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Validation of Tools for 6Dof Orbital Dynamics Simulation

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Abstract: This paper describes the validation activities of the 6Dof Orbital-Sim tool developed by Italian Aerospace Research Centre (CIRA). These activities had the goal of defining, implementing and executing all the tests necessary to check the accuracy of the model's representation of the real system. The main benchmark used for the Validation activities is STK, identified as the best one for flexibility and functionalities presented. Results show that the accuracy of simulation model is within the requirements defined at the beginning of the validation activities.

Keywords: Orbital Dynamics, Simulation Tool, Validation

Introduction

Numerical state vectors are the current choice to perform various flight dynamics operations since they have been replacing the Two-Line Element sets (TLEs), as explained in (Vallado, 2005). Several flight dynamics programs are available nowadays, therefore the problem of evaluating their accuracy arises. As a matter of fact, even though the math behind the numerical programs is well known, there are many potential error sources going from inaccurate models to mathematical model simplifications or computational precision (Vallado, 2005).

Orbital-Sim is an Orbital Platforms Simulation tool for the design and development of a space mission in low Earth orbit, developed by Italian Aerospace Research Centre. In particular, Orbital-Sim implements the 3DoF and 6DoF orbital platforms dynamics, which can be used for the design and development of Guidance, Navigation and Control technologies for space missions as well as for their verification.

The model, developed in a MATLAB/Simulink® (R2017a) environment, contains 3DoF or 6DoF flight dynamics, spacecraft systems (like Sensors, Actuators and Engine) and environment effects due to gravity, atmospheric drag, solar radiation pressure, third body perturbation, gravity gradient and magnetic field.

The main objective of this paper is the presentation of the validation activities carried out for the simulation tool Orbital-Sim, with the detailed description of the considered test cases and the related results, in order to demonstrate the accuracy and reliability of the simulation model. It's worth specifying that the activities reported in this study complete the ones already described in (Poderico and Morani, 2020) where only the translational part of the Orbital Sim was handled (i.e., only the 3Dof configuration was validated).

In the next sections, a high level overview of the Orbital-Sim tool will be presented. Then, a high level overview of the Validation program including the driving goals and philosophy, high-level testing methodology and the test environment will be provided. Finally, a detailed discussion of testing methodology and results will be given.

Orbital-Sim System - Overview

Six Dof Orbital-Sim

The 6DoF Orbital Simulator is a 6-degree-of-freedom model, developed in MATALB/Simulink® environment (ver. R2017a), capable of simulating the orbital flight dynamics of a generic spacecraft. The 6DoF Orbital-Sim tool is composed by a Simulink model and a set of Matlab scripts and files used mainly for the configuration and initialization procedure. The simulation model includes a detailed model of a 6 degree of freedom rigid vehicle (three translational and three rotational DoF) including its actuators and sensors and the whole relevant environment in which orbital flight takes place.

The 6DoF Orbital-Sim simulation model adopts the general assumptions listed below:

1. Aerodynamic side force is considered negligible
2. Aerodynamic moments are considered negligible
3. The spacecraft is assumed to be a rigid body

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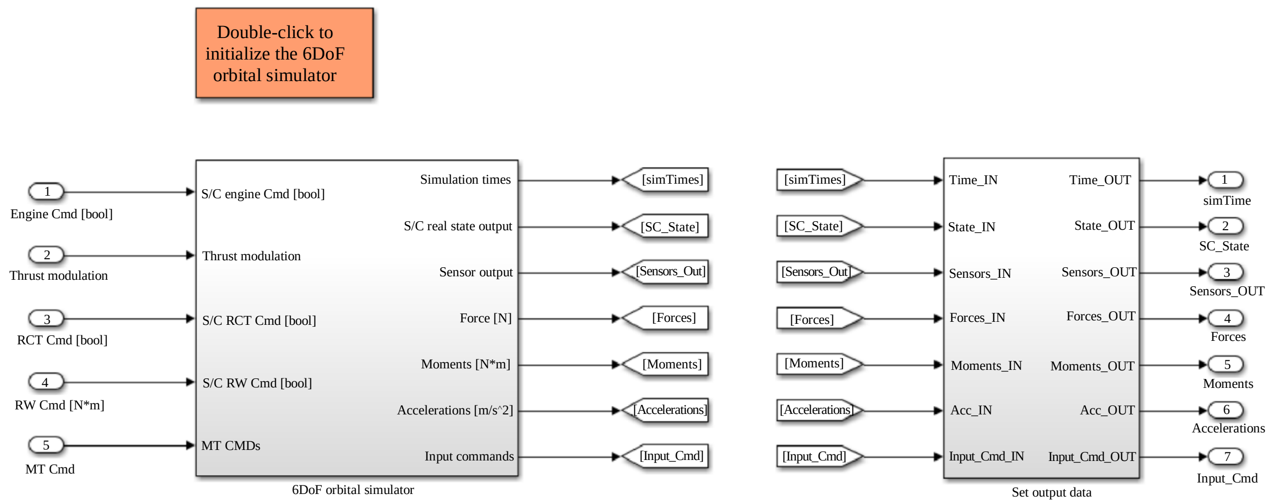

