Meteosat Third Generation (MTG) pre-phase A and its applicability was eventually extended to other Earth Observation missions, its foreseen applications being:

- simulation, analysis and verification of AOCS concepts;
- pointing error budgets verification
- support trade-off for different design options
- parametric analysis of AOCS performance
- performance degradations due to partial/total failure of AOCS components

At the current state, the AOCSim allows the rapid analysis of satellite dynamics for some assigned configuration during the early phases of a project. Alternately, it can be turned into a design tool to demonstrate alternative AOCS concepts in a representative environment.

According to the application, the AOCSim targets two levels of potential users. In the first case, the user task consists mainly in tuning the desired parameters in the simulator input files and reviewing the output data. In case the user decides to replace some of the current models with any other available in the provided libraries, the set up of the simulator can be modified at a mouse click.

When the activity requires a specific design effort or requires extending the AOCSim libraries, then the user should have some programming skills. The coding languages of the simulator are mainly Matlab/Simulink™ and C/C++. Modules developed in FORTRAN and ADA can be integrated too. Matlab™ and Simulink™ are used as a supporting structure for the simulator and to provide all the basic functions such as the integrators, the algebraic functions and above all graphical capabilities. The possibility to integrate pieces of code in different languages allows taking advantage of the number of certified models developed for other applications or available on the Internet. A block template is available to simplify the implementation of new models. The main features of the template are (see Fig. 1):

- Model core: the central core of the model can be a Simulink™ block, an S-function or an external DLL; this allows one to plug any model into the AOCSim with almost no modification.
- Input/Output Interfaces (I/F): they convert the exchanged data from the specific format request by the model core into the fixed format of the AOCSim and viceversa.
- Internal Scheduler: the simulator calls the model block at every cycle (integration step); the internal scheduler set the appropriate execution frequency for the model core.

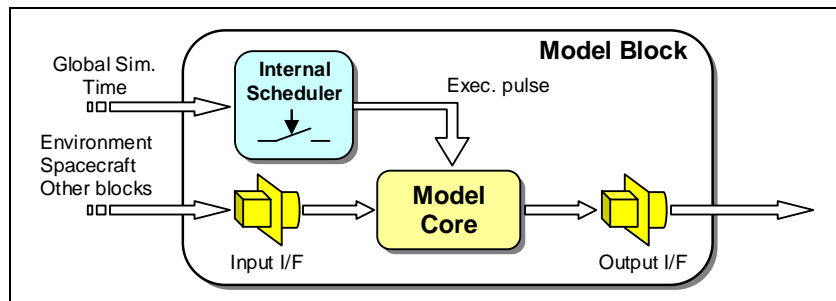


Fig. 1. AOCSim model basic structure

AOCSIM DESCRIPTION

The simulator in its basic configuration is composed of five macro blocks (see Fig. 2)

- Spacecraft: main spacecraft properties;
- Environment: computation of the environmental properties at spacecraft location;
- External disturbances: interaction between the spacecraft and the environment;
- Internal disturbances: disturbances generated by internal sources such as mechanisms or oscillating appendages;
- AOCS: sensors, actuators and on-board software.

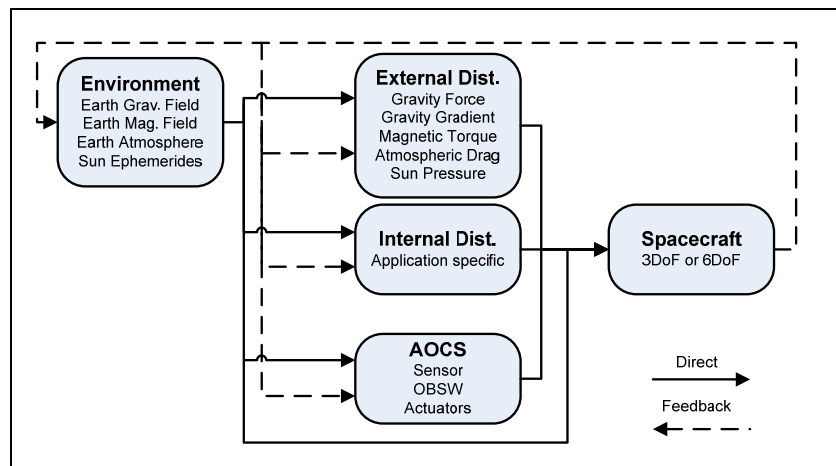


Fig. 2. AOCSim overview.

