Precise Gravitational Modelling of Planetary Moons and Small Bodies

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Executive Summary Report

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1 Applicable and Reference Documents

1.1 Applicable Documents

[AD1] ESA, GRAVMOD2-ECM-SoW-0901, Gravitational Modeling of Planetary Moons and Small Bodies, 2009

1.2 Reference Documents

[RD1] ECSS-E-40 Part 1B; Space Engineering, Software, Principles and Requirements

[RD2] Seidelmann, P. K., Abalakin, V. K., Bursa, M., Davies, M. E., de Bergh, C., Lieske, J. H., Oberst, J., Simon, J. L., Standish, E. M., Stooke, P. and Thomas, P. C., Report of the IAU/IAG Working Group on Cartographic Coordinates and Rotational Elements of the Planets and Satellites: 2000, Celestial Mechanics and Dynamical Astronomy, Vol. 82, No. 1, January 2002

[RD3] ESA Planetary Database, http://pdb.estec.esa.int/, Last accessed: 11-05-2012

2 Terms, Definitions and Abbreviated Terms

2.1 Acronyms

The following abbreviations are used throughout this document.

Acronyms	
AD	Applicable Document
ESA	European Space Agency
GPM	Gravity Parameter Message
IAU	International Astronomical Union
ICD	Interface Control Document
MPM	Multiple Point Mass Model
PDB	Planetary Database
RD	Reference Document
SoW	Statement of Work
SPH	Spherical Harmonics Model
TN	Technical Note

2.2 Terminology

The following terminology is used throughout this document.

GRAVMOD-1 GRAVMOD software created by Deimos within the GSP study "Novel gravitational modelling of irregular celestial bodies"

GRAVMOD-2 GRAVMOD software that shall be the output of this project

3 Introduction and Objectives

This document describes the work performed in the Project *Precise Gravitational Modelling of Planetary Moons and Small Bodies* done by Astos Solutions under contract of the European Space Agency.

This activity is a follow-up and extension of the GSP study “Novel gravitational modelling of irregular celestial bodies” (GRAVMOD-1), which developed a preliminary version of the gravity modelling tool and delivered a set of gravity models for the solar system’s planets and main moons.
This GSTP activity shall complement the tool with mathematical propagators and integrators for planetary exploration, as well as other additional side features. The propagators shall target two distinct working environments: guidance analysis and on-board manoeuvres. Gravity models obtained shall be made available through a dedicated web interface on the ESA Planetary Database (PDB). Various adjustments of the PDB architecture and interface shall be made in order to meet the needs of all potential users of GRAVMOD [AD1].

The key objectives of this activity are:
- to develop a comprehensive set of gravity models of all main solar system bodies, validated and verified against reference data.
- complement, expand and upgrade the GRAVMOD tool with missing features and side functionalities.
- to develop an interface between GRAVMOD and the ESA PDB for inclusion of all gravity models within the database, according to different formats, applications and user needs.
- to validate the toolset with concrete application cases: precise trajectory modelling of a passive de-orbiting spacecraft and determination of stable orbits around asteroids.

4 Software Architecture

The new GRAVMOD software has been designed as a toolbox and not just one single tool. The GNC propagator and the mission analysis propagator will be fully independent from the core GRAVMOD tool and may be used as standalone software.

The mission analysis propagator has been based on the ASTOS software. By this approach optimization applications can be incorporated into the set of test cases as it was requested in the SoW [AD1].

A brief overview of the main different functionalities of this tool is given here, in order to better understand the architecture of the software (shown in Figure 1).

Figure 1 GRAVMOD-2 toolbox global architecture

The core GRAVMOD-2 application has two main modules: the Gravity Modelling module (former Representation module) and the Orbit Propagation and Determination module (former Determination module).

- The Gravity Modelling Module is able to compute gravity fields not considering time as part of the input data, as done in the Orbit Propagation and Determination module. This module is able to:
  - For a given gravity field provided as input, allow the comparison between different gravity field models, in terms of accuracy and computational effort. The following models are considered:
    - Spherical Harmonics;
    - Multiple Point Mass Model;
    - Geometrical Models.
    - For instance it makes more sense to represent regular bodies (like planets) by using the spherical or elliptical harmonics expansion than assuming a geometrical representation. On the other hand, in the case of more irregular bodies as asteroids, any of the other two options (multiple point mass or geometrical approach) surely represents a more appropriate representation.
    - The Geometrical model here used is the Polyhedron Model.
  - Compute the gravity field that best fits with a given set of distributed (real or simulated) external measurements. This is done by sequentially running two sub-processes: initial guess generation and adjustment through a least squares / NLP approach. Since this module does not consider time as part of the input data, the provided measurements must be directly related to the concerned gravity field. This means that only accelerations and gravity gradients generated by the gravity field at certain locations can be used, but not tracking data (used in the other module). Therefore the measurements provided won´t be time-specific.
- The Orbit Propagation and Determination module is dealing with two different main functionalities of the tool: precise orbit propagation and gravity field estimation from satellite tracking data through a filtering scheme.