Fig. 1: Orbital-Sim 6DoF simulation model

Figure 1 reports the highest level of the “6DoF Orbital Simulator”, which mainly includes the following elements:

- 6DoF Equations of motion integration
- Spacecraft
    - Sensor (Star-Tracker, IMU, GPS, AHRS, Magnetometer)
    - Engine (main engine)
    - Actuators (Reaction Control Thruster, electric and chemical, Reaction Wheels, Magnetorquers)
- Environment
- Gravity
- Atmospheric Drag
- Solar Radiation Pressure
- Third body Perturbation
- Gravity gradient
- Magnetic field

Verification and Validation Approach

The primary strategic goals of the Validation activities of the Orbital-Sim tool, presented in this study, were to:

- Create an autonomous Orbital Simulator, to avoid using very expensive tools
- Create an effective tool for CIRA and Italian community needs

On the other hand, the primary technical goals were to:

- Systematically evaluate and validate all models and components of the tool
- Fix all critical system bugs
- Update working specifications that define tool behavior
- Provide good quality end user documentation
- Prepare for system maintenance and further development

V&V Philosophy

The Validation program of Orbital-Sim considers the following main activities (Fig. 2): Explore, Document, Test and Debug, as the majority of Verification and Validation programs recommends in the researcher community (Hughes *et al*., 2014).

The Explore phase includes the exploration and use of system components to determine the current state. Documentation activities include updating working specifications, writing test cases and procedures and updating documentation. Testing phase includes performing additional tests to ensure full coverage. These activities are not necessarily sequential but for a given component a few cycles through these activities could be needed.

V&V Methodology

The V&V methodology used to validate the Orbital-Sim tool is the industry standard one. The major goal is to implement test procedures in repeatable and automated test environments to support the testing of the whole simulator tool during development activities.

In particular, the numerical tests concerned physical and mathematical model and were performed by comparing model outputs to the external “truth”.

V&V Environment

The Validation activities has been carried out through a MATALB/Simulink® simulation environment to perform automated script regression testing.

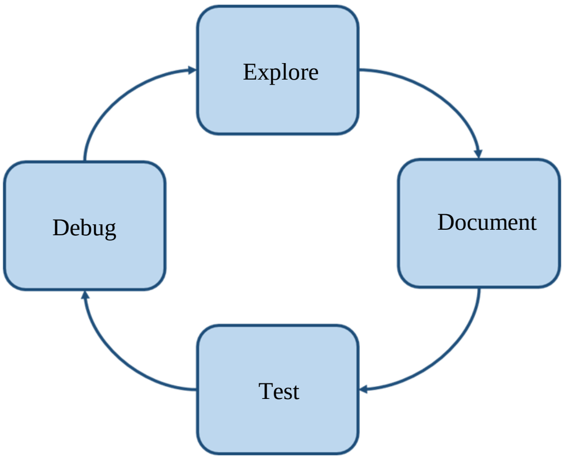

Fig. 2: High level V&V approach

In particular, MATLAB scripts implement test procedures (more details are reported in the next section) in order to compare the results of the Orbital Simulator with the Systems Tool Kit (STK), version 9, used as a reference benchmark (AGI, STK. http://www.agi.com/home).

STK is a physics-based software package from Analytical Graphics, Inc., AGI, that allows engineers and scientists to perform complex analyses of ground, sea, air and space platforms and share results in one integrated environment. It's currently considered the most reliable Orbital Simulation toolkit.