Existing modules are organized in libraries, thus giving to the user the possibility to choose the configuration that better suits the current application. This holds true not only for sensor and actuators, but also for blocks of the AOCs and the models used for the environment. In general these blocks can be added to the simulator using the Simulink™ model browser by either “copy and paste” or “drag or drop” from the respective library (see Fig. 3).

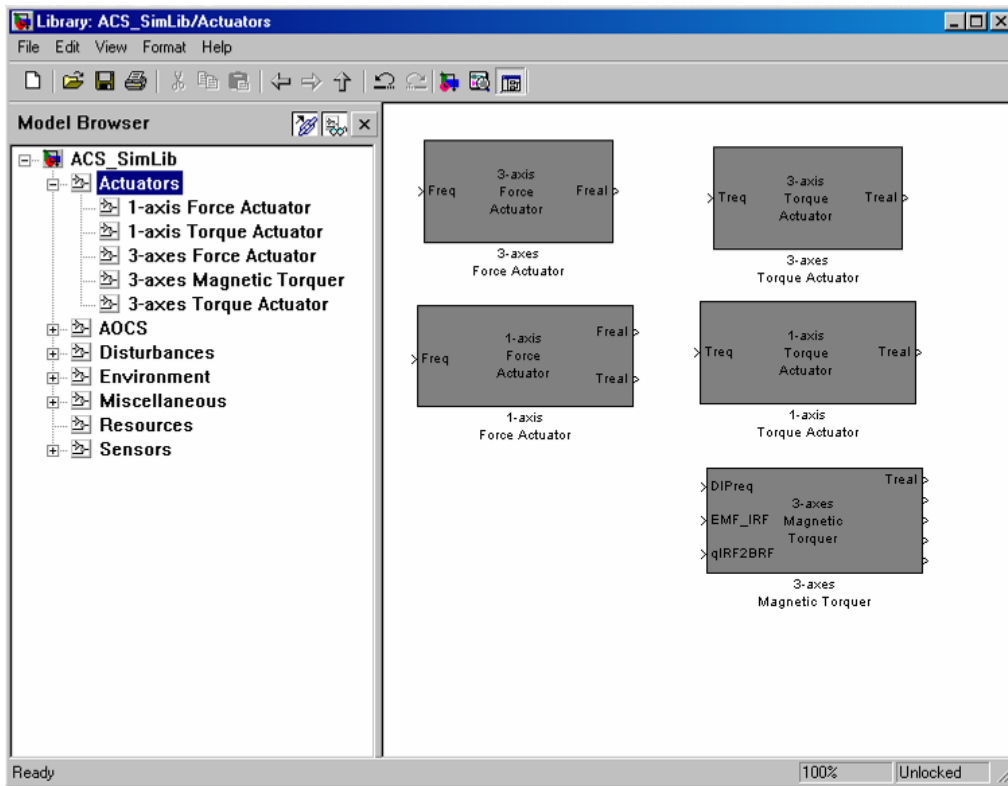


Fig. 3. Access blocks with the Model Browser.

Fundamental blocks are arranged in families, for which a placeholder, called configurable block, is always present in the simulator. In the default configuration this placeholder is empty or points to simplest model of the family. According to specific needs any member of the family can be selected with a mouse click.

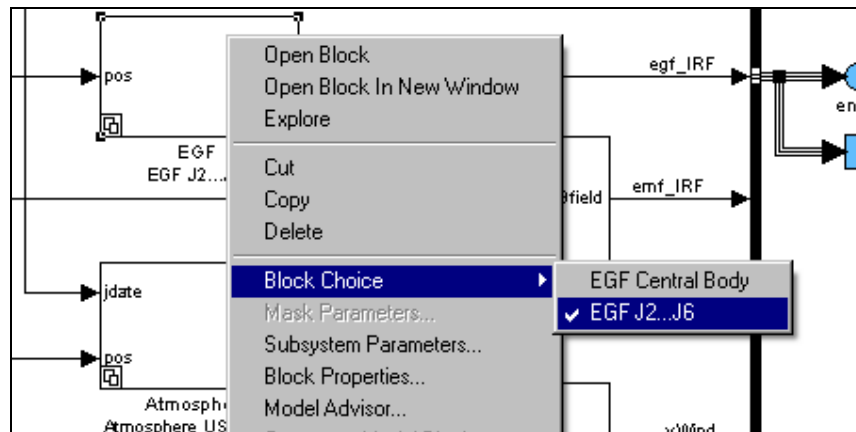


Fig. 4. Select the desired model with a mouse click.