  For the second of these purposes, it also implements a measurements generation mode that feeds the filtering process. In a certain way, this module completed the

Gravity Modelling Module, since here also the evolution in time of the involved variables is considered in the gravity field representation

Four different main modes can be distinguished:

- Trajectory Propagation. Its main purpose is the propagation of an initial state (position and velocity) in the presence of a certain (user configurable) dynamic environment and of the initial covariance matrix (uncertainties), if specified by the user. Differently from GRAVMOD-1, the propagation of the covariance matrix is provided also for this mode. The propagation of the trajectory, once specified the environment and the initial conditions, is perform independently from the other modes. In order to generate the appropriate environment, it simulates the real world dynamic effects that perturb the satellite motion including the one produced by the central body gravity field (that can be computed by using the Gravity Modelling Module). Two different propagators can be used: Mission Analysis Propagator (for planetary or interplanetary missions), that allows the propagation of the S/C trajectory, and Hi-Fi Asteroid Propagator (for missions around asteroids), that allows the propagation of the S/C and of the asteroid trajectories.
- Measurements Generation. It allows the generation of measurements to feed the estimation process. These measurements are generated by taking the dynamic variable of interest from the Trajectory Propagator and adding the previously user-configured errors affecting the measurements. This mode can be executed independently in order to generate a set of measurements or can be called by the higher-level mode devoted to the determination process. It makes use of the Trajectory Propagation module to compute the set of measurements that shall be afterwards used by the orbit and gravity field determination module.
- Trajectory Determination Mode (and Montecarlo Simulation). This mode is responsible for the optimal determination of the involved parameters of the problem, typically the satellite orbit and the gravity field under study (but also other dynamical parameters can be estimated) by using a least-square method. This mode makes use of the Trajectory Propagation (it can be run with both the propagators) and Measurement Generation modes. On top of it a Montecarlo Simulation can be run. In that case the orbit determination process is repeated many times changing the values of some dynamical parameters.Stable Orbits Determination Mode. The objective of this mode is to provide the user with a set of initial conditions, in terms of initial state vector or orbital elements for which the orbit of a spacecraft under certain asteroid environment will remain stable. Due to the perturbations in the vicinity of the asteroids there are no closed orbit solutions, therefore the stability criteria is defined in terms of time in which the spacecraft is enclosed within a given boundary. The approach follows a two step procedure. In a first step, simplified (though complex) dynamical models are used to described the surroundings of a single or binary asteroid. At this stage, a search for candidate orbits is carried out using state-of-the-art methods reported in the literature. The second step consists of checking the validity of the previously selected solution fulfils the bound conditions in the complete scenario.It is very important to understand that, from the point of view of the subsequent filtering process, a (simulated or external provided) gravity field must exist a priori. The reason is clearly defined by considering the only alternative option: providing to the filtering process measurements gathered by a certain (real or simulated) mission: in this case, any computation process would always miss the accuracy estimation of the selected determination method. A gravity field would then be computed, but nothing would be known about how good or bad it is.

In addition to these two main modules GRAVMOD-2 has an Auxiliary Functions Module that is providing the main interfaces to external components or to functions required in the computational layer. It is composed of the following components:

- Mission Analysis Propagator;
- Hi-Fi Orbits around Asteroid Propagator;
- PDB Interface;
- PANGU Interface;
- User Perturbations Interface;
- NLP Solver.

For instance, the Orbit Propagation and Determination Module needs to set perturbations to be used in one of the two propagators available (Mission Analysis Propagator and Hi-Fi Orbits around Asteroid Propagator), while the Gravity Modelling module makes use of the NLP Solver. Furthermore, the GRAVMOD-2 tool has interfaces with PANGU and PDB (that requires some modifications in the PDB) in order to exchange input/output data.

A dedicated GUI allows the user to insert the required inputs for the computational layer depending on the functionality required.

External components to the GRAVMOD-2 main software are: the ASTOS Mission Analysis Propagator and the GNC Propagator. They will be developed and used outside GRAVMOD-2 software as external packages, but they will share perturbation and gravity models (for instance those created in GRAVMOD-2 can be imported in these external propagators) with it.

4.1 New Features

Not only an upgrade of GRAVMOD-1 has been performed but many new features have been added. All the newly developed features are shortly listed here:

- License manager
- History manager
- Newly developed GUI including plotting capabilities
- Propagator extension (integrators, EoM, new perturbation models)
- Monte Carlo simulation
- Stable Orbit Determination function
- GNC Propagator
- New External Interfaces (PANGU, ASTOS, PDB, WHORP)

5 Conclusions

This document presented the main GRAVMOD-2 tool features. The objectives were achieved and the results coming from the testing phase and the study cases are quite promising. No big limitation/problems have been identified and the software results to be flexible and quite good performing.

GRAVMOD-2 has been completely recoded (only few GRAVMOD-1 algorithms have been reused) due to many problems encountered while testing/running GRAVMOD-1. Even though a lot effort had to be spent on recoding also the old functionalities, many new features have been added.