V&V Approach

Validation of 6Dof Orbital-Sim was not an easy task due to limitations of available STK license, which does not allow to observe the free evolution of the spacecraft attitude and attitude rates (required to perform a full comparison between 6Dof Orbital-Sim output and STK one); this functionality is, instead, included in the SOLIS STK package, not available for these validation activities. In the basic STK functionality, it is only possible to set a fixed attitude that the spacecraft maintains for all the simulation. It is also possible to observe the Gravity Gradient and Magnetic field vectors, even if they are not configurable (i.e., the default values shall be used). On the other hand, we have to consider that 6Dof Orbital-Sim tool differs from the 3Dof one (already validated in (Poderico and Morani, 2020)) only for the subsystem that concerns the simulation of rotational dynamics, which are almost decoupled from the translational ones, since the forces acting on satellite do not depend on the satellite attitude. For this reason, the translational part of 6Dof Orbital-Sim will be assumed already validated. With this assumption, the 6Dof validation will be then focused on the validation of the rotational part.

From the basic STK propagator the following quantities useful for 6Dof Orbital-Sim validation are available:

- Attitude (fixed and set by user)
- Magnetic Field
- Gravity Gradient

As also explained earlier, attitude (and also attitude rate) is not provided as the result of a rotational dynamic model (integration of torques acting on satellite), but it's fixed and predetermined, therefore it cannot be used for comparison with attitude (and attitude rate) provided by Orbital-Sim.

For what concerns magnetic field and gravity gradient, they are instead essential components of 6Dof Orbital-Sim as they represent the only torques that depend on the external environment. Therefore, comparison between STK and 6Dof Orbital-Sim has been carried out by considering the difference between torques generated by the gravity gradient and magnetic fields, as will be explained later.

In this way, validation of Gravity Gradient and Magnetic Field model have been carried out. To this end the following procedure, reported in Fig. 3 and 4, has been used:

- An orbital propagation with STK has been done by assigning a given attitude and recording all the output (in particular, position, speed, magnetic fields and gravity gradient torques)
- 6Dof Orbital-Sim magnetic field and gravity gradient models have been fed with the inputs data taken from STK simulation (for instance, input for magnetic model field is the satellite position, therefore the satellite position recorded by STK simulation has been given in input to Orbital Sim magnetic field model)
- Magnetic Field and Gravity Gradient models outputs from Orbital-Sim models are compared to the one provided by STK simulations

The above steps allow evaluating the accuracy of both magnetic field and gravity gradient models of 6DOf Orbital-Sim tool, even though 6Dof Orbital-Sim validation should involve the evaluation of the attitude and attitude rates accuracy. However, this has been done by computing the effect of Magnetic field and Gravity gradient models discrepancies on the attitude and attitude rates.

This has been obtained through the following steps:

- Computation of the difference between the outputs of magnetic field and gravity gradient models
- Computation of the related torque differences
- Integration of the torque differences to obtain attitude and attitude rates

With the above-described procedure, the 6DoF validation plan integrates the 3DoF one (Poderico and Morani, 2020) considering two more environment effects due to the Gravity Gradient and Magnetic Field

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effect. As explained earlier, these other additional models produce torque on a spacecraft. The effect of magnetic field and gravity gradient model mismatch (between STK and Orbital-Sim) on the attitude and attitude rates gives an estimation of Orbital-Sim accuracy in reproducing the satellite rotational dynamics (the translational dynamics being already taken into account by the 3Dof Orbital Sim as explained before).