The features described here after refers to the default libraries available with the simulator.

Spacecraft

The spacecraft (S/C) is here considered in terms of its mass and inertia, aerodynamics, reflectivity and residual magnetic moment [1] [2].

Dynamics

The dynamic behaviour of the S/C is described by the set of 6 equations of a rigid body having mass m and inertia matrix J . The translational dynamic is described by Newton's equation. The rotational dynamics around the centre of mass is described by Euler's equation. Two versions of the kinematics equations, linearised and not-linearised, are available. It is also possible to freeze the rotations, thus reducing the degree of freedom (DoF) from 6 to 3.

Aerodynamic and Reflective Properties

The external shape of the S/C defines the interaction with the residual atmosphere and Sun radiation. The S/C shape is described by a mesh of tiles. Each tile has an aerodynamic property, namely the drag coefficient, and reflective properties, absorption and reflection coefficient.

Residual magnetic dipole

The residual magnetic dipole is assumed static, i.e. no time varying contribution is considered. The strength and the orientation of the dipole are assigned by its components projected along the S/C axes. More complex models need to be implemented ad hoc.

Environment

The Environment is a collection of properties (potential fields, air density, and Sun illumination) relevant to the selected epoch and the instantaneous position occupied by the spacecraft. Different models are available to describe the same properties. Those described below are based on some simplified assumptions and are sufficient for almost all the basic applications of the simulator for LEO and GEO missions.

Earth Gravity Field (EGF)

The following models are available for the EGF [3] [4]

- Central body [5];
- Central body + first 6 zonal harmonics [4] [5];
- Earth Gravity Model 1996 (EGM1996) [6].

Earth Magnetic Field (EMF)

The following models are available for the EGF

- Dipole Model [5];
- International Geomagnetic Reference Field 1995 (IGRF95) [7].

Neutral Earth Atmosphere (NEA)

The neutral Earth atmosphere is described in terms of density and, when available, temperature and chemical composition. The following models are available for the Earth atmosphere:

- U.S. Standard Atmosphere 2000 (USSA2000) [8];
- Mass Spectrometer and Incoherent Scatter 1990 (MSISE90) [9];
- Reduced MSISE90.

Furthermore, models are available describing the strength and direction of winds at high altitude.

- Rotating Atmosphere [5];
- Horizontal Wind Model 1993 (HWM93)[10].

The above models cover an altitude range between 100 km and 1000 km. Beyond 1000 km the residual atmosphere can be considered negligible. For missions on high orbits, like in GEO, the atmosphere model should not be enabled.

Sun Ephemerides (SE)

Models of Sun ephemerides are based on a solver of the Kepler equation [11]. The Earth orbit around the Sun is assumed to be an ideal Keplerian orbit. The eclipse condition, or conversely the illumination ratio, is computed by comparison of the angular separation between the two bodies, Sun and Earth, and their angular diameter at the current position.

External Disturbances

The interactions between the environment and the spacecraft result in forces and torques that influence the orbit and the attitude, respectively:

- Earth Gravity Field Forces and Torques [1] [4] [12];
- Earth Magnetic Field Torques [1] [4] [12];
- Aerodynamic Forces and Torques [13];
- Sun Radiation Forces and Torques [1] [4] [12].

Each of these macro-blocks assumes by default quite simple interaction model between the environment and the spacecraft. Once more, a different model can be easily selected instead.

