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Validation of Tools for 3Dof Orbital Dynamics Simulation

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Abstract: This paper describes the validation activities of the 3Dof Orbital-Sim tool developed by Italian Aerospace Research Centre (CIRA) and capable of simulating the orbital flight dynamics of a generic spacecraft. The primary strategic goals of the Validation Program of the Orbital-Sim tool were to create an autonomous and effective Orbital Simulator tool for CIRA and Italian community needs. This paper then describes the workflow for the processes and results of Verification and Validation (V&V) for the 3DoF Orbital Dynamics simulation tools. Test cases and results demonstrate that the Orbital-Sim tools have passed successfully all the test cases foreseen by the Validation Program.

Keywords: Orbital Platform Simulator, LEO Orbit, 3DOF, Verification and Validation

Introduction

Nowadays the Aerospace community exploits a huge number of flight dynamics available programs as they are very useful to perform various flight dynamics operations (Vallado, 2005).

The availability of multiple flight dynamics programs suggests the need for standardization. In this framework, the problem of evaluating their accuracy must be considered. As a matter of fact, there are many potential error sources which may depend on several reasons, for instance mathematical model simplifications or computational precision as well as modeling inaccuracies (Vallado, 2005).

Orbital-Sim is an Orbital Platforms Simulation tool developed by Italian Aerospace Research Centre. It has the aim of reproducing the orbital dynamics of a generic spacecraft with different level of accuracy. As a matter of fact, it can be used both to model only the translational dynamics (3DoF configuration) but also to reproduce the complete spacecraft dynamics, i.e., the translational and rotational ones (6DoF configuration). The model has been developed in a MATLAB/Simulink® environment and contains all the elements required to reproduce the dynamic behavior of a spacecraft. Therefore, besides the equations of motion, the subsystems having an impact on spacecraft dynamics are also modelled (i.e., Sensors, Actuators and Engine). Furthermore, the external environment in which the spacecraft flight takes place is also reproduced; therefore, all the effects due to gravity, atmospheric drag, solar radiation pressure, third body perturbation, gravity gradient and magnetic field are taken into account.

Orbital Sim has been developed as an effective tool for mission analysis as well as for the design, development and verification of Guidance, Navigation and Control technologies for space missions.

In this study, the validation activities carried out for the 3Dof part of Orbital-Sim simulation tool will be described and presented. All the test cases and the related results will be reported with the aim of showing the accuracy and reliability of the simulation model.

The paper is made of several sections; at the beginning, an overview of the Orbital-Sim tool is given. The subsequent sections describe the structure of the Validation, i.e., approach, methodology, etc. Finally, the test cases are presented and discussed.

Orbital-Sim System Overview

Three Dof Orbital-Sim

Orbital-Sim is a 3-degree-of-freedom model, developed in MATLAB/Simulink® environment (ver. R2017a), capable of simulating the orbital flight dynamics of a generic spacecraft.

It is an Orbital Propagator, which executes the integration of inertial acceleration acting on the spacecraft to obtain velocity and position. Initial position and speed values in ECI reference frame are taken from the orbital initial parameters set in the initialization script. The integration is carried out in inertial ECI reference frame.

During the model development, the following general assumptions have been taking into account:

1. No rotational dynamics are taken into account, i.e., the spacecraft is always in trimmed conditions
2. Aerodynamic side force is considered negligible
3. The spacecraft is assumed to be a single point of mass

The MATLAB/Simulink® 3DoF tool, Orbital-Sim, is made of a Simulink® model and a set of MATLAB scripts and files, mainly used for the configuration and initialization procedure.

Figure 1 reports the highest level of the “3DoF Orbital Simulator”, which mainly includes the following elements:

- 3DoF Equations of motion integration
- Spacecraft
 - Sensors
 - Engine
- Environment
 - Gravity
 - Atmospheric drag
 - Solar radiation pressure
 - Third body perturbation

The environment effects have been implemented according to the models described in (Vallado, 2013) as configurable library blocks, configured in the main script at the initialization.

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 includes 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.