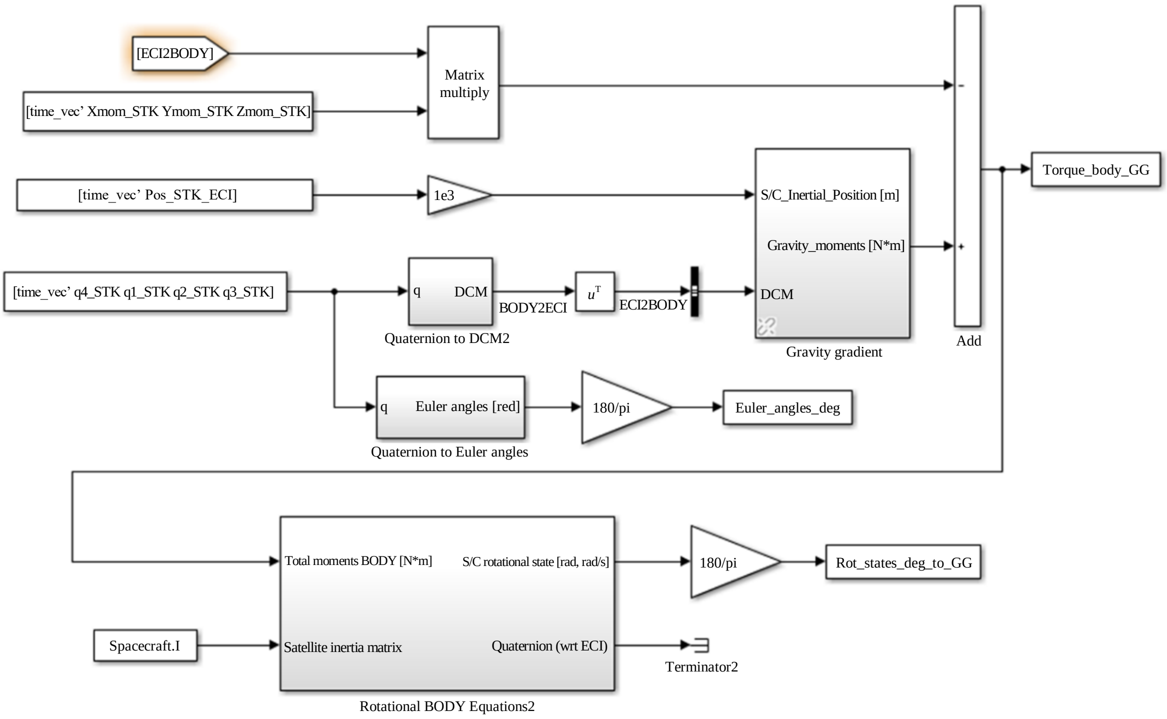

Fig. 3: Effect of gravity gradient error on attitude

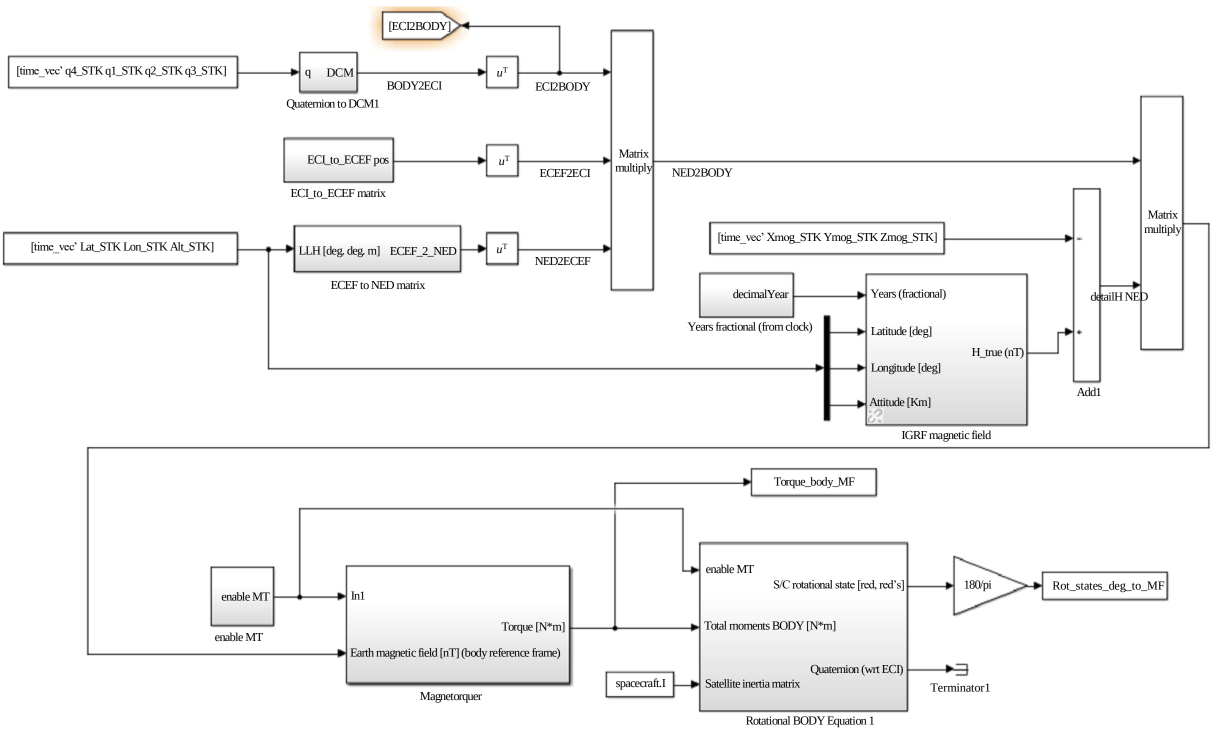

Fig. 4: Effect of magnetic field error on attitude

From the torques generated by the difference between the Gravity Gradient and Magnetic field of the 6DoF Orbital-Sim and the ones of STK, a sort of pointing error due to models errors will be obtained (as explained earlier). Furthermore, the evaluation of the GNC system performances accuracy can be done considering maximum allowable attitude errors for different space applications.

Concerning the magnetic field, it is worth specifying that the torques are generated due to the presence of magnetorquers. Therefore, in order to reproduce the effect of magnetic field on the rotational dynamics, a magnetorquer maneuver has been simulated for a given duration.

Verification and Validation Results

This section reports the results of a test cases selection of the Validation process.

The used settings for all the test cases for Earth and Sun parameters is in accordance with (Vallado 2013; IERS Conventions 2010; NASA Sun Fact Sheet; NRLMSISE00 model (https://ccmc.gsfc.nasa.gov/modelweb/models/nrlmsise00.php).

Each test descriptions include the following fields:

- Test id: A label identifying the test
- Objective: Functionality to be tested
- Conditions: Configuration and initialization needed to execute the test
- Test procedures: Description of the procedure step by step to carry out the test
- Test results: Results are reported as RMS error (on given variables).
- Criterion: To determine whether a propagator test case comparison value was acceptable. To this end, acceptance matrices (Table 1 and 2) have been defined considering benchmark error bounds with reference to Space applications of interest such as Fire Monitoring, Weather Monitoring, Earth Observation, with different pointing requirements, taken from the reference literature (Starin, Scott R., Eterno, J, table 19.9). In particular, Table 1 shows more stringent pointing requirements wrt the second one in Table 2