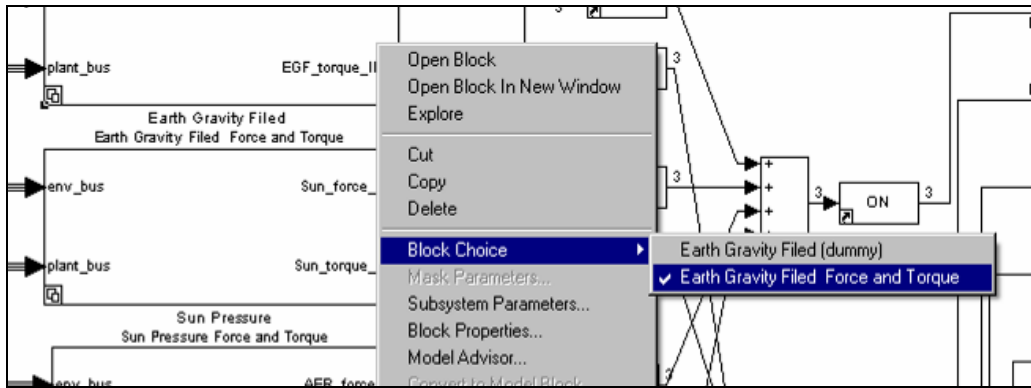


Fig. 5. Configuration of the External Disturbances macro block.

Internal Disturbances

Moving parts, scanning/rotating mechanism, flexible appendages can generate disturbances to the attitude of the satellite. The objective of this macro-block is to deal with these internal sources of disturbance in a simplified way. By default this block is empty, being its specification very specific for each application.

Attitude and Orbit Control Sub-system

The AOCS macro-block accounts for the entire sub-system, i.e. sensors, actuators and on-board software for the attitude control.

Sensors and Actuators

The unit models available have been developed starting from a common template.

Table 1. AOCS unit library contents

Sensors	Actuators
3-axed attitude sensor (STR);	1- and 3-axes force actuator (THR);
single and 3-axes angular rate sensor (GYR);	1- and 3-axes torque actuator (RWL);
single and 3-axes magnetometer (MGM);	3-axes magnetic torquer (MTR).
Earth sensor (ES);	
Sun sensor (SS);	

In general for each type of unit it is possible to specify its execution frequency, mounting matrix, bias and noise

On-board software

The AOCSim library contains two ready-to-use attitude control blocks:

- Rate damping:
This block is designed to effectively reduce initial angular rates after separation, using a limited set of sensor and actuator, i.e. MGM and MTR.

- Fine pointing [14] [2]:
S/C fine pointing is achieved using STR, GYR and RWL. The attitude control is based on a Kalman filter and a PID controller [15].

ENVISAT TEST CASE

The objective of this test case is to validate the concept of the simulator against a real mission.

The ENVISAT satellite is an Earth-observing satellite flying in a sun-synchronous orbit at a height of 790 km (± 10 km). It orbits the Earth in about 101 minutes with a repeat cycle of 35 days. ENVISAT carries an array of nine Earth-observation instruments that gather information about the Earth (land, water, ice, and atmosphere) using a variety of measurement principles [16].

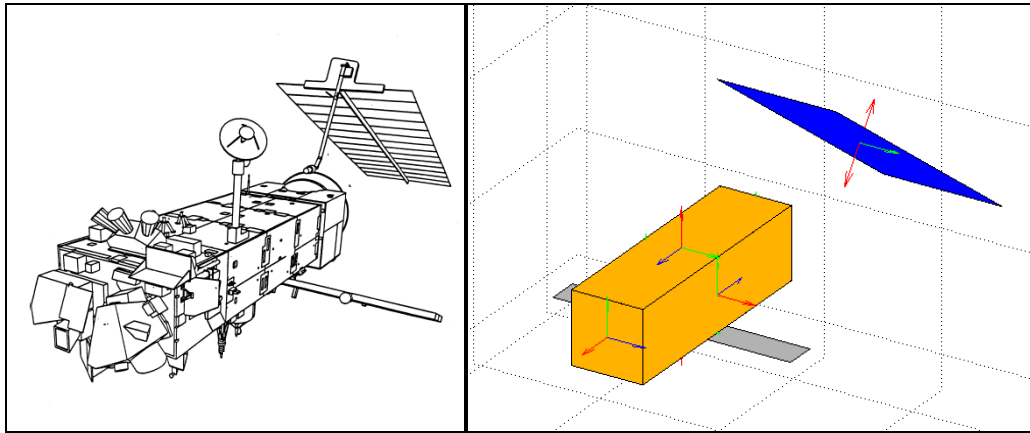


Fig. 6. Real Envisat Vs AOCSim Envisat (aerodynamic model)

Envisat AOCS

The Envisat AOCS, in fine pointing mode, uses star sensor measurements updated at 1 Hz for attitude correction and accurate angular rates measurements updated at 8 Hz for propagation, provided by a gyro-package. The attitude reference generator is fed by a precise orbit propagator. The actuation is performed by a Reaction Wheel Assembly.