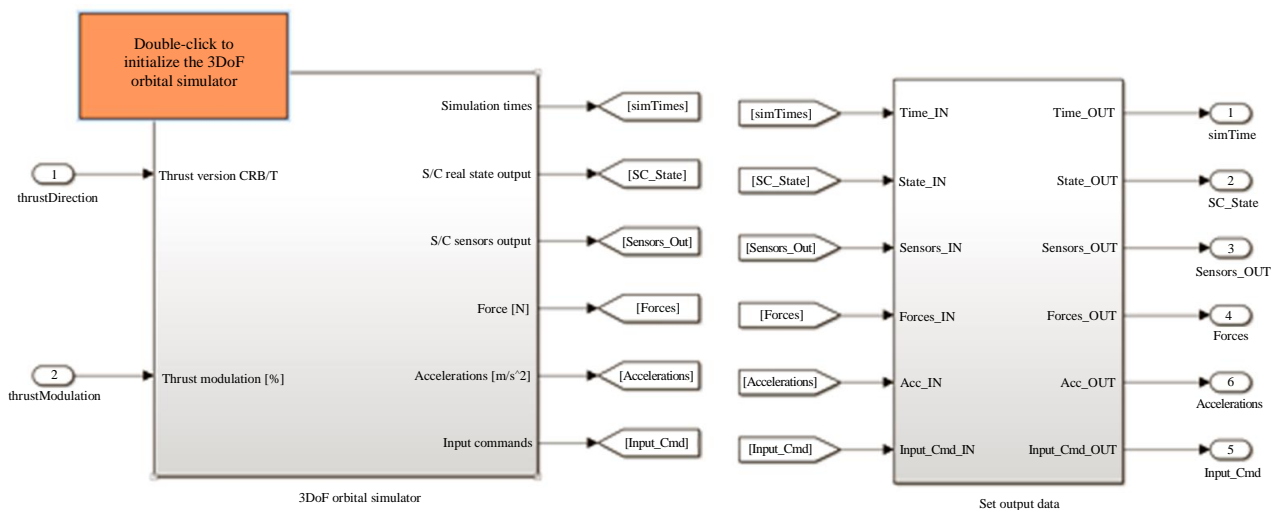


Fig. 1: Orbital-Sim 3DoF simulation model

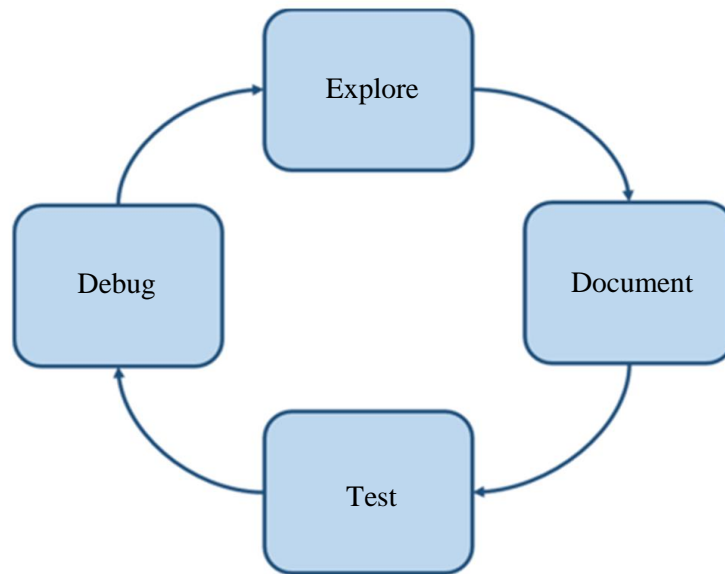


Fig. 2: High level V&V approach

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.

The primary Test Typologies performed are the following ones (Hughes *et al.*, 2014):

- Numeric Tests: Tests of physical and mathematical model. Numeric tests are performed by comparing output to the external “truth”
- End-to-end tests: Test that solve an end-to-end problem such as orbital maneuvers. These tests are applications of Orbital Simulator to the real-world problems

In order to carry out the Validation plan, system components have been grouped under two categories:

- Dynamics and Models: Numerical models for orbit propagation, coordinate system models, environment effects
- Powered Flight: Numerical models for impulsive and finite maneuvering including tanks and thrusters

V&V Environment

The Validation activities have been carried out through a MATLAB/Simulink® simulation environment

by which automated regression tests have been performed.