Test cases Dyn&Mod_6DoF_001-004 Attitude Aligned to Inertial Frame

Objective: Validation of the Gravity Gradient and Magnetic field Models.

Conditions: Propagation of circular orbits at altitude of 300 Km with different Gravity models. The attitude of the spacecraft is fixed and it is set aligned to the inertial reference frame: Euler angles sequence 321 (yaw, pitch, roll) is equal to [0 0 0] deg. The configuration parameters are reported in Table 3.

Test results: As explained earlier, the evaluation of the models has been done on the Euler angles and angular rates errors. Results (Table 4 to 7) show that the RMS error on the attitude is of the order of hundredths of a degree for Gravity gradient and thousandths of a degree for Magnetic field, while on the omega is even smaller.

Test cases Dyn&Mod_6DoF_005-006 Attitude Fixed wrt Inertial Frame

Objective: Validation of the Gravity Gradient and Magnetic field Models.

Conditions: Propagation of circular orbits at altitude of 300 Km with different Gravity models. The attitude of the spacecraft is fixed and it is set to: Euler angles sequence 321 is equal to [60 80 90] deg. The configuration parameters are reported in Table 8.

Test results: Results (Table 9 to 12) show that the RMS error on the attitude is of the order of tenths of a degree for Gravity gradient and thousandths of a degree for Magnetic field, while on the omega is even smaller.

Table 1: Acceptance Matrix for pointing requirements for Space applications (challenge).

Difference in	Acceptable error (1 σ)
Euler Angles [deg]:	0.034

Table 2: Acceptance Matrix for pointing requirements for Space applications (weak).