For the ENVISAT test case:

- The star sensor is modelled as a *3-axes Attitude Sensor*;
- The gyro-package is modelled as a *3-axes Angular Rate Sensor*;
- The orbit propagator has been replaced by a *Navigation Sensor*;
- The RWA is modelled as a *3-axes Torque Actuator*.

The OBSW is based on the “fine pointing” block previously mentioned. The reference generator uses a simplified model of the EGF (central body and J2) to project ahead S/C position and velocity and compute the Local Orbiting Reference Frame to be chased by the AOCS. The state observer propagates the current state (attitude, angular rates and external torques) at gyro sample frequency (8 Hz) and updates/corrects the projected state using at the star sensor sample frequency (1 Hz).

Internal Disturbances

The internal disturbances for ENVISAT take into account the disturbances induce by

- Rotating solar array (ASAR)
- Vibrations caused by reaction wheels assembly (RWA)

Neglecting the variation of angular rate of the solar array, the disturbance torque is given by:

$$\mathbf{T}_{ASAR} = \boldsymbol{\omega}_{S/C} \times \mathbf{H}_{ASAR} \quad (1)$$

where $\omega_{S/C}$ is the spacecraft angular rate vector and H_{ASAR} the angular momentum of the solar array. The RWA vibrations are modelled through a band-limited white noise, the sample time being the same as for the AOCS.

Results

Plots for the Attitude Measurement Error (AME), Attitude Pointing Error (APE) are presented in Fig. 7. A comparison between Envisat performance, according to the information collected (AOCS budgets and performance [17], available telemetry), and the AOCSim is presented in Table 2, with the addition of the daily orbit decay (see Fig. 8) and torque requested to the RWA (plot not available).

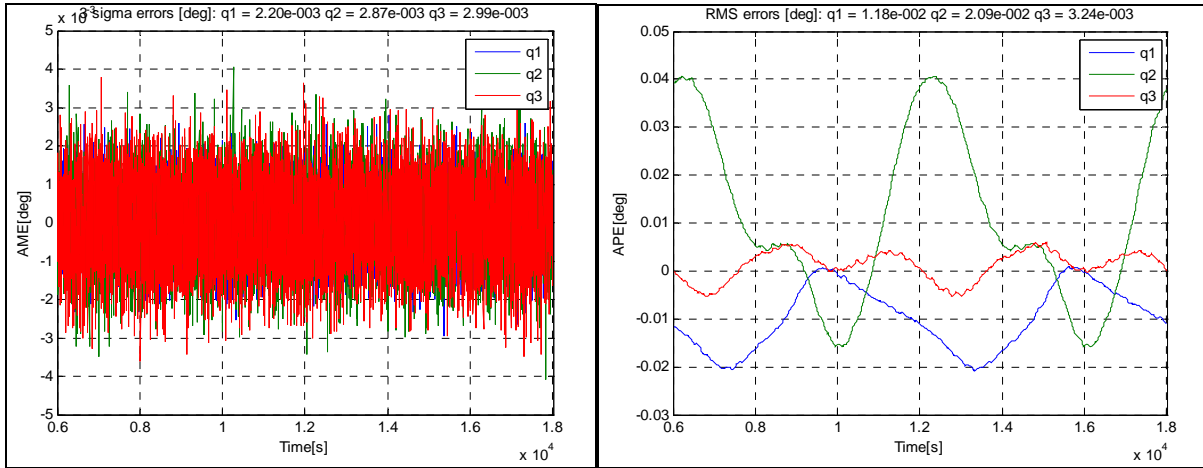


Fig. 7. AME (left), APE (right)