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 two benchmarks selected for these validation activities, i.e.:

1. General Mission Analysis Tool (GMAT), version R2018a (NASA 2018a). It is a space mission design software for the design and optimization of missions (anywhere in the solar system) ranging from low Earth orbit to lunar, Libration point and deep space missions
2. Systems Tool Kit (STK), version 9, (AGI, STK, 2020). 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 is worth noting that, due the limited licenses of the above benchmark tools, neither GMAT nor STK allowed a complete (i.e., for all the test cases) validation process. Therefore, for some test cases only GMAT has been used, for other cases only STK.

It's worth noting that GMAT propagator itself has been validated (Dove and Hughes, 2007; Hughes *et al.*, 2014) through comparison with STK propagator, which is currently considered the most reliable Orbital Simulation toolkit.

Table 1: Validation test summary

Test_Dyn&Mod_001	Orbit Propagation and gravity effects	STK
Test_Dyn&Mod_002	Orbit Propagation and gravity effects	STK
Test_Dyn&Mod_003	Solar radiation pressure effect	STK
Test_Dyn&Mod_004	Solar radiation pressure effect	STK
Test_Dyn&Mod_005	Solar radiation pressure effect	STK
Test_Dyn&Mod_006	Third body perturbation effect	STK
Test_Dyn&Mod_007	Third body perturbation effect	STK
Test_Dyn&Mod_008	Atmospheric drag	STK
Test_Dyn&Mod_009	Orbit Propagation and environment effects	STK
Test_PowFlight_001	In plane electric orbital maneuver	GMAT
Test_PowFlight_002	In plane electric orbital maneuver	GMAT
Test_PowFlight_003	In plane chemical orbital maneuver	GMAT
Test_PowFlight_004	In plane chemical orbital maneuver	GMAT
Test_PowFlight_005	In plane chemical orbital maneuver	GMAT
Test_PowFlight_006	In plane chemical orbital maneuver	GMAT
Test_PowFlight_007	Out of plane chemical orbital maneuver	GMAT
Test_PowFlight_008	Out of plane chemical orbital maneuver	GMAT
Test_PowFlight_009	Out of plane chemical orbital maneuver	GMAT
Test_PowFlight_010	Deorbiting maneuver	GMAT

V&V Approach

As explained earlier, the Validation plan includes a comparison two by two between Orbital-Sim and GMAT and STK. It's worth noting that STK has not been used for the Powered Flight comparison, due to the lack of the license for STK tool that includes the orbital maneuvers.

Table 1 provides a summary of the Validation program. In the following sections, all the test cases will be reported with the results.

Verification and Validation Results

This section details the results of the test cases reported in Table 1. As explained earlier, the tests have been grouped under two categories, i.e., "Dynamics and Models" and "Powered Flight".

In particular, in the category "Dynamics and Models" all the significant environmental effects for the Low Earth Orbits are included, while for what concerns the category "Powered Flight", some relevant maneuvers have been considered such as in-plane, out-of-plane and De-orbit with both Chemical and Electric Thrust.

Parameters settings for Earth and Sun, applied to all the test cases, are in accordance with Vallado (2013; IERS Conventions, 2010; NASA, 2018b).

Each test description includes 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 evaluate the outcome of a test case, in terms of orbit propagation accuracy, an acceptance matrix was created on the basis of what contained in (Dove and Hughes, 2007) (which considers also the analyses reported in Vallado, 2005). The values in Table 2 were obtained from the above references, applying a conservative scale factor, which depends on the following aspects:
 - The values reported in (Dove and Hughes, 2007) are referred to instantaneous values while test cases results are RMS errors. In this respect, assuming an oscillating (quasi) sinusoidal behavior for the error, the applied scale factor is square root of 2
 - The values are referred to the norm of position error, while test cases are referred to the error components. Therefore a conservative scale factor equal to square root of 3 has been considered

Furthermore, the obtained results will be also compared with the ones reported in Robson (2018) where an Orbit and Attitude Simulation Environment has been described and validated.