Difference in	Acceptable error (1 σ)
Euler Angles [deg]:	0.34

Table 3: Initialization and configuration

Altitude [km]	300
Gravity models	Spherical, J2, J3, J4
Fixed Attitude	Euler Angles sequence 321 = [0 0 0] deg
Orbital elements	Inclination = 0 deg
Environment effects	Gravity Gradient Magnetic Field
Magnetotorquer maneuver duration	1 h starting from 1000 sec
Satellite epoch	01/06/2010
Satellite mass [kg]	250
Reference frame	ICFR
Earth model	WGS84-EGM 2008
Simulation Duration [sec]	54000 (about 10 orbit periods)
Numerical Solver	Fixed step, Runge-Kutta 4

Table 4: Test cases Dyn&Mod_6DoF 001-004 results – Gravity Gradient (Euler Angles components RMS error wrt ECI)

Orbit Altitudes [km]	X RMS error	X RMS error	X RMS error
300 with Spherical gravity	0	0	0.0277
300 with J2	1.08e-10	6.66e-07	0.0277
300 with J3	9.505e-10	3.83e-06	0.0277
300 with J4	9.382e-10	3.79e-06	0.0277

Table 5: Test cases Dyn&Mod_6DoF 001-004 results – Gravity Gradient (Omega body components RMS error wrt ECI)

Orbit Altitudes [km]	X RMS error	X RMS error	X RMS error
300 with Spherical gravity	0	0	1.09e-06
300 with J2	0	6.50e-11	1.09e-06
300 with J3	0	1.68e-10	1.09e-06
300 with J4	0	1.68e-10	1.09e-06

Table 6: Test cases Dyn&Mod_6DoF 001-004 results – Magnetic Field (Euler Angles components RMS error wrt ECI)

Orbit Altitudes [km]	X RMS error	X RMS error	X RMS error
300 with Spherical gravity	0.00252	8.67e-05	0.000454
300 with J2	0.00254	8.65e-05	0.000458
300 with J3	0.00254	8.65e-05	0.000458
300 with J4	0.00254	8.65e-05	0.000458

Table 7: Test cases Dyn&Mod_6DoF 001-004 results – Magnetic Field (Omega body components RMS error wrt ECI)

300 with Spherical gravity	2.134e-07	8.85e-09	4.20e-08
300 with J2	2.148e-07	8.86e-09	4.23e-08
300 with J3	2.148e-07	8.86e-09	4.23e-08
300 with J4	2.148e-07	8.86e-09	4.23e-08
300 with Spherical gravity	2.134e-07	8.85e-09	4.20e-08

Table 8: Initialization and configuration

Altitude [km]	300
Gravity models	Spherical, J2
Fixed Attitude	Euler Angles sequence 321 = [60 80 90] deg
Orbital elements	Inclination = 0 deg
Environment effects	Gravity Gradient Magnetic Field
Magnetotorquer maneuver duration	1 h starting from 1000 sec
Satellite epoch	01/06/2010
Satellite mass [kg]	250
Reference frame	ICFR
Earth model	WGS84-EGM 2008
Simulation Duration [sec]	54000 (about 10 orbit periods)
Numerical Solver	Fixed step, Runge-Kutta 4

Table 9: Test cases Dyn&Mod_6DoF 005-006 results – Gravity Gradient (Euler Angles components RMS error wrt ECI)

Orbit Altitudes [km]	X RMS error	X RMS error	X RMS error
300 with Spherical gravity	0.0144	0.233	0.0146
300 with J2	0.0143	0.234	0.0145

Table 10: Test cases Dyn&Mod_6DoF 005-006 results – Gravity Gradient (Omega body components RMS error wrt ECI)

Orbit Altitudes [km]	X RMS error	X RMS error	X RMS error
300 with Spherical gravity	2.400e-11	1.339e-07	1.107e-05
300 with J2	1.547e-11	1.33e-07	1.11e-05

Table 11: Test cases Dyn&Mod_6DoF 005-006 results – Magnetic Field (Euler Angles components RMS error wrt ECI)

Orbit Altitudes [km]	X RMS error	X RMS error	X RMS error
300 with Spherical gravity	0.000146	6.70e-05	0.00262
300 with J2	0.000146	6.79e-05	0.00264

Table 12: Test cases Dyn&Mod_6DoF 005-006 results – Magnetic Field (Omega body components RMS error wrt ECI)

300 with Spherical gravity	2.175e-07	4.00e-08	8.25e-09
300 with J2	2.192e-07	4.03e-08	8.38e-09