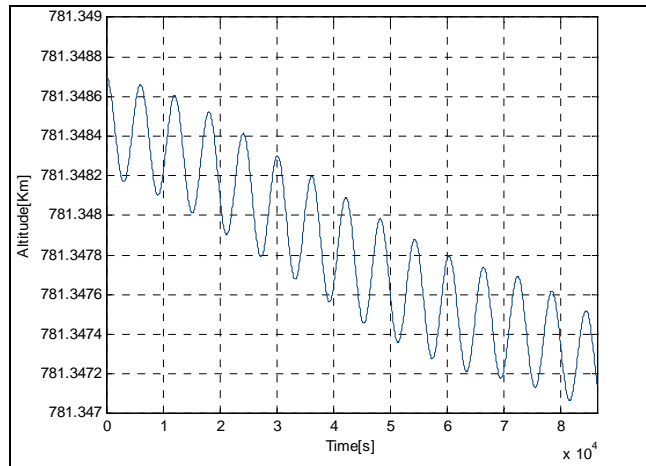


Fig. 8. Orbit decay over one day

Table 2. Results comparison

	Envisat	AOCSim
AME (3σ) [deg]	0.03 all axes	0.002 x-axis 0.003 y-axis 0.003 z-axis
APE (RMS) [deg]	0.02 all axes	0.01 x-axis 0.02 y-axis 0.003 z-axis
RWA req. torque [Nm]	± 0.1 x-, z-axis ± 0.05 y-axis	± 0.1 x-axis ± 0.05 y-axis ± 0.05 z-axis
Orbit decay	≈ 100 m/day	≈ 15 m/day

In general, the simulated ENVISAT performs slightly better than the real one for the AME. This is consequence of the slightly different/favourable AOCS configuration assumed for the state observer. The APE is in line with the real Envisat and the controller operates the always within the prescribed limits, though the control action is not as smooth as expected. This could have been achieved dedicating more effort to gain tuning, thus improving pointing as well.

The computation of the various disturbances is consistent with the mission scenario. A remark should be made about the atmosphere model. The orbit decay is observed during the simulation is slower than the real one. The contribution of the solar array needs to be reassessed. Furthermore the USSA2000 model used to asses the orbit decay tends to be conservative at very low altitudes but not for an orbit as high as the ENVISAT one.

FUTURE ACTIVITIES

In general the success of tools such as the AOCSim depends on their effective and continues utilisation. Currently some additional resources are allocated to the AOCSim maintenance. Among the possible missions that could be simulated are MTG, for which it was originally developed, and Geo-Oculus, a mission for real-time monitoring through high-resolution imaging from geostationary orbit.

REFERENCE DOCUMENTS

- [1] Fortesque, P. & Stark, J., *Spacecraft Systems Engineering 3rd Ed.*, Wiley & Sons, 2003.
- [2] Wiley L.J., Wertz J.R., *Space Mission Analysis and Design 3rd Ed.*, Space Technology Library, 2004.
- [3] ECSS at SPENVIS web page, <http://www.spnevis.oma.be>.
- [4] Vallado D.A., *Fundamentals of Astrodynamics and Applications second ed.*, Space Technology Library, 2004.
- [5] ECSS Working Group, *Space Engineering - Space Environment*, ECSS-E-10-04, January 2000.
- [6] EGM96 info web page, <http://cddis.nasa.gov/926/egm96/egm96.html>.
- [7] IGRF info web page, <http://www.ngdc.noaa.gov/IAGA/vmod/igrf.html>.
- [8] U.S. Standard Atmosphere model info web page, http://modelweb.gsfc.nasa.gov/atmos/us_standard.html.
- [9] MISISE90 info web page, <http://ccmc.gsfc.nasa.gov/modelweb/atmos/msise.html>.
- [10] HWM93 info web page, <http://ccmc.gsfc.nasa.gov/modelweb/atmos/hwm.html>.
- [11] Approximate Solar Coordinates algorithm, <http://aa.usno.navy.mil/faq/docs/SunApprox.php>.
- [12] Wertz J.R., *Spacecraft Attitude Determination and Control*, Space Technology Library, 1980.
- [13] Monti R., Zuppari G., *Lezioni ed Esercitazioni di Aerodinamica Ipersonica*, Ilardo Editore, Napoli, 1996.
- [14] Cramer G., "Spacecraft Attitude Determination Using Gyro and wide Field-Of-View Star Cameras", *AIAA, 1996*.
- [15] Zarchan P., Musoff H., *Fundamentals of Kalman Filtering, Progress in Astronautics and Aeronautics*, American Institute of Aeronautics and Astronautics, 2000.
- [16] Envisat home page at ESA, <http://envisat.esa.int>.
- [17] Envisat operations at ESA http://www.esa.int/SPECIALS/Operations/SEMOZY8L6VE_0.html.