As explained earlier, some tests concern numerical models for impulsive and finite maneuvering including tanks and thrusters, the "Powered Flight" category. In this respect, the following engine models will be considered:

- Electric Thruster model: It has been obtained considering a polynomial function for the thrust and

mass flow rate (as in GMAT User Guide, 2018). Values of the coefficients are reported in Table 3

- **Chemical Thruster** model: Thrust and specific impulse are defined as a polynomial function of pressure. As a consequence, the mass flow rate is also polynomial (GMAT User Guide, 2018). In Tables 4 and 5 the parameters of the thruster model are reported

Table 2: Acceptance matrix for position error (km)

Difference in	Acceptable position error (km)
Point mass gravity	< 4.082482904639e-07
Non-spherical gravity	< 4.082482904639e-07
Drag	< 8.164965809277e-03
Solar radiation pressure	< 2.449489742783e-04
Third body perturbation	< 2.449489742783e-06
Combined perturbation	< 8.164965809277e-03

Table 3: Electric thruster coefficients

Mass flow coefficients		Thrust coefficients	
	Values		Values
Electric prop Cm1	-0.004776	Electric Prop Ct1	-5.19082
Electric prop Cm2	0.05717	Electric Prop Ct2	2.96519
Electric prop Cm3	-0.09956	Electric Prop Ct3	-14.4789
Electric prop Cm4	0.03211	Electric Prop Ct4	54.05382
Electric prop Cm5	2.13781	Electric Prop Ct5	0.00100092

Table 4: Chemical thruster-thrust coefficients

Thrust coefficients	Values	Units
C1	270	N
C 2	0.01	N/kPa
C 3	0	N/kPa ²
C 4	0	N/kPa ⁵
C 5	0	None
C 6	0	N/kPa ⁷
C 7	0	None
C 8	0	N/kPa ⁹
C 9	0	None
C 10	0	N
C 11	0	none
C 12	0	1/kPa
C 13	0	none
C 14	0	1/kPa

Table 5: Chemical thruster – specific impulse coefficients

Thrust coefficients	Values	Units
K1	280	s
K2	0.01	s/kPa
K3	0	s/kPa ²
K4	0	s/kPa ⁵
K5	0	None
K6	0	s/kPa ⁷
K7	0	None
K8	0	s/kPa ⁹
K9	0	None
K10	0	s
K11	0	none
K12	0	1/kPa
K13	0	none
K14	0	1/kPa

Test Cases Dyn&Mod_001-002 Orbit Propagation and Gravity Effects

Objective: Validation of orbital dynamics at different altitudes with different Gravity models.

Conditions: Propagation of circular orbits at altitudes of 300 km with different gravity models. The configuration parameters are reported in Table 6.

Test results: Results show that the RMS position error is of the order of cm on the Z component wrt STK one (Table 7).

Criterion: RMS errors < 4.082482904639 e-07 (see Table 2). Tests PASSED.

Test Cases Dyn&Mod_003-005 Solar Radiation Pressure Effect

Objective: Validation of the Environment: Solar Radiation Pressure effect (SRP).

Conditions: Propagation of circular orbits at altitudes of 300, 10000 km with the solar radiation pressure effect. Notice that, in Orbital-Sim, the effect of the shadow of the Earth on the satellite has been implemented. In particular, cylindrical and conical shadows have been considered. The configuration parameters are reported in Table 8.

Test results: Results show that the RMS position error is of the order of mm wrt STK one (Table 9).

Criterion: RMS errors < 2.449489742783 e-04 (Table 2). Tests PASSED.

Test Cases Dyn&Mod_006-007 Third Body Perturbation Effect

Objective: Validation of the Environment: Third Body perturbation effect (3B).

Conditions: Propagation of circular orbits at altitudes of 300 Km with the third body perturbation effect. It's worth noting that the third body perturbations of Moon and Sun have been considered. The configuration parameters are reported in Table 10.

Test results: Results show that the RMS position error is of the order of cm-mm wrt STK one (Table 11).

Criterion: RMS errors < 2.449489742783e-06 (Table 2). Tests PASSED.

Table 6: Initialization and configuration

Altitude [km]	300
Gravity model	J2,J3
Environment effects	Neglected
Satellite epoch	01/06/2010
Satellite mass [kg]	250
Reference frame	ICFR
Earth model	WGS84-EGM2008
Numerical Solver	Fixed step, Runge-Kutta 4

Test Cases Dyn&Mod_008 Atmospheric Drag

Objective: Validation of the Environment: Atmospheric drag.

Conditions: Propagation of circular orbits at altitudes of 300 km with the effect of the atmospheric drag effect. The model of atmosphere used in Orbital Sim is NrmLMSISE00 (NRLMSISE, 2000). The configuration parameters are reported in Table 12.

Test results: Results show that the RMS position error is of the order of m wrt STK one (Table 13).