Table 13: Initialization and configuration

Altitude [km]	300
Gravity models	Spherical, J2, J3, J4
Fixed Attitude	Euler Angles sequence 321 = [0 0 0] deg
Orbital elements	Inclination = 51.6 deg
Environment effects	Gravity Gradient Magnetic Field
Magnetotorquer maneuver duration	1 h starting from 1000 sec
Satellite epoch	01/06/2010
Satellite mass [kg]	250
Reference frame	ICFR
Earth model	WGS84-EGM 2008
Simulation Duration [sec]	54000 (about 10 orbit periods)
Numerical Solver	Fixed step, Runge-Kutta 4

Table 14: Test cases Dyn&Mod_6DoF 007-008 results – Gravity Gradient (Euler Angles components RMS error wrt ECI)

Orbit Altitudes [km]	X RMS error	X RMS error	X RMS error
300 with Spherical gravity	4.368e-06	0.0217	0.0172
300 with J2	3.215e-06	0.0317	0.00729

Table 15: Test cases Dyn&Mod_6DoF 007-008 results – Gravity Gradient (Omega body components RMS error wrt ECI)

Orbit Altitudes [km]	X RMS error	X RMS error	X RMS error
300 with Spherical gravity	3.443e-28	8.545e-07	6.772e-07
300 with J2	6.896e-28	1.397e-06	7.08e-07

Table 16: Test cases Dyn&Mod_6DoF 007-008 results – Magnetic Field (Euler Angles components RMS error wrt ECI)

Orbit Altitudes [km]	X RMS error	X RMS error	X RMS error
300 with Spherical gravity	0.00115	0.000280	3.46e-05
300 with J2	0.00115	0.000280	3.54e-05

Table 17: Test cases Dyn&Mod_6DoF 007-008 results – Magnetic Field (Omega body components RMS error wrt ECI)

300 with Spherical gravity	9.701e-08	2.46e-08	1.31e-08
300 with J2	9.701e-08	2.47e-08	1.32e-08

Test Cases Dyn&Mod_6DoF_007-008 Attitude Aligned to Inertial Frame

Objective: Validation of the Gravity Gradient and Magnetic field Models.

Conditions: Propagation of circular orbits at altitude of 300 Km with different Gravity models. The attitude of the spacecraft is fixed and it is set aligned to the inertial reference frame: Euler angles sequence 321 is equal to [0 0 0] deg. The Orbital inclination is set to 51.6 deg. The configuration parameters are reported in Table 13.

Test results: Results (Table 14 to 17) show that the RMS error on the attitude is of the order of hundredths of a degree for Gravity gradient and thousandths of a degree for Magnetic field, while on the omega is even smaller.

Conclusion

The paper presented the results of validation activities for the tool Orbital-Sim. These activities had the goal of comparing physical and mathematical models output to external "truth", represented by the results obtained with a benchmark simulation tool.

The main benchmark used for the Validation activities is STK, identified as the best one for flexibility and functionalities presented. Anyhow, being available only a very limited license, there was no possibility of simulating maneuvers and rotational dynamics.

For the above reason, the 6DoF Validation has been focused on the validation of the rotational part (with the assumption that translational part of 6Dof Orbital-Sim was already by the 3Dof Orbital-Sim validation previously carried out by the same authors). In particular, 6Dof validation concerned the accuracy analysis of two models, which are not included in the 3Dof simulator, i.e., Gravity Gradient and Magnetic Field models. To this end, the effect of Gravity Gradient and Magnetic field model errors on attitude and attitude rates has been estimated and compared to reference thresholds identified through the reference literature, available for different Space applications.

Results showed that all tests are passed as they satisfy the accuracy requirements reported in Table 2. Furthermore, almost all test scenarios satisfy also the requirements of a more challenging application (see Table 1), since only two test cases produce higher errors on Euler angles (only for Gravity Gradient model), which exceed the threshold of pointing requirements.

In this respect, future works will concern the improvement of Gravity Gradient model in order to reduce the modelling error up to obtain the values of the pointing requirement related to more stringent Space applications, such as the one reported in Table 1 (for all test scenarios), looking also at very challenging goals, as the reaching of pointing accuracies in compliance with the Italian Earth Observation application Cosmo SkyMed (De Luca *et al*., 2018).

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Author’s Contributions

Mariana Poderico: Contributed to the methodological aspects and to the definition of the validation process as well as to the paper preparation. She was also involved in the simulation set-up and in the execution of the numerical verification.

Gianfranco Morani: Contributed to the methodological aspects and to the definition of the validation process as well as to the paper preparation.

Ethics

No ethical issues may arise after the publication of this manuscript.

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