It's worth noting that this error is higher than the ones obtained with the other environment effects. This may be due to some differences and/or inaccuracies in the atmospheric models used for the drag force computation which may lead to differences on the propagated orbit (Vallado and Finkleman, 2014).

Criterion: RMS errors < 8.164965809277 e-03 (Table 2). Tests PASSED.

Table 7: Test cases Dyn&Mod_001-002 STK results (ICRF position components RMS error)

Orbit Altitudes [km]	X RMS error	Y RMS error	Z RMS error
300 with J2	9.731937158848e-07	9.824023496630e-07	1.107676797431e-04
300 with J3	1.189376191472e-06	1.272762825925e-06	1.104716302140e-04

Table 8: Initialization and Configuration

Altitude [km]	300, 10000
Gravity model	Spherical, J2
Environment effects	Solar radiation pressure with cylindrical/conical shadow
Satellite epoch	01/06/2010
Satellite mass [kg]	250
Reference frame	ICFR
Earth model	WGS84-EGM 2008
Numerical Solver	Fixed step, Runge-Kutta 4

Table 9: Test cases Dyn&Mod_003-005 STK results (ICRF position components RMS error)

Orbit Altitudes [km]	X RMS error	Y RMS error	Z RMS error
300, spher, SRP cil	6.317587478296e-06	6.017363999036e-06	2.122786087498e-07
300, spher, SRP con	6.256720082275e-06	5.996560754663e-06	2.108647197596e-07
10000, spher, SRP cil	7.283507429331e-06	7.07469520217e-06	1.111607603126e-06
10000, spher, SRP con	6.734326806202e-06	6.642108840629e-06	1.026466583987e-06

Table 10: Initialization and configuration

Altitude [km]	300
Gravity model	Spherical, J2
Environment effects	Third body perturbation
Satellite epoch	01/06/2010
Satellite mass [kg]	250
Reference frame	ICFR
Earth model	WGS84-EGM 2008
Numerical Solver	Fixed step, Runge-Kutta 4

Table 11: Test cases Dyn&Mod_006-007 STK results (ICRF position components RMS error)

Orbit Altitudes [km]	X RMS error	Y RMS error	Z RMS error
300, spherical, 3B	1.697755701269e-06	1.656983191464e-06	2.873346803037e-07

Table 12: Initialization and Configuration.

Altitude [km]	300
Gravity model	Spherical
Environment effects	Atmospheric drag
Satellite epoch	01/06/2010
Satellite mass [kg]	250
Reference frame	ICFR
Earth model	WGS84-EGM 2008
Numerical Solver	Fixed step, Runge-Kutta 4

Table 13: Test cases Dyn&Mod_008 STK results (ICRF position components RMS error)

Orbit Altitudes [km]	X RMS error	Y RMS error	Z RMS error
300, spherical, NRLMSISE00	1.565158852334e-3	2.747121968042e-3	1.001938030072e-06

Test Cases Dyn&Mod_009 Orbit Propagation and Environment Effects

Objective: Validation of Orbit Propagation and environment effects.

Conditions: Propagation of circular orbits at altitudes of 300 km with the enabling all the above effects put together. The model of atmosphere used in Orbital Sim is NRMLSISE00. The configuration parameters are reported in Table 14.

Test results: Results show that the RMS position error is of the order of m wrt STK one (Table 15).

Criterion: RMS errors < 8.164965809277e-03 (Table 2). Tests PASSED.

Test Cases PowFlight_001-002 In plane Electric Orbital Maneuver

Objective: Validation of Powered Flight: In plane electric orbital maneuver.

Conditions: Propagation of circular orbits at altitudes of 300 km with spherical gravity model. At time t = 5430 sec, the electric thruster has been switched on in order to execute an in plane maneuver. The configuration parameters are reported in Table 16.

Test results: Results show that the RMS position error is of the order of meters wrt GMAT for the in plane components and up to millimeters for the out of plane component (Table 17).

Criterion: N/A.

Test Cases PowFlight_003-006 In plane Chemical Orbital Maneuver

Objective: Validation of Powered flight: in plane chemical orbital maneuvers.

Conditions: Propagation of circular orbits at altitudes of 300 with spherical gravity model. At time t = 5430 sec, the chemical thruster has been switched on in order to execute an in plane maneuver. The configuration parameters are reported in Table 18.

Test results: Results show that the RMS position error wrt GMAT goes from the meters to dozens of meters depending on the maximum thrust and the thrust duration (Table 19).

Criterion: N/A.

Test Cases PowFlight_007-009 Out of plane Chemical Orbital Maneuver

Objective: Validation of Powered flight: Out of plane chemical orbital maneuvers.

Conditions: Propagation of circular orbits at altitudes of 300 with spherical gravity model. At time t = 5430 sec the chemical thruster has been switched on in order execute out an out of plane maneuver. The configuration parameters are reported in Table 20.

Test results: Results show that the RMS position error is of the order of hundreds of meter wrt GMAT one for the 270 N case and dozens of meter for the 27 N case (Table 21).

Criterion: N/A.

Table 14: Initialization and configuration

Altitude [km]	300
Gravity model	Spherical
Environment effects	Solar radiation pressure Third body perturbation Atmospheric drag
Satellite epoch	01/06/2010
Satellite mass [kg]	250
Reference frame	ICFR
Earth model	WGS84-EGM 2008
Numerical solver	Fixed step, Runge-Kutta 4

Table 15: Test cases Dyn&Mod_009 STK results (ICRF position components RMS error)

Orbit Altitudes [km]	X RMS error	Y RMS error	Z RMS error
300, J2, SRP, 3B, NRMLSISE00	4.457323850167e-03	5.631685877329e-03	4.430447618301e-05

Table 16: Initialization and configuration

Altitude [km]	300
Gravity model	Spherical
Environment effects	Neglected
Electric Thruster	Polynomial thrust with parameters defined in Table 1 ISP = 1765 sec firing duration = 170000 sec Time of firing= 5430 sec ECI thruster direction [0 1 0] ((x y z))
Satellite epoch	01/06/2010
Satellite mass [kg]	250
Reference frame	ICFR
Earth model	WGS84-EGM 2008
Numerical solver	Fixed step, Runge-Kutta 4

Table 17: Test cases PowFlight_001-002 GMAT results (ICRF position components RMS error)

Orbit Altitudes [km]	X RMS error	Y RMS error	Z RMS error
300, spherical, polynomial thrust	1.860524260727e-03	1.896805578657e-03	5.662283546193e-07

Table 18: Initialization and Configuration

Altitude [km]	300
Gravity model	Spherical
Environment effects	Neglected
Chemical Thruster	<ol style="list-style-type: none"> 1. Polynomial thrust with: C1 = 270 N (max thrust), C2 = 0.01N/KPa K1 = 280s (ISP), K2 = 0.01s/KPa firing duration = 20 sec Time of firing = 5430 sec ECI thruster direction [0 1 0]([x y z]) 2. Polynomial thrust with: C1 = 27 N (max thrust), C2 = 0.001 N/KPa K1 = 280 s (ISP), K2 = 0.01 s/KPa firing duration = 20 sec Time of firing = 5430 sec ECI thruster direction [0 1 0]([x y z]) 3. Polynomial thrust with: C1 = 270 N (max thrust), C2 = 0.01N/KPa K1=280 s (ISP), K2 = 0.01 s/KPa firing duration = 200 sec Time of firing = 5430 sec ECI thruster direction [0 1 0]([x y z]) 4. Polynomial thrust with: C1 = 27 N (max thrust), C2 = 0.001 N/KPa K1 = 280s (ISP), K2 = 0.01 s/KPa firing duration = 200 sec Time of firing = 5430 sec ECI thruster direction [0 1 0]([x y z])
Satellite epoch	01/06/2010
Satellite mass [kg]	250
Reference frame	ICFR
Earth model	WGS84-EGM 2008
Numerical Solver	Fixed step, Runge-Kutta 4

Table 19: Test cases PowFlight_003-006 GMAT results (ICRF position components RMS error)

Orbit Altitudes [km]	X RMS error	Y RMS error	Z RMS error
300, spherical, polynomial thrust, C1 = 270, fir = 20 sec	1.516022719385e-01	1.360756365133e-01	8.025890423907e-07
300, spherical, polynomial thrust, C1 = 27, fir = 20 sec	1.454481335788e-03	3.487257449750e-03	2.550305761330e-07
300, spherical polynomial thrust, C1 = 270, fir = 200 sec	2.066235658546e-01	3.059260493165e-01	6.493924391780e-06
300, spherical polynomial thrust, C1 = 27, fir = 200 sec	2.102005231742e-02	3.733377336443e-02	7.866869210687e-07

Table 20: Initialization and configuration

Altitude [km]	300
Gravity model	Spherical
Environment effects	Neglected
Chemical Thruster	<ol style="list-style-type: none"> 1. Polynomial thrust with: C1 = 270 N (max thrust), C2 = 0.01 N/KPa K1 = 280 s (ISP), K2 = 0.01 s/KPa firing duration = 200 sec Time of firing = 5430 sec ECI thruster direction [0 0 1]([x y z]) 2. Polynomial thrust with: C1 = 27 N (max thrust), C2 = 0.001N/KPa K1 = 280 s (ISP), K2 = 0.01 s/KPa firing duration=200sec Time of firing= 5430 sec ECI thruster direction [0 0 1] ([x y z])
Satellite epoch	01/06/2010
Satellite mass [kg]	250
Reference frame	ICFR
Earth model	WGS84-EGM 2008
Numerical Solver	Fixed step, Runge-Kutta 4

Table 21: Test cases PowFlight_007-009 GMAT results (ICRF position components RMS error)

Orbit Altitudes [km]	X RMS error	Y RMS error	Z RMS error
300, Spherical gravity Polynomial thrust, C1 = 270, fir = 200 sec	1.100000000000e-02	1.490000000000e-02	1.419000000000e-01
300, Spherical gravity Polynomial thrust, C1 = 27, fir = 200 sec	4.358993920808e-05	1.462113517434 e-03	1.502941504840e-02

Table 22: Initialization and configuration

Altitude [km]	300
Gravity model	Spherical
Environment effects	Neglected
Electric Thruster	Constant thrust with: C1 = 750 N (max thrust), C2 = 0 N/KPa K1 = 280 s (ISP), K2 = 0 s/KPa firing duration = 45 sec Time of firing = 5430 sec ECI thruster direction [0 -1 0]([x y z])
Satellite epoch	01/06/2010
Satellite mass [kg]	250
Reference frame	ICFR
Earth model	WGS84-EGM 2008
Numerical Solver	Fixed step, Runge-Kutta 4

Table 23: Test cases PowFlight_003-006 GMAT results (ICRF position components RMS error)

Orbit Altitudes [km]	X RMS error	Y RMS error	Z RMS error
400, spherical, constant thrust, C1 = 750, fir = 45sec	1.090918804118e-02	6.484779794648e-02	1.354801415772e-06

Test cases PowFlight_0010 Deorbiting Maneuver

Objective: Validation of Powered flight: Deorbiting maneuver.

Conditions: Propagation of circular orbits at altitudes of 400 with the execution of a deorbiting maneuver at $t = 5430$ sec. The configuration parameters are reported in Table 22.

Test results: Results show that the RMS position error wrt GMAT one is of the order of dozens of meters (Table 23).

Criterion: N/A.

Conclusion

The paper presents the results of validation the activities for the 3DoF part of the Orbital-Sim tool, developed by Italian Aerospace Research Centre. 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 Validation program considered two main categories of testing cases:

- Testing of Dynamics and models, which includes tests of all the models used to describe orbit propagation and environment effects
- Testing of Powered flight, which concerns all the test cases related to the validation of maneuvers: Electrical and chemical maneuver, deorbiting and Hohmann Transfer

The main benchmark used for the Validation program are GMAT and STK, both identified as the best ones for flexibility and functionalities presented.

Test cases and results demonstrate that the Orbital-Sim tools have passed successfully all the Validation Program test cases falling under the category named “Dynamics and Models”. Furthermore, the results are even better (in terms of comparison with the reference benchmark) than the ones reported in Robson (2018) where an Orbital Propagator has been validated with similar simulation scenarios.

With reference to the Powered flight test cases, for all the reasons explained in the paper, there are no sufficient elements to evaluate the test outcomes.

Therefore, results showed that all tests are passed as they satisfy the accuracy requirements defined at the beginning of validation process.

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Author’s Contributions

All the authors contributed to the methodological aspects and to the definition of the Validation process as well as to the paper preparation.

M. Poderico was also involved in the simulation set-up and in the execution of the numerical verifications.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues involved